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Tribological Behaviour of Bio-lubricants for Machinery using a Four-ball Tribotester: A Review

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Abstract: The world's oil reserves are depleting, and the effort to reduce the dependency on mineral oil-based products has been carried out since the late 90s. The pursue of bio-lubricants made of vegetable and animal fats has become the top candidates as the base of the alternative bio-lubricant. However, for the bio-lubricant to be used in the industrial machinery sector, it needs to be tested for its tribological properties (coefficient of friction, wear scar diameter, flash temperature parameter, worn scar diameter). To ensure that the compound is suitable for machinery since machinery consists of smaller parts that function together. The most suitable test machine utilised in the tribological investigation is the four-ball tribotester test machine. The results found that fatty acid inside vegetable oil can reduce the coefficient of friction and the flash temperature parameter. However, at the same time, the wear scar diameters and worn scar observations indicate that the surface of the metals is attacked by the chemical reaction of oxygen present inside the fatty acid chain of vegetable oil.

Keywords: Bio-lubricants, Mineral Oil, Tribological Behaviour, Vegetable Oil.

1. Introduction

Due to the predicted circumstances of the depletion of crude oil, worldwide organisations and researchers have pushed forward research regarding replacing any product using petroleum with a more accessible and affordable alternative. Bio-lubricants are being intensively researched to develop a replacement for petroleum-based hydraulic oil. Bio-lubricants are mostly made of vegetable oil [1]. The only problem in creating bio-lubricants by using vegetables is unsaturated fatty acid inside the vegetable oil, which reduces the efficiency of the bio-lubricants. Since vegetable oils cannot be used directly as base stock oils for different applications, additives are needed to improve or enhance the samples' performance properties [2]. Additive materials are preferably multi-functional. In mineral oil, water, or even both, they are soluble. Chemists also search for additives that can be multi-functional and

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compatible with various chemicals in a mixture, both with other additives and base fluid, with such a range of results. [3].

This paper will review the method of testing the parameters of the compounds, which are the tribological behaviour of the compounds that determines the suitability of the mixture to be used as bio-lubricants. The method is known as the four-ball tribotester test. The parameters of produced compound (bio-lubricants) need to be tested before it is approved to be further developed to replace the commercial lubricants. This paper aims to determine the tribological behaviour of the bio-lubricants and mineral oils, review the tribological behaviour of the bio-lubricants using the four-ball tribotester method, and compare the tribological behaviour of the bio-lubricants with mineral oils.

2. Materials and Methods

The study was carried out to review the tribological behaviour of compounds to be developed as bio-lubricants The vegetable oil and mineral oil were compared for their tribological behaviour using a four-ball tribotester test using a suitable testing standard. The four-ball tribotester was used to test its tribological behaviour using articles and journals from 2012 to 2021, sourced from Elsevier, Scopus, and Google Scholar.

2.1 Focused parameters

Four parameters are reviewed and compared in this paper: coefficient of friction, wear scar diameter, flash temperature parameter and worn scar observation.

2.1.1 Coefficient of friction

The coefficient of friction is the ratio of the force of friction between two bodies to the force forcing them together [4]. The coefficient of friction can be calculated using the following Equation 1 and Equation 2:

$$\mu = \frac{T\sqrt{6}}{3Wr} \qquad (Eq. 1)$$

$$\mu = 0.22248 \text{ X } \frac{T}{W} \qquad (Eq. 2)$$

where μ is the coefficient of friction, *T* is the frictional torque in kg/mm, *W* is the applied load in kg and *r* is the distance from the centre of the contact surface on the lower balls to the axis of rotation. Equation 1 is used when *r* is needed to be measured, while Equation 2 is used when the *r* is already told, which would generally be 3.67 mm.

2.1.2 Wear scar diameter

Wear scar diameter refers to the diameter of the abrasion that occurs on the contacting surfaces. The wear scar diameter is mainly observed using CCD micrographs and a high-resolution microscope with I-Lite Solution software.

2.1.3 Flash temperature parameter

Flash temperature parameter indicates whether the lubricating film will break at a specific temperature. The flash temperature parameter can be calculated using Equation 3:

$$FTP = \frac{W}{d^{1.4}} \qquad (Eq. 3)$$

W is the average load in kilogrammes, and *d* is the mean wear scar dimension in millimetres at the given load in this equation.

2.1.4 Worn scar observation

Worn scar observation refers to the shape and condition of the abrasion that occurs on the object's surface. The worn scar observation is observed with a CCD micrograph, Scanning Electron Microscope (SEM) and high-resolution microscope with I-Lite Software.

3. Results and Discussion

3.1 List of oil used

The type of oils and the name of oils used in Table 1 are obtained from previous articles and journals.

Table 1: List of compounds used

Reference	Vegetable oil	Mineral oil	Nanoparticles
Chiong *et al.* (2012) [5]	RBD Palm Olein (RBD PO)	Paraffinic Mineral Oil (PMO)	Not used
Tiong *et al.* (2012) [6]	RBD Palm Stearin (RBD PS)	Paraffinic Mineral Oil (PMO)	Not used
Syahrullail *et al.* (2013a) [7]	Palm Fatty Acid Distillate (PFAD)	Commercial Metal Forming Oil (CMFO)	Not used
Syahrullail *et al.* (2013b) [8]	RBD Palm Olein (RBD PO)	Paraffinic Mineral Oil (PMO)	Not used
Zulkifli *et al.* (2013) [9]	Trimethylolpropane (TMP)	Paraffin Oil	Titanium Dioxide (TiO_2)
Habibullah *et al.* (2014) [10]	Jatropha Oil	SAE 40 (EO)	Not used
Jabal *et al.* (2014) [11]	RBD Palm Olein (RBD PO)	SAE 40 (EO)	Not used
Shaari *et al.* (2015) [12]	Palm Oil (PO)	Not used	Titanium Dioxide (TiO_2)
Hassan *et al.* (2016) [13]	RBD Palm Olein (RBD PO)	Mineral Engine Oil (EO)	Not used
Aiman *et al.* (2017a) [14]	Palm Kernel Oil (PKO)	Pour Point Depressants (PPD)	Not used
Aiman *et al.* (2017b) [15]	Palm Olein (PO)	Engine Oil (EO)	Not used
Zulhanafi *et al.* (20170 [16]	Palm Kernel Oil (PKO)	Not used	Copper Oxide (CuO)
Jabal (2018) [17]	Sunflower Oil	Not used	Not used
Afifah *et al.* (2019) [18]	Palm Stearin Methyl Ester (PSME)	SAE 40 (EO)	Not used

Rasheed (2019) [19]	Palm Oil (PO), Trimethylolpropane (TMP)	10W – 40	Graphene plate, Copper Oxide (CuO), Aluminium Oxide (Al_2O_3), Titanium Silicon Oxide ($TiSiO_4$), Nano glass powder
Zulhanafi *et al.* (2019) [20]	Super Olein (SPL)	Tertiary-butyl-hydroquinone (TBHQ)	Not used
Afifah *et al.* (2020) [21]	Palm Stearin Methyl Ester (PSME), Epoxidized Palm Stearin Methyl Ester (EPSME)	SAE 40	Not used
Suresha *et al.* (2020) [22]	Neem Oil (NO)	Not used	Graphene Nanoplatelets (GNP)
Zulhanafi *et al.* (2020) [23]	RBD Palme Olein (RBD PO), Double Fractionated Palm Olein (SPL), Palm Mid Olein (PMO)	VG 68	Not used
Mushtaq *et al.* (2021) [24]	Jatropha Oil (JO)	Not used	Graphene Nanoflakes

3.2 Coefficient of Friction

From previous articles and journals, the findings for the coefficient of friction are shown in Table 2.

Table 2: Coefficient of friction

Reference	Summary
Chiong *et al.* (2012) [5]	The presence of fatty acids in RBD PO help maintain the lubricant layer between the surface of the ball bearings, which minimised material transfer and adhesion between surfaces, resulting in RBD PO having a lower coefficient of friction than PMO even as the load increased.
Tiong *et al.* (2012) [6]	The fatty acid chains in vegetable oil produced monolayer film formation on the surface, prohibiting metal-to-metal contact. RBD PS showed a lower coefficient of friction compared to PMO even though the load was increased.
Syahrullail *et al.* (2013a) [7]	CMFO with the addition of PFAD shows a lower coefficient of friction than pure CMFO due to the presence of fatty acid chains that provides lubricating film on the metallic surfaces. These films significantly reduce the metal-to-metal contact between surfaces.
Syahrullail *et al.* (2013b) [8]	RBD PO has a lower coefficient of friction than PMO as fatty acid chains are present inside RBD PO, which helps maintain the lubricant layer, which coats the surface of the ball bearing, resulting in fewer contacts.

Zulkifli *et al.* (2013) [9]	TMP added with nanoparticles are observed to have a lower friction coefficient than pure TMP when observed under various loads. The addition of nanoparticles helps in creating an additional protective layer embedded in the contact surfaces.
Jabal *et al.* (2014) [11]	RBD PO mixed with EO showed a lower coefficient of friction than pure RBD PO and pure EO due to the combination of the presence of fatty acid inside RBD PO that acts as protecting film on the surfaces, and the presence of nanoparticles inside EO that functions as an additional lubricating film on the surfaces of the bearings.
Shaari *et al.* (2015) [12]	Palm oil added with Titanium Oxide (TiO_2) showed a lower coefficient of friction than pure palm oil due to the extra layer of nanoparticles that works as a lubricating film, aiding in lowering metal-to-metal contact between surfaces.
Hassan *et al.* (2016) [13]	RBD PO blended with mineral oil derivatives shows a relatively lower frictions coefficient than pure mineral oil samples due to the presence of fatty acid chains and nanoparticles mixtures that act as a lubricating film on the ball bearings' surfaces less metal-to-metal contact.
Aiman *et al.* (2017a) [14]	The coefficient of friction for PKO added with PPD variants shows a relatively higher friction coefficient than pure PKO and mineral oil because the amount of fatty acid in the mixture of PKO added with PPD is less than the amount of fatty acid present in pure PKO.
Aiman *et al.* (2017b) [15]	Palm olein added with engine oil shows a remarkably lower friction coefficient than semi synthetic engine oil due to fatty acid that helps maintain the lubricant layer between then contacting metal surface, thus reducing contacts.
Zulhanafi *et al.* (2017) [16]	The coefficient of friction is lower for PKO + CuO (Copper Oxide), followed by PKO and SAE 40 at high speed. This is due to the presence of nanoparticles (CuO) with a smaller size that interacts directly with the surfaces and forms an additional protective layer with the fatty acids from PKO, thus preventing metal-to-metal contact between surfaces.
Jabal *et al.* (2018) [17]	Sunflower oil shows a lower coefficient of friction under different loads compared to mineral oil. This condition is because the fatty acid chains in sunflower oil lubricate the contacting surface of the metals. While under pressure from the increasing loads, the fatty acid chains do not thin out or break down mineral oil particles.
Afifah *et al.* (2019) [18]	PSME showed a lower coefficient of friction than SAE 40 due to the ester functionality presence in the chemical structure of PSME and the presence of fatty acid.
Rasheed (2019) [19]	Due to the addition of nanoparticles into the samples, the coefficient of friction was observed to increase. This condition is because of the aggregation of nanoparticles that form larger particles that causes friction to happen between the two surfaces. Unlike nanoglass, which has a softer surface, proven to help reduce the coefficient of friction.

Zulhanafi *et al.* (2019) [20]	SPL + TBHQ showed the lowest coefficient of friction due to TBHQ, which acts as an antioxidant that prevents oxidation at high speed. At extreme pressure, TBHQ managed to prevent oxidation of oxygen molecules in fatty acid presents in SPL, thus maintaining the lubricative film that lubricates the surface of the metal.
Afifah *et al.* (2020) [21]	EPSME showed a relatively lower coefficient of friction than PSME and SAE 40 due to thicker protective film emitted by EPSME compared to PSME and SAE 40 due to the modification of the chemical structure of EPSME.
Suresha *et al.* (2020) [22]	The readings of the coefficient of friction were seen to be decreasing with the increasing amount of GNP added into the NO. The situation is caused by the increase in viscosity of the oil with the addition of GNP, which increases the thickness of the lubricating film enveloping the surface of the ball bearings.
Zulhanafi *et al.* (2020) [23]	The coefficient of friction of PMO in both test conditions (various temperatures and rotational speed) is lower than SPL and RBDPO. Although SPL has more fatty acid content and managed to maintain a low coefficient of friction in both test conditions, it was still outperformed by the performance shown by PMO.
Mushtaq *et al.* (2021) [24]	The addition of GPN was seen to have improved its lubricating properties. This condition was seen through the readings of the coefficient of friction after GPN was added into JO.

3.3 Wear Scar Diameter

From previous articles and journals, the findings for wear scar diameter are shown in Table 3.

Table 3: Wear scar diameter

Reference	Summary
Chiong *et al.* (2012) [5]	The wear scar diameter for bearings that encountered RBD PO was bigger than PMO due to oxygen in the fatty acid chains that oxidise with the metal surface, which then weakened the bearings surface.
Tiong *et al.* (2012) [6]	The wear scar diameter of RBD PS is higher than PMO due to sliding that occurred under different loads, which removes the metallic soap film from the surface of the bearings, which caused the wear to increase.
Syahrullail *et al.* (2013a) [7]	The wear scar diameter of CMFO + PFAD and pure PFAD are bigger than pure CMFO. This observation is due to the oxidation rate on the surface of the ball bearings originating from oxygen molecules in the fatty acid chains inside PFAD.
Syahrullail *et al.* (2013b) [8]	Because of incremental loads, RBD PO shows lower wear scar diameters than PMO. This is because the metallic soap film, which was rubbed away during sliding, producing an increase in wear due to the absence of the non-reactive detergents.
Zulkifli *et al.* (2013) [9]	The nanoparticles inside the TMP + nanoparticles improved the wear scar diameter at different loads. This because the nanoparticles successfully

	created a protective layer surrounding the surface of bearings, reducing metal-to-metal contact, compared to pure TMP.
Habibullah *et al.* (2014) [10]	Lube oil contaminated with Jatropha oil showed higher wear scar diameter due to the increase of fatty acid, which consists of oxygen molecule, which then oxidised with the metal's surface, thus increasing the wear scar diameter.
Jabal *et al.* (2014) [11]	It is found that RBD PO in RBD PO + SAE 40 variants worked as an anti-wear additive by creating a protective layer on the surface of the bearings, reflecting the results shown by the blends in producing lower wear scar diameter compared to pure RBD PO and pure EO.
Shaari *et al.* (2015) [12]	The recorded wear scar diameter of palm oil + TiO_2 is lower than pure palm oil due to the nanoparticles that act as an additional protective layer and the protective layer provided by fatty acid chains inside palm oil.
Hassan *et al.* (2016) [13]	The wear scar diameter of RBD PO + mineral oil blends is lower than pure RBD PO and pure mineral oil due to the extra layer of a protective layer provided by fatty acid chains inside RBD PO and nanoparticles inside mineral oil that lubricates the bearings.
Aiman *et al.* (2017a) [14]	The wear scar diameter of mineral oil is lower than PKO. However, the readings for PKO are not that far apart from mineral oil, indicating that PKO has the potentials to be developed in further research according to the benchmark, which is fully formulated mineral oil.
Aiman *et al.* (2017b) [15]	EO + PO blends show lower wear scar diameter compared to pure EO and pure PO. This is due to the extra protection layer provided from fatty acid from PO and nanoparticles from EO that acts as a protective film on the surface of the bearings.
Zulhanafi *et al.* (2017) [16]	PKO + CuO compound showed the highest reading for wear scar diameter due to the addition of oxygen molecules from CuO, thus increasing the chemical reaction between oxygen and the metallic surface of the bearings.
Jabal *et al.* (2018) [17]	Sunflower oil showed a smaller wear scar diameter than mineral oil due to the presence of unsaturated fatty acid that reacts with the bare metallic surfaces that created a thin metallic soap layer. Adsorption layers cause this.
Afifah *et al.* (2019) [18]	Due to the presence of unsaturated fatty acid in PSME, it has a bigger wear scar diameter compared to SAE 40 that was formed on the ball bearings. The unsaturated double bonds are easily oxidised and much reactive compared to saturated fatty acids in oxygen compounds.
Rasheed (2019) [19]	Due to the addition of nanoparticles into the compounds, the wear scar diameter was observed to be more compared to compounds without the addition of nanoparticles. Nanoglass managed to help reduce the reading of wear scar diameter due to its softer surface area.
Zulhanafi *et al.* (2019) [20]	With the addition of TBHQ, the existence of the thin protective film was prolonged, and the wear scar diameter observed was comparatively

	smaller. TBHQ also provided a smoother contact surface, leading to a smaller wear scar diameter.
Afifah *et al.* (2020) [21]	EPSME, compared to PSME, shows a lower wear scar diameter, proving the efficiency of the formation of thicker protective film on the steel surfaces due to the epoxidation reaction where the chemical structure of PSME was modified into EPSME.
Suresha *et al.* (2020) [22]	The viscosity of NO becomes thicker as the amount of GNP added into NO increases. Due to this, there is less metal-to-metal contact between the ball bearings, and thus, the reading of wear scar diameter decreases as the GNP added helps coats the surface of the bearings.
Zulhanafi *et al.* (2020) [23]	In all test conditions, PMO showed a smaller wear scar diameter compared to SPL and RBDPO. The oxidation process that occurs due to the oxygen molecules inside the fatty acid chains is to blame in both SPL and RBDPO, which causes chemical attacks on the surface of the ball bearings, which results in a larger wear scar diameter.
Mushtaq *et al.* (2021) [24]	Due to the improved lubricating properties with the addition of GPN into JO, the reading of wear of scar diameter was seen to become lower as the amount of GPN added into the JO increased.

3.4 Flash Temperature Parameter

From previous articles and journals, the findings for flash temperature parameters are shown in Table 4.

Table 4: Flash temperature parameter

Reference	Summary
Tiong *et al.* (2012) [5]	PMO has a higher value for flash temperature parameters indicating that it is unlikely for the lubricant film to break down or thin out as it is coating the surface of the bearing.
Syahrullail *et al.* (2013b) [8]	At high pressure, RBD PO showed a higher flash temperature parameter compared to PMO.
Habibullah *et al.* (2014) [10]	The flash temperature parameter in this experiment was found to increase proportionally to the increment of the amount of Jatropha oil added into lube oil.
Jabal *et al.* (2014) [11]	The RBD PO + EO blends show increasing reading for flash temperature parameters with the increasing concentration of RBD PO added into the mixture.
Hassan *et al.* (2016) [13]	Blends of EO + RBD PO of various concentrations show higher flash temperature parameters than pure RBD PO and pure EO.
Aiman *et al.* (2017b) [15]	Flash temperature for various blends of EO + PO at various loads showed that all the samples perform well under extreme pressure compared to pure PO.

Jabal *et al.* (2018) [17]	The highest flash temperature value was shown by sunflower oil, indicating sunflower oil can help minimise the possibility of the thin protective film from breaking down under high pressure.

3.5 Worn scar observation

From previous articles and journals, the findings for worn scar observation are shown in Table 5.

Table 5: Worn scar observation

Reference	Summary
Chiong *et al.* (2012) [5]	The surface of the ball bearing lubricated with RBD PO was observed to have a more significant wear scar. However, the fatty acid in RBD PO seeped into the asperities formed and acts as a lubricating film on the surface of the bearings, resulting in a lower coefficient of friction.
Tiong *et al.* (2012) [6]	The surface topography of the worn surface of the ball bearings that encountered RBD PS, rough surfaces were observed (deep valley of asperities) that created an oil reservoir that acts as a lubricating film on the surface bearings.
Zulkifli *et al.* (2013) [9]	The nanoparticles are proven to provide help in minimising the scar produced on the surface of the bearings, but only to some extent. As the load was increased, boundary lubrication occurred, and the nanoparticles start to breaks out. In a high-pressure condition, the nanoparticles were observed to have molten and welded on the surface of the bearings.
Hassan *et al.* (2016) [13]	RBD PO + EO blends show a lower diametric wear scar value than pure RBD PO and pure EO. This is due to the increase in kinematic viscosity and fatty acid that prevents the surface from experiencing rubbing contact.
Aiman *et al.* (2017a) [14]	The sample with a minor concentration of fatty acid inside the blends (A2-30%; RBD PKO 70% + PPD 30%) was the most affected. The observation on the ball bearing surface shows that these blends produced deep scars at various loads due to the lack of fatty acid inside the sample.
Aiman *et al.* (2017b) [15]	The surface of the bearings shows that the various blends of RBD PO + EO underperformed compared to the EO. This observation is due to the observed surface of bearings, which shows shallow grooves, coarse deep scratches, and adhesive wear that occurs for bearings lubricated with RBD PO + EO blends under increasing pressure.
Zulhanafi *et al.* (2017) [16]	PKO sample and various PKO + CuO blends exhibit light and dark scratches onto the bearings. As the speed increased, the heat produced promoted the oxidation process towards the oxygen double bond molecules inside the fatty acid chain, which then attacked the bearings' surface.
Afifah *et al.* (2019) [18]	In an oxygen compound, unsaturated double bonds are more reactive and easily oxidised than saturated fatty acids. Steel surfaces lubricated with PSME, on the other hand, generated a smoother scar than those greased with commercial lubricant. This observation demonstrated that PSME

	provided a better surface protection film by absorbing and forming a monolayer film to separate metal-to-metal interfaces.
Rasheed (2019) [19]	With the addition of nanoparticles, it was discovered that the scar grew larger. This condition is because nanoparticles clump together to produce larger particles, causing friction and wear between the two surfaces. In contrast to previous nanomaterials, the nanoglass, due to its softer surface area, reduced scarring.
Zulhanafi *et al.* (2019) [20]	SPL was rapidly oxidised at higher speeds and loads. In contrast, SPL + TBHQ could protect the base oil and postpone the oxidation process, resulting in good appearances of physical wear. The capacity to protect the thin layer boundary film contributed to a smoother contacting surface as well.
Afifah *et al.* (2020) [21]	Bearings lubricated with EPSME showed less worn scar than SAE 40 due to the epoxidation of the vegetable oil, which proves that altering the chemical structure of the vegetable oil results in a high capability of minimising the collisions between asperities and reduce metal-to-metal contact.
Suresha *et al.* (2020) [22]	Lower concentrations of GNPs in the oil produced darker concentric grooves, indicating abrasive wear. In contrast, more significant percentages of GNPs produced a smoother wear track, indicating reduced contact between steel balls. The deeper grooves are darker, whereas the shallower grooves are lighter.
Zulhanafi *et al.* (2020) [23]	Saturated fatty acid molecules with a stronger molecular connection with the metal surface gave the best protection from asperities contact, resulting in a smoother Ra. SPL, which has a high unsaturated fatty acid content, has more oxidation effects in physical wear studies, resulting in severe degradation on the contact surface at high temperatures and rotational speeds.
Mushtaq *et al.* (2021) [24]	Through surface analysis, with the addition of GPN into JO, a smooth surface was observed. Despite few ploughing marks, minimum wear was observed, and the surface looks smooth.

Based on the data, it can be concluded that the addition of fatty acid from vegetable oil reduced the coefficient of friction readings when compared to the readings for mineral oil. This condition is due to the fatty acid, which acts as a protective layer or film on the ball bearings' surfaces, minimising metal-to-metal contact and rubbing impacts, lowering the coefficient of friction. The addition of nanoparticles to vegetable oil improves the protective layer on bearing surfaces.

The wear scar diameters, on the other hand, reveal a variety of effects. This is due to the presence of oxygen particles inside fatty acids from vegetable oil, which underwent oxidation as a result of being exposed to extreme pressure or speed, which produces high heat, triggering oxidation between oxygen molecules and the surface of the ball bearings, or oxygen molecules with surrounding particles. Asperities and burn scars appear on the surface of the ball bearing as a result of the oxidation process. These asperities can be seen in worn scar observation using SEM and CCD micrographs, indicating that ball bearings with deep asperities have a lower coefficient of friction because the asperities act as a reservoir for fatty acid, which helps lubricate the bearings' surfaces, resulting in minimal contact between the bearings.

The load applied and the worn scar diameter has an impact on the flash temperature parameter. Under heavy load, the compound with a high viscosity was shown to be less likely to crack or thin out, resulting in a higher flash temperature parameter. The lubricant must have a slight wear scar diameter to provide the best flash temperature parameter. This is because the worn scar diameter and the flash temperature parameter are inversely related.

4. Conclusion and Recommendations

It is concluded that all the objectives mentioned are successfully achieved. The tribological behaviour of all the compounds is successfully determined from the results in previous research articles and journals. The tribological behaviour of all the tested compounds is successfully resolved by using a four-ball tribotester. A few recommendations can be made through this study to introduce antioxidants into the mixture of bio-lubricants. First, the introduction of antioxidants helps prevent oxygen atoms from oxidising during high temperatures or in a high-pressure situation when the lubricant is in contact with the metallic surface of the ball bearing. Finally, introducing the addition of additives into the bio-lubricant. Although the bio-lubricant works well in reducing friction coefficient and produces high flash temperature parameters, anti-wear agents are needed to reduce the wear scar diameter and reduce worn scar observations.

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