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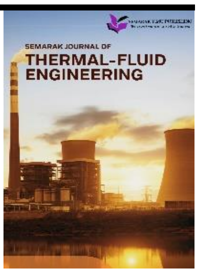

Wear-Preventive Characteristics of a Lubricating Bio-Fluid Using a Four-Ball Method

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ABSTRACT

This project studies the tribological performance of blended coconut oil as an environmentally friendly lubricant using a four-ball experiment. There has been growing concern over the use of mineral oils as lubricants in environmental issues such as soil and water pollution due to their persistence and potential to leach harmful chemicals into the environment. Several studies have been conducted on using coconut oils as alternatives to industrial gear oil; however, limited research has been conducted, especially regarding the different concentrations of blended coconut oil. Therefore, the tribological characteristics of lubricants with different ratios of Industrial Gear Oil VS 220 and coconut oil (5%, 10%, 15%, 20%, 25%, and 30%) were experimentally tested. The coefficients of friction and wear-preventive characteristics were evaluated with control based on the ASTM D4172 standard. Additionally, six (6) samples were blended using the sonication technique with the help of bench-top ultrasonic cleaner (DELTA). Hence, the result clearly indicates that 30% exhibited a lower friction coefficient (0.055) than 10%, which showed the highest value at 0.09. The surface morphology of the worn surfaces was observed using an Olympus Metallurgical Microscope. Under microscopic analysis, the 30% oil concentration yielded a smaller scar diameter than the other concentrations. As a result, increasing the mixed coconut oil concentration in the blend, specifically to 30%, resulted in a noticeable improvement in tribological performance. This included a reduction in the coefficient of friction and a decrease in the scar diameter compared with the other samples, suggesting that higher concentrations of coconut oil can enhance the lubricant's environmental friendliness and performance in industry.

1. Introduction

In industrial applications, lubricants, such as lubricating greases, lengthen the life of machine parts with moving parts. Lubricants have two functions: reducing friction and energy consumption and preventing premature machine element failure in the bearing sector due to wear [1]. In comparison to mineral-based lubricants, bio-lubricants have improved biodegradability, reduced toxicity, a higher viscosity index, and are more recyclable and renewable. As a result, they provide excellent replacements for mineral-based lubricants [2]. However, low-temperature properties, wax

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formation, poor cold flow, high pour point (PP), and limited oxidative stability are some of the cons of bio-lubricants that need to be addressed [3, 4] which this study aims to address. It has been shown that compared with mineral-based lubricants, bio-lubricants have better biodegradability, lower toxicity, and a higher viscosity index. They are also better alternatives to mineral-based lubricants because they are more recyclable and renewable [5]. While their eco-friendly properties and renewable sources have made them increasingly popular in various industries, researchers are also exploring their potential in enhancing the performance and biocompatibility of medical implants [6].

Vegetable oils are plentiful, whereas mineral oils only rely on a limited supply of petroleum, giving bio-based lubricants from the petrochemical industries a bigger advantage over mineral oil lubricants in terms of sustainability and economics [7]. Vegetable oils have excellent temperature-viscosity characteristics and little volatility. Additionally, they have excellent metal surface adherence, which is necessary for lubricating properties [8].

Vegetable oils are highly biodegradable, renewable, and low in toxicity; thus, they are preferred over mineral oils as lubricating base oils. Due to their amphiphilic character stemming from polar groups and a triacylglycerol structure with fatty acid chains, vegetable oils are effective lubricants. Coconut oil is one of the vegetable oils with the lowest coefficient of friction at metallic interfaces; nonetheless, it has a higher wear rate and pour point than mineral oils, which restrict its use as a commercial lubricant [9]. Growing worldwide support for vegetable oil as the base oil for car lubricants stems from growing concerns about the harm that mineral oil-based lubricants bring to the environment. Due to its high congelation temperature, coconut oil is not commonly used, although it is more stable than many other vegetable oils [10].

Even though there has not been much research on using pure vegetable oil as fuel without converting it to biodiesel, it remains an important field of study. Using pure vegetable oil as fuel has many potential advantages, including improved sustainability and lower greenhouse gas emissions [11, 12]. Vegetable oils alone are considered insufficient for large-scale or widespread fuel use. This is due to the high viscosity of straight vegetable oils, which prevents them from effectively mixing with air in combustion chambers, resulting in insufficient fuel atomisation [13]. Blending vegetable oil with gasoline is one of the three methods frequently used to solve this problem [14]. Diesel fuel and vegetable oil were mixed in different volume ratios. Engine performance decreased as the mixtures' vegetable oil concentration of the mixtures increased; however, the emission characteristics improved [15, 16]. In addition, a few studies have been conducted to investigate the tribological properties of palm oil mixed with food-grade lubricants at varying concentrations using pin-on-disc experiments and the Response Surface Methodology (RSM) approach [17, 18].

However, there are inherent disadvantages to vegetable oils that are typically addressed by modification [19]. As a result, vegetable oils performed better in antiwear and friction without additives than mineral base oils [20, 21], scratching the load limit [22], and endurance to fatigue [23]. The prospective options that are becoming increasingly common because of their superior qualities are vegetable oils (VO) [24]. Among the vegetable oils considered in the study, coconut oil demonstrated the highest pour point and the lowest weight gain, an indication of oxidative stability, under oxidative conditions [25].

The industry currently uses the four-ball tester, also called the Shell four-ball tester, extensively to assess the lubricating properties of lubricating oils and greases, specifically extreme pressure (EP), wear prevention (WP), and frictional behaviour, under various international standard procedures [26]. Among the other contaminated lubricant samples, the lubricant contaminated with vegetable oil biodiesel fuel with nanoparticles showed a significant reduction in the parameters, COF coefficient, and wear scar diameter WCD [27]. In addition, a few studies have addressed the use of coconut oil as a lubricant, primarily from the perspective of incorporating different nanoparticles to enhance their characteristics [28]. Moreover, it was discovered from the published studies that there had been no investigation into how the development level of coconuts affected the lubricating qualities of the resulting oils. Therefore, it has not been clarified how the development degree of coconuts on the change in lubricating characteristics [29].

According to a study, a blend of bio-lubricants and nano-additive provides superior lubrication performance [30, 31]. In addition, current research has stated that vegetable oils are becoming increasingly popular due to growing environmental consciousness and their substantial environmental benefits [32]. Numerous studies, especially on lubricants containing nano-additives, have revealed reduced wear, improved load-bearing capability, and decreased friction [33]. Figure 1 shows study on coconut oil in 2010 to 2024. The graph illustrates research trends in coconut oil over 15 years from 2010 to 2024. It shows a steady increase in publications from 642 in 2010 to 1063 in 2015, followed by growth to 1533 in 2018 and 2161 in 2020. The number of publications peaked at 3458 in 2023. In 2024, the value recorded indicates that there is still ongoing research using coconut oil. Overall, the graph highlights a significant rise in research interest in coconut oil.

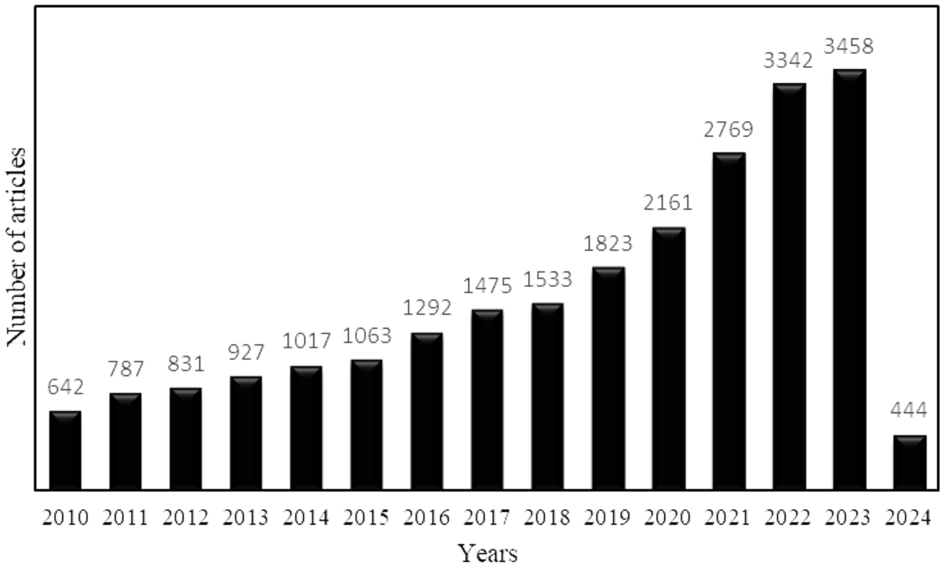

Fig. 1. Research trends on coconut oil during the years

2. Methodology

The tribological characteristics of lubricants with different ratios of Industrial Gear Oil VS 220 and coconut oil (5%, 10%, 15%, 20%, 25%, and 30%) were experimentally tested. The coefficients of friction and wear-preventive characteristics were evaluated with control based on the ASTM D4172 standard. Additionally, six (6) samples were blended using the sonication technique with the help of bench-top ultrasonic cleaner (DELTA).

2.1 Preparation of oil Samples

This experiment used gear oil (GO) mixed with different concentrations of coconut oil (CCO). The gear oil used was 85W140 GL5. There will be 6 samples of the lubricant with different coconut oil concentrations. This oil composition is prepared by measuring it using a syringe and beaker and then mixed. Table 1 lists the properties of 85W140 GL5 Gear oil and coconut oil. During handling the oil, all required safety procedures and personal protection equipment were considered.

Table 1
Properties of base oil and coconut oil

Properties	85W140 GL5 gear oil	Coconut oil
Pour point (℃)	-15	24
Flash point (℃)	245	260
Density at 15 (℃) (kg/L)	0.907	0.924
Viscosity at 40 (℃) (mm^2/s)	340.0	35
Viscosity at 100 (℃) (mm^2/s)	27.0	8

The biodegradable and lubricating characteristics of gear oils can be enhanced to be environmentally friendly. Coconut oil ideally has high oxidative stability, meaning it resists breakdown under high pressure and temperature, making it an effective lubricant for machinery that operates under extreme conditions. Therefore, in this study, coconut oil is used to be blended with the base oil, and the tribological characteristic is being analysed.

In this experiment, oil samples were prepared in the range of 0%-30% coconut oil. There are 6 samples of the lubricant with different coconut oil concentrations. The coconut oil concentrations are 0%, 5%, 10%, 15%, 20%, 25%, and 30%. A total volume of 50 ml is prepared for each sample, from which 10 ml will be used for both the four-ball and viscosity tests. A bench-top ultrasonic cleaner was used to mix the oil composition after its measurement using a syringe. For 30 min, the ultrasonic cleaner is operated at 55 °C. Eq. (1) is used to determine the oil composition. The oil composition is calculated using Eq. (1).

$$\text{Oil composition} = \mathrm{Y}\,\frac{\mathrm{X}}{100} \tag{1}$$

where Y is the total oil composition (30 ml), and X is the composition for 5%, 10%, 15%, 20%, 25%, and 30%. Table 2 lists the oil compositions of the blended coconut oil. Coconut oil and gear box oil are blended using the sonication technique with the help of an ultrasonic.

Table 2
Percentage of blended coconut oil and food grade gear box oil VS 220

Sample	Volume of food grade (ml)	Coconut oil (ml)	Percentage (coconut oil)
CCO 5	47.5	2.5	5%
CCO 10	45.0	5.0	10%
CCO15	42.5	7.5	15%
CCO 20	40.0	10.0	20%
CCO 25	37.5	12.5	25%
CCO 30	35.0	15.0	30%

2.2 Experimental Apparatus and Material

2.2.1 Viscometer

A viscometer is an apparatus that determines the viscosity of a fluid, which fundamentally varies as resistance to motion. Viscosity is an important property in many applications because it plays a role in determining how fluids behave under different conditions. From glass capillary tubes to sophisticated rotational devices that give exactly accurate measurements, viscometers now come in a wide variety of setups. Liquids with high viscosity are more resistant to flow. Hence, it offers good lubrication and protection against wear for mechanical applications, but it could cause heightened energy consumption and movement that is slower. On top of that, fluids with a lower viscosity flow more easily and hence reduce energy consumption and enable faster movement but may not provide satisfactory lubrication and protection, consequently increasing wear and tear on mechanical components. Therefore, it is important to select the appropriate viscosity for a particular duty to balance the performance, efficiency, and component life.

In this study, a capillary (glass) viscometer was chosen owing to its availability and functions. The major apparatus for the capillary viscometer is a U-shaped glass tube. The U-tube is preferably a Cannon-Fenske routine viscometer in which each tube has a specific temperature constant. This is indicated in the Table 3 below. The temperature constant for each U-tube Equipment, Cannon-Fenske 100 and 150 series) used to measure the viscosity at 40℃. The tube was filled with the oil sample to a specific level. Subsequently, the sample is submerged in a temperature-controlled bath set to 40℃. The configuration of the oil level is as indicated in Figure 2. A and B are timing marks, C is filling mark. The time in seconds for a fixed amount of fluid to flow within the tube from one level to another via suction or the force of gravity was recorded using a stopwatch. The time taken was determined by calculating the readings using the time (stopwatch).

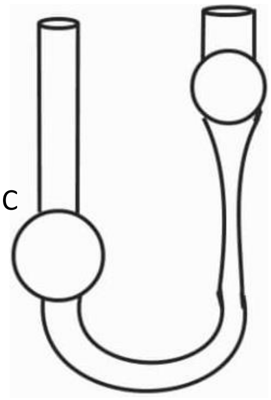

Fig. 1. Ostwald type capillary viscometer

For precision, the procedure should be repeated at least three times. Through the use of Eq. (2), the kinematic viscosity of the oil sample was determined; the constant chosen depended on the specific tube used to conduct the experiment. For this experiment, the following procedures were performed using an ASTM D445-97 Gravity Flow U-shaped Glass Tube Capillary Viscometer.

$$\mathrm{v} = \mathrm{T}_{\mathrm{constant}}\mathrm{t} \tag{2}$$

where v is the absolute kinematic viscosity, $\mathrm{T}_{\mathrm{constant}}$ is the temperature constant specify to the particular tube (C) and t time taken in seconds. Table 3 indicates the specification of Cannon-Fenske Routine Viscometer.

Table 3
Cannon-Fenske Routine Viscometer specification

Size tube	Serial number	Temperature 40℃ constant	Temperature 100℃ constant	Kinematic viscosity range
150	259D	0.03199	0.03185	7 to 35
	P982	0.03602	0.03586	7 to 35
	J140	0.2467	0.2456	50 to 250
300	59W	0.24427	0.24454	50 to 250
	60W	0.23374	0.23406	50 to 250

2.2.2 Fourball tester tribology machine

ASTM D2266 and D4172 are used to determine the wear characteristics of lubricating oils and greases, respectively. The four-ball test method was used to assess the anti-wear properties of the fluid lubricants in sliding contact. The four-ball test method demonstrates the effectiveness of a lubricant in reducing wear; the smaller the wear scars, the more effective the lubricant is at reducing wear. In a typical test, three stationary balls are arranged in a cloverleaf pattern and clamped together, while a fourth ball is placed on top and rotated against them under controlled loads, temperatures, and speeds. The test generates data on parameters such as the wear scar diameter on the stationary balls, friction coefficient, and frictional torque. This standard method is ASTM D4172, which provides valuable insights into the lubricant's ability to minimise wear and friction between contacting surfaces, making it essential for assessing the performance and suitability of lubricants in various industrial applications. The results can help compare different lubricants and optimise formulations for better performance and longer equipment life. Figure 3 shows a schematic of the four-ball test.

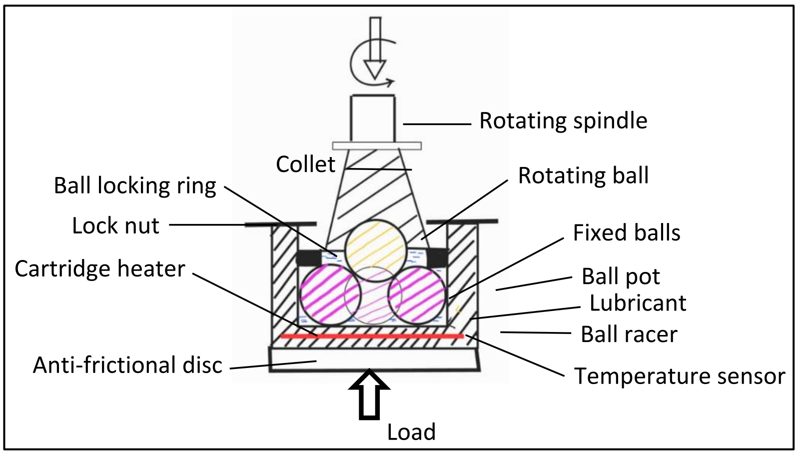

Fig. 3. Schematic diagram of the four-ball test (section view)

The four-ball test uses three steel balls that are strapped together and coated in lubricating grease or oil. Next, a fourth steel ball is forced into the steel balls either with 15 or 40 kg of force. After 60 min of testing, the wear scars were determined using a computer programme and a microscope. The average wear scars were collected and reported, and these average wear scars were used to compare lubricants. The four-ball data, which only have one load setting at 40 kg of force, is excellent for differentiating various lubricants with different physical features, such as wear protection, load-bearing capacity, and friction reduction temperature and speed parameters, as in D4172. The time setting for each of the four ball wear techniques was 60 min. The test ball machine parameter is shown in Table 4.

Table 4
Four-ball tribological test operating conditions and specifications of tested ball

Test parameter	Operating hours
Spindle rotational speed	1200 rpm
Load	40kg
Sample temperature	75 °C
Required time	60 min
Characteristics	Specification of tested ball
Hardness	62
Surface roughness	0.04µm
Diameter of the ball	12.7 mm
Material	Carbon chromium stell (SKF)

3. Results

3.1 Kinematic Viscosity

Kinematic viscosity impacts the production and maintenance of a lubricating film, which keeps surfaces in contact apart and prevents metal-to-metal contact while also lowering wear. A suitable kinematic oil viscosity guarantees effective lubrication, providing sufficient film strength to support loads while reducing energy dissipation due to internal fluid friction. Although too low a viscosity may fail to sufficiently separate and protect surfaces, increasing wear and perhaps equipment failure, too high a viscosity can led to higher drag and energy consumption. Therefore, to maximise the balance between preservation and efficiency in lubricating systems, selecting an appropriate kinematic viscosity is important.

All six samples were examined and experimented. Figure 4 shows that the highest kinematic viscosity was observed for the 5% (156.432) coconut oil blended sample, followed by 10% (137.6093) and 25% (142.1429), while the lowest kinematic viscosity was observed for the 30% (113.2704) coconut oil composition, followed by 15% (116.5895) and 20% (136.4981). Therefore, the fact that the lower the kinematic viscosity, the better the lubricant correlated with the value of the coefficient of friction and the stability of the friction torque. Hence, 30% of coconut oil has the lowest kinematic viscosity as it has the lowest COF. From this study, it is proven that coconut oil blended with mineral oil lubricants can exhibit favourable tribological properties, such as reduced kinematic viscosity, when a suitable ratio of oil and additives is incorporated into the lubricant composition.

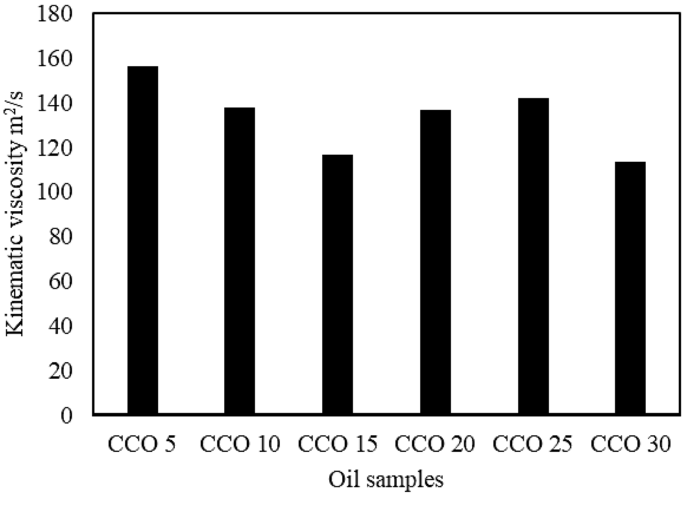

Fig. 4. Kinematic viscosity for different oil composition of coconut oil

3.2 Wear Scar Diameter

Wear scar diameter provides information regarding the effectiveness of the lubricant in protecting the contacting surfaces and saving the material from loss due to frictional forces. Many studies discuss wear-scarce diameters and lubricant performance. For example, a report on lubricant viscosity and its effect on wear scar diameter revealed a significant relationship between high-viscosity lubricants and less wear. Another report has studied the impact of lubricant additives on the wear scar diameter and found that some lubricant additives can substantially reduce wear, resulting in a smaller wear scar diameter. Consequently, in this study, the wear scar diameter of each oil was measured using an Olympus metallurgical microscope. The wear scar diameter of each composition had been showed in Figure 5.

From Figure 5, the graph shows the wear scar diameter (in mm) for different coconut oil samples labelled CCO 5, CCO 10, CCO 15, CCO 20, CCO 25, and CCO 30, representing various concentrations of coconut oil in a lubricant blend. With a wear scar diameter of 0.022 mm, CCO 10 provided the least amount of wear protection. The wear scar diameters of the remaining samples (CCO 5, CCO 15, CCO 20, CCO 25, and CCO 30) are comparable at 0.02 mm, with CCO 5 and CCO 30 demonstrating slightly higher wear protection. This indicates that most coconut oil blends, except for CCO 10, offer equal levels of wear protection, emphasising the importance of optimising blend ratios for better results. Figures 6 and 7 show the images of wear scar for each percentage of coconut oil samples.

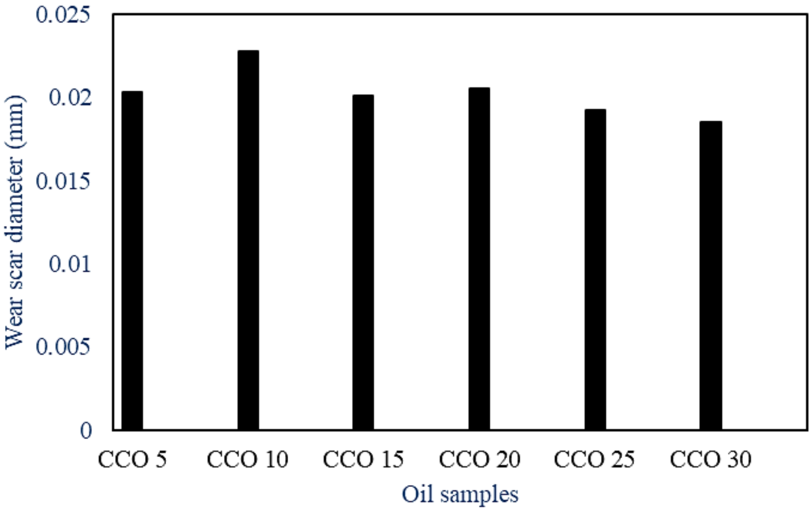

Fig. 5. Wear scar diameter for different oil composition of coconut oil

(a) (b) (c)

Fig. 6. Wear scar under Olympus microscope for each coconut oil samples (a) 5% (b) 10% (c) 15%


(a) (b) (c)

Fig. 7. Wear scar under Olympus microscope for each coconut oil samples (a) 20% (b) 25% (c) 30%

3.3 Friction Torque and Coefficient of Friction

A specialised data collecting system is employed to record the friction torque from the four-ball tribometer machine. At the beginning of the test, it was expected that the friction torque of each tested lubricant would increase rapidly. After 5-10 min, the friction torque data should stabilise. The average friction torque and friction coefficient under steady-state conditions were recorded. We used Eq. (3) to calculate the coefficient of friction.

$$\text{Coefficient of friction} = Y\,\frac{T\sqrt{6}}{3Wr} \tag{3}$$

where, T is the frictional torque (kg.mm), W is the applied load (kg), and r is the distance from the centre of the contact surface on the lower balls to the axis of rotation. The results are plotted as follows.

In Figure 8, the samples are labelled as CCO 5, CCO 10, CCO 15, CCO 20, CCO 25, and CCO30, indicating the percentage of coconut oil in the blend. At onset (time = 0), all samples exhibited a sharp increase in friction coefficient. Notably, CCO 30 (green line) achieved the lowest stable CoF at approximately 0.05, indicating superior lubricating properties and minimal friction resistance. In contrast, CCO 5 (orange line) stabilised at a CoF of approximately 0.08, denoting higher frictional resistance among the samples. The intermediate concentrations of CCO 10, CCO 15, CCO 20, and CCO 25 showed CoF values that lie between these two extremes, with CCO 15 (green line) stabilising around 0.06, reflecting better performance than CCO 5, but not as low as CCO 30. Overall, the data suggest that higher coconut oil concentrations in the blend tend to lower the friction coefficient, enhancing the lubricating efficiency of the mixture. This pattern demonstrates the potential of coconut oil as an effective component for reducing friction in lubricating applications.

Figure 9 shows the graph of friction torque against time for different oil compositions of coconut oil, providing a comprehensive view of how these blends behave under operational conditions. Figure 8 shows the graph of friction torque against time for different oil compositions of coconut oil, providing a comprehensive view of how these blends behave under operational conditions. The compositions tested include various ratios of coconut oil mixed with industrial gear oil. Over time, compositions with higher percentages of coconut oil exhibited a decrease in friction torque, suggesting that coconut oil's lubricating properties improved with increasing concentration. The 30% coconut oil blend exhibited the lowest friction torque consistently over time, indicating stable and effective lubrication. In contrast, low coconut oil concentrations demonstrated higher and more fluctuating friction torques, which may imply less stable lubrication.

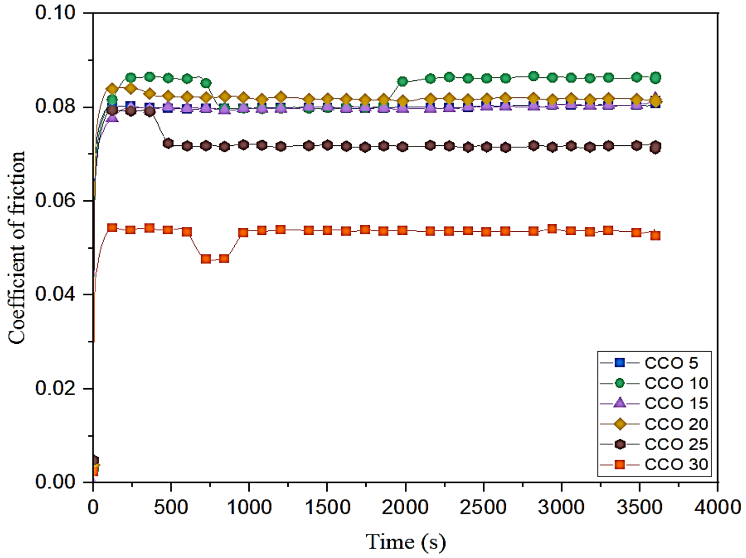

Fig. 8. Coefficient of friction against time for different oil composition of coconut oil

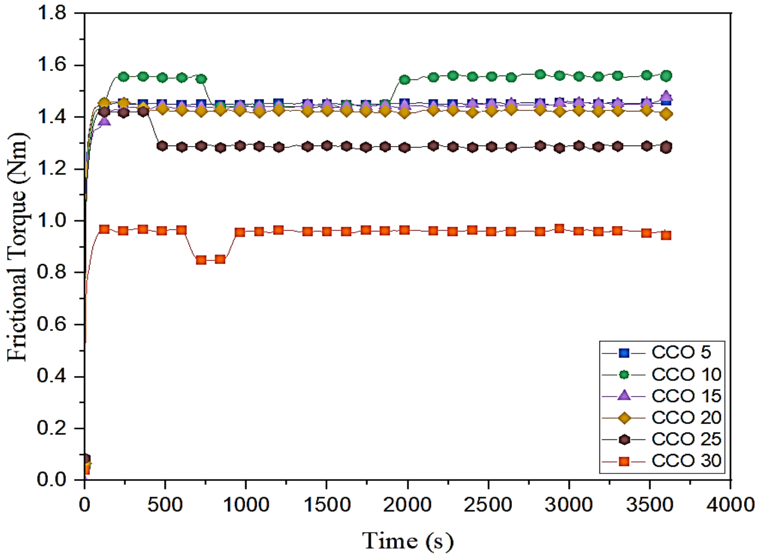

Fig. 9. Friction torque against time for different oil composition of coconut oil

Based on Figure 10, the coefficient of friction for three different lubricants is shown on the graph over time: "Current" (Coconut Oil), "Olive Oil" and "Soybean Oil". The lubricant labelled as "Current" (Coconut Oil), (circled) demonstrated the lowest and most consistent coefficient of friction, remaining between 0.05 and 0.06 during the test. It exhibits superior ability to reduce friction and maintains steady performance over an extended period. The "Olive Oil" lubricant, which is marked by squares, on the other hand, shows a greater and more variable coefficient of friction, beginning at 0.08 and rising to roughly 0.10, indicating less stability and higher friction levels. The triangle-designated "Soybean Oil" lubricant performs intermediately, with a relatively steady coefficient of friction of 0.08. Based on these findings, the “Coconut Oil” lubricant is the best at lowering friction out of the three, making it a better option for applications that require low and consistent friction. The "Coconut Oil" lubricant exhibits the best overall performance in this setting, highlighting the significance of lubricant selection in achieving optimal tribological performance.

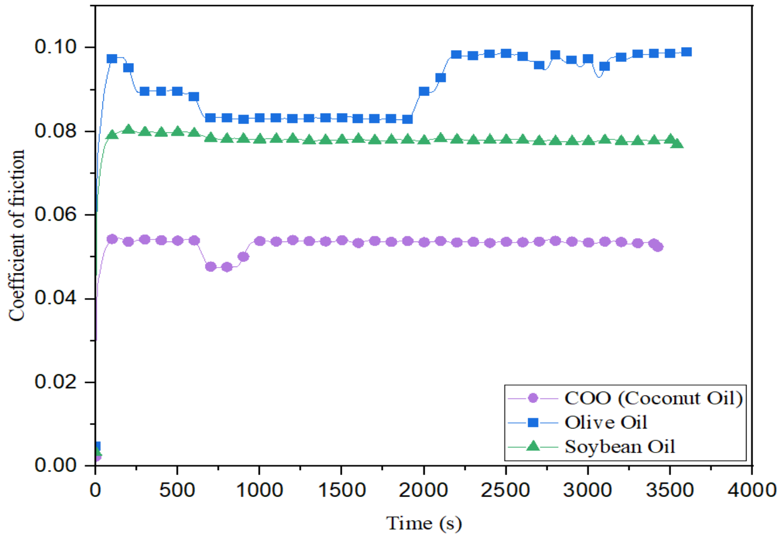

Fig. 10. Comparison graph of coefficient of friction with 3 different oil samples

Figure 11 illustrates the variation in frictional torque (in Nm) over time (in seconds) for three different lubricants: "Coconut Oil" (marked with circles), "Olive Oil" (marked with squares), and "Soybean Oil" from (marked with triangles). The "Coconut Oil" lubricant demonstrates a stable and lower frictional torque, maintaining approximately 0.8–1.0 Nm throughout the test duration, indicating consistent performance and low friction. In contrast, the "Olive Oil" lubricant shows higher and more fluctuating frictional torque values, starting around 1.4 Nm and rising to approximately 1.7 Nm, suggesting less stability and higher friction. The "Soybean Oil" lubricant exhibits intermediate performance with a slightly higher initial torque of approximately 1.2 Nm, stabilising at this value throughout the test. These results suggest that the "Coconut Oil" lubricant has superior friction-reducing properties compared to the other two lubricants tested, highlighting its potential effectiveness in applications requiring stable and low frictional torque.

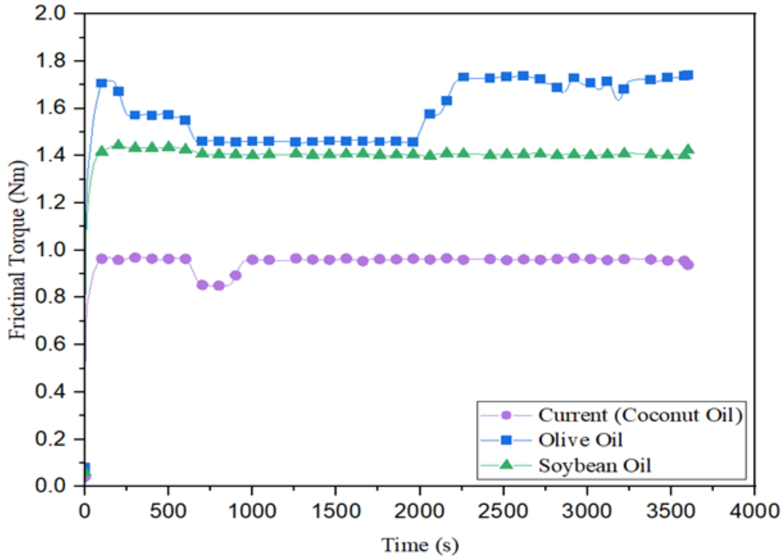

Fig. 11. Comparison graph of frictional torque (Nm) with 3 different oil sample

4. Conclusions

In conclusion, the potential benefits of using coconut oil as an environmentally friendly lubricant are highlighted by the comparative testing of the coefficient of friction and friction torque data for various oil samples, including different compositions of coconut oil. The blend with the largest percentage (30%) of coconut oil among the tested samples exhibited the most stable friction torque and the lowest coefficient of friction over time, indicating excellent lubricating ability. This indicates that higher coconut oil concentrations may effectively lubricate surfaces, decreasing wear and friction more effectively than traditional petroleum-based lubricants. The blend with the highest content of coconut oil (30%) recorded the lowest coefficient of friction and had the most uniform friction torque over time, according to the coefficient of friction. This demonstrates coconut oil's potential as a competitive substitute for traditional lubricants, providing both efficient operation and environmental advantages. The sample with the highest coefficient of friction exhibited the least desirable traits, indicating that its use could result in greater wear and inefficiency. As a result, the study suggests using higher coconut oil concentrations to obtain the best lubricating properties.

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References

[1] Vafaei, Seyedmohammad, Max Jopen, Georg Jacobs, Florian König, and Ralf Weberskirch. "Synthesis and tribological behavior of bio-based lubrication greases with bio-based polyester thickener systems." *Journal of Cleaner Production* 364 (2022): 132659. https://doi.org/10.1016/j.jclepro.2022.132659

[2] Hettiarachchi, Sunil Jayantha, Suela Kellici, Matthew Kershaw, and James Bowen. "Enhancing physicochemical properties of coconut oil for the application of engine lubrication." *Tribology International* 190 (2023): 109060. https://doi.org/10.1016/j.triboint.2023.109060

[3] Syahir, A. Z., N. W. M. Zulkifli, H. H. Masjuki, M. A. Kalam, Abdullah Alabdulkarem, M. Gulzar, L. S. Khuong, and M. H. Harith. "A review on bio-based lubricants and their applications." *Journal of cleaner production* 168 (2017): 997-1016. https://doi.org/10.1016/j.jclepro.2017.09.106

[4] Zainal, N. A., N. W. M. Zulkifli, M. Gulzar, and H. H. Masjuki. "A review on the chemistry, production, and technological potential of bio-based lubricants." *Renewable and sustainable energy reviews* 82 (2018): 80-102. https://doi.org/10.1016/j.rser.2017.09.004

[5] Hettiarachchi, Sunil Jayantha, James Bowen, Matthew Kershaw, Ioan-Alexandru Baragau, Adela Nicolaev, and Suela Kellici. "Nanostructured Al2O3/graphene additive in bio-based lubricant: A novel approach to improve engine performance." *Tribology International* 186 (2023): 108619. https://doi.org/10.1016/j.triboint.2023.108619

[6] Mahat, M. Mazwan, Farah Nabillah Kazwa, S. Kasolang, and Nurul Nadiah Mohd Kamaldin. "Application of response surface methodology experimental design to optimize tribological lubrication characteristics." *Journal of Advanced Research in Experimental Fluid Mechanics and Heat Transfer* 11, no. 1 (2023): 1-8. https://doi.org/10.37934/arefmht.11.1.18

[7] Morina, Ardian, and Anne Neville. "Understanding the composition and low friction tribofilm formation/removal in boundary lubrication." *Tribology International* 40, no. 10-12 (2007): 1696-1704. https://doi.org/10.1016/j.triboint.2007.02.001

[8] Erhan, Sevim Z., Brajendra K. Sharma, and Joseph M. Perez. "Oxidation and low temperature stability of vegetable oil-based lubricants." *Industrial Crops and Products* 24, no. 3 (2006): 292-299. https://doi.org/10.1016/j.indcrop.2006.06.008

[9] Sajeeb, Ayamannil, and Perikinalil Krishnan Rajendrakumar. "Comparative evaluation of lubricant properties of biodegradable blend of coconut and mustard oil." *Journal of Cleaner Production* 240 (2019): 118255. https://doi.org/10.1016/j.jclepro.2019.118255

[10] Jayadas, N. H., K. Prabhakaran Nair, and G. Ajithkumar. "Tribological evaluation of coconut oil as an environment-friendly lubricant." *Tribology international* 40, no. 2 (2007): 350-354. https://doi.org/10.1016/j.triboint.2005.09.021

[11] Panchasara, Heena V., Benjamin M. Simmons, Ajay K. Agrawal, Scott K. Spear, and Daniel T. Daly. "Combustion performance of biodiesel and diesel-vegetable oil blends in a simulated gas turbine burner." (2009): 031503. https://doi.org/10.1115/1.2982137

[12] Alagumalai, Avinash, Omid Mahian, Frank Hollmann, and Wuyuan Zhang. "Environmentally benign solid catalysts for sustainable biodiesel production: A critical review." *Science of the Total Environment* 768 (2021): 144856. https://doi.org/10.1016/j.scitotenv.2020.144856

[13] Sidibe, Sayon, Joel Blin, Tizane Daho, Gilles Vaitilingom, and Jean Koulidiati. "Comparative study of three ways of using Jatropha curcas vegetable oil in a direct injection diesel engine." *Scientific African* 7 (2020): e00290. https://doi.org/10.1016/j.sciaf.2020.e00290

[14] Uyumaz, Ahmet. "Experimental evaluation of linseed oil biodiesel/diesel fuel blends on combustion, performance and emission characteristics in a DI diesel engine." *Fuel* 267 (2020): 117150. https://doi.org/10.1016/j.fuel.2020.117150

[15] Atmanli, Alpaslan, and Nadir Yilmaz. "An experimental assessment on semi-low temperature combustion using waste oil biodiesel/C3-C5 alcohol blends in a diesel engine." *Fuel* 260 (2020): 116357. https://doi.org/10.1016/j.fuel.2019.116357

[16] Xue, Rong, Yixiao Ruan, Xiufang Liu, Liang Chen, Xingqun Zhang, Yu Hou, and Shuangtao Chen. "Experimental study of liquid nitrogen spray characteristics in atmospheric environment." *Applied Thermal Engineering* 142 (2018): 717-722. https://doi.org/10.1016/j.applthermaleng.2018.07.056

[17] Kamaldin, Nurul Nadiah Mohd, M. Mazwan Mahat, Ahmad Hussein Abdul Hamid, Amirul Hamizan Lokman, and Nur Syuhada Iman Abdul Talib. "Application of Response Surface Methodology (RSM) for Optimizing the Food Grade Bio Lubricant." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 51, no. 2 (2025): 177-186. https://doi.org/10.37934/araset.51.2.177186

[18] Mahat, Mohamad Mazwan, Nur Syuhada Iman Ahdul Talib, Wan Zulhilmi Wan Suhaidi, and Nurul Nadiah Mohd Kamaldin. "Evaluation of Tribological Performances of Palm Oil-Blended Food Grade Lubrication." *Journal of Applied Engineering Design and Simulation* 4, no. 2 (2024): 45-60. https://doi.org/10.24191/jaeds.v4i2.80

[19] Khan, Shoyeb, Probir Das, Mohammed Abdul Quadir, Mahmoud Thaher, Senthil Nagappan Annamalai, Chandan Mahata, Alaa H. Hawari, and Hareb Al Jabri. "A comparative physicochemical property assessment and techno-economic analysis of biolubricants produced using chemical modification and additive-based routes." *Science of the Total Environment* 847 (2022): 157648. https://doi.org/10.1016/j.scitotenv.2022.157648

[20] Kahsay, Mulu Bayray, and Ole Jorgen Nydal. "Degradation of viscosity of vegetable oils employed for thermal energy storage due to oxidation in ambient temperature." *Journal of Energy Storage* 73 (2023): 108816. https://doi.org/10.1016/j.est.2023.108816

[21] Sarker, Majher I., Kalidas Mainali, Brajendra K. Sharma, Madhav P. Yadav, Helen Ngo, and Richard D. Ashby. "Synthesized biolubricants from naturally derived oleic acid: Oxidative stability and cold flow performance." *Industrial Crops and Products* 204 (2023): 117315. https://doi.org/10.1016/j.indcrop.2023.117315

[22] Folayan, Adewale Johnson, Adewale Dosunmu, and Aleruchi Boniface Oriji. "Synthesis and characterization of polyvalent high-performance synthetic base oil for drilling operations in recalcitrant and unconventional oil and gas reservoirs." *South African Journal of Chemical Engineering* 46 (2023): 143-164. https://doi.org/10.1016/j.sajce.2023.08.001

[23] Tiwari, Saurabh, M. Amarnath, and Munish Kumar Gupta. "Synthesis, characterization, and application of Al2O3/coconut oil-based nanofluids in sustainable machining of AISI 1040 steel." *Journal of Molecular Liquids* 386 (2023): 122465. https://doi.org/10.1016/j.molliq.2023.122465

[24] Muthurathinam, Samuel Gemsprim, and Ashoka Varthanan Perumal. "Synthesis, characterization and tribological investigation of vegetable oil methyl esters based bio-lubricants." *Industrial Crops and Products* 203 (2023): 117098. https://doi.org/10.1016/j.indcrop.2023.117098

[25] Jayadas, N. H., and K. Prabhakaran Nair. "Coconut oil as base oil for industrial lubricants—evaluation and modification of thermal, oxidative and low temperature properties." *Tribology international* 39, no. 9 (2006): 873-878. https://doi.org/10.1016/j.triboint.2005.06.006

[26] Aguilar-Rosas, Oscar A., Leonardo I. Farfan-Cabrera, Ali Erdemir, and Julio Alberto Cao-Romero-Gallegos. "Electrified four-ball testing–A potential alternative for assessing lubricants (E-fluids) for electric vehicles." *Wear* 522 (2023): 204676. https://doi.org/10.1016/j.wear.2023.204676

[27] Mujtaba, M. A., Md Abul Kalam, Haji Hassan Masjuki, Manzoore Elahi M. Soudagar, Haris Mehmood Khan, H. Fayaz, M. Farooq et al. "Effect of palm-sesame biodiesel fuels with alcoholic and nanoparticle additives on tribological characteristics of lubricating oil by four ball tribo-tester." *Alexandria Engineering Journal* 60, no. 5 (2021): 4537-4546. https://doi.org/10.1016/j.aej.2021.03.017

[28] Pengon, Sirikarn, Nawinda Chinatangkul, Chutima Limmatvapirat, and Sontaya Limmatvapirat. "The effect of surfactant on the physical properties of coconut oil nanoemulsions." *Asian Journal of Pharmaceutical Sciences* 13, no. 5 (2018): 409-414. https://doi.org/10.1016/j.ajps.2018.02.005

[29] Panchal, Tirth M., Ankit Patel, D. D. Chauhan, Merlin Thomas, and Jigar V. Patel. "A methodological review on bio-lubricants from vegetable oil based resources." *Renewable and Sustainable Energy Reviews* 70 (2017): 65-70. https://doi.org/10.1016/j.rser.2016.11.105

[30] Prasannakumar, Pranav, Sabarinath Sankarannair, Chinchu Bose, Rani Santhakumari, and S. N. Jyothi. "Influence of techniques on synthesizing cashew nut shell oil as a prospective biolubricant on its physicochemical, tribological, and thermal behaviors." *Journal of Cleaner Production* 401 (2023): 136717. https://doi.org/10.1016/j.jclepro.2023.136717

[31] Pawar, Rajendra V., Dattatray B. Hulwan, and Maruti B. Mandale. "Recent advancements in synthesis, rheological characterization, and tribological performance of vegetable oil-based lubricants enhanced with nanoparticles for sustainable lubrication." *Journal of Cleaner Production* 378 (2022): 134454. https://doi.org/10.1016/j.jclepro.2022.134454

[32] Tulashie, Samuel Kofi, and Francis Kotoka. "The potential of castor, palm kernel, and coconut oils as biolubricant base oil via chemical modification and formulation." *Thermal Science and Engineering Progress* 16 (2020): 100480. https://doi.org/10.1016/j.tsep.2020.100480

[33] Opia, Anthony Chukwunonso, Mohd Kameil Bin Abdul Hamid, Samion Syahrullail, Abu Bakar Abd Rahim, and Charles AN Johnson. "Biomass as a potential source of sustainable fuel, chemical and tribological materials–Overview." *Materials Today: Proceedings* 39 (2021): 922-928. https://doi.org/10.1016/j.matpr.2020.04.045