

Research Article

A Comparative Investigation on Friction and Wear Behavior of Green Lubricants

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Abstract:

Green lubricants are gaining increased attention due to the rising demand for environmentally friendly and sustainable solutions. To evaluate their suitability as base oils for lubricants in local automobile and power plant engines, the tribological performance of refined, bleached, and deodorized palm and jojoba oils was assessed and compared. The tests were conducted using a four-ball tester. The bio-based oils' performance was evaluated under various load and temperature conditions using a tribological testing system. The results showed that unprocessed palm oil outperformed jojoba oil in terms of load-bearing capacity and friction reduction in its raw state. Additionally, palm oil exhibited wear protection performance similar to jojoba oil. With the radical incorporation of suitable anti-wear agents, palm oil can be transformed into a highly effective alternative to mineral oils, offering advantages in terms of tribology, environmental impact, and non-food competition.

Keywords: *Green lubricant, Contact wear diameter, Viscosity, Frictional coefficient, Shear stress*

1. Introduction

A lubricant is a substance used between moving surfaces to reduce wear, dissipate heat, and improve efficiency. It is a highly effective method for minimizing wear and frictional interaction between the surfaces [1]. In the automotive industry, common liquid lubricants include automatic transmission fluids, engine oils (for diesel and petrol engines), brake fluids, hydraulic fluids, and gearbox fluids [2]. Mineral-based and synthetic lubricants are the most commonly available types on the market. While these lubricating oils perform effectively, they are not environmentally friendly. The complex mix of chemicals present in mineral oil can lead to mutations and carcinogenesis, which can contribute to increased infant mortality rates and malnutrition in children (IMR) [3]. Moreover, the world's mineral oil reserves are depleting, and growing environmental concerns about their negative impacts are increasing. When used in internal combustion (IC) engines, and if not fully miscible with basic fuels like diesel, mineral oils can leak into the combustion chamber and burn partially, leading to the production of pollutants. Consequently, the use of mineral oils contributes to significant engine emissions of smoke and unburned hydrocarbons (UBHC). Due to the considerable environmental harm caused by the impurities from combustion residues, as well as damage to cylinder surfaces from the high friction caused by metallic additives in the lubricant, mineral oils are no longer recommended for use [4].

Compared to mineral lubricating oils, synthetic lubricating oils offer several advantages, such as enhanced low-temperature fluidity, oxidation stability, and thermal stability. However, despite these benefits, they have some drawbacks that limit their use as lubricants. The most notable disadvantage is their higher cost, with synthetic oils being twofold to fourfold more costlier than conventional oils. Additionally, cold storage of synthetic oils may increase the risk of additive precipitation [5].

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Research has focused on finding new alternatives to replace mineral-based and synthetic lubricants with renewable options that are less harmful to the environment [6]. Plant-based oils, which resemble the long-chain hydrocarbons present in mineral oils, offer several benefits, including renewability, non-toxicity, affordability, and environmental friendliness. These oils show great potential and are considered promising candidates to replace traditional mineral oils in lubricant production [7]. In general, plant-based oils are extracted from plants using either solvent or pressing methods [8]. Compared to mineral-based lubricating oils, vegetable-based bio-lubricating oils are over 95% biodegradable and decompose 2–30% more rapidly [9]. Plant-based oils are split into four essentials based on the fatty acids they contain: ricinoleic acid, oleic-linoleic acid, lauric acid, and erucic acid [10]. Oleochemical esters, a form of compound, meet the essential requirements for lubricant base stocks and enhance the heat transfer and low-temperature flow stability of pure plant-based oils [11].

In industrial applications, wear and friction between sliding surfaces can lead to various issues, including increased costs, reduced machine lifespan, malfunctions, energy loss, and decreased system efficiency [12]. The global push to conserve energy by reducing friction and wear on components has prompted the development of several alternative technologies for sustainability, such as thin film coatings, green lubricants, and bio/eco-materials [13]. Wear refers to the undesirable change in surface particles caused by mechanical actions on a material's surface. On contact surfaces, friction forces weaken strength, while wear compromises operating tolerances and hinders the optimal performance of machine parts [14]. Furthermore, prolonged friction increases the wear rate, leading to metal deformation [15]. In industrial machinery, friction and wear result in energy loss and material waste, highlighting the need for effective control. When mechanical components in relative motion make contact, friction occurs, dissipating energy and reducing the efficiency of mechanical systems [16]. As noted by [17], approximately 50% of fuel energy is lost to friction in internal combustion engines. Diesel and plant-based oil fuel mixtures enhance lubrication, as around 40-50% of the energy wasted due to internal mechanical friction of the engine is attributed to piston ring-cylinder friction. This aligns with [18], who stated that engine fuels also serve to lubricate engine injection equipment components. Although the direct use of biofuels in internal combustion engines may increase component wear due to increased friction, their use as diesel additives has been shown to mitigate wear by improving the durability of the lubricating film. Furthermore, lubrication decreases friction in engine components, reducing wear and extending the engine's lifespan.

Plant-based bio-lubricants support environmental sustainability, such performance still requires improvement through continued research under extreme conditions, such as wear resistance, cold flow properties, and oxidation stability. Additionally, cost-effective solutions are needed to enhance their effectiveness compared to conventional mineral and synthetic oils [20]. Among the various renewable feedstocks investigated for green lubrication, jojoba and palm oils have emerged as two of the most extensively researched possibilities due to their favorable physicochemical and tribological properties. Palm oil, in particular, has attracted attention for its versatility and wide availability. Studies on palm oil have demonstrated its potential both as a biolubricant and as a baseline fluid for advanced formulations. For instance, palm kernel oil blended with copper oxide nanoparticles was reported to significantly reduce friction and wear in four-ball tribometry, highlighting the combined effect of bio-oil and nano-additives in enhancing load-carrying capacity and surface protection [21]. In another comparative evaluation, palmolein oil and its chemically modified trimethylolpropane (TMP) ester were tested under ASTM standards using a four-ball apparatus. Results indicated that while both possessed wear-preventive and extreme-pressure properties, the TMP ester exhibited a noticeably lower coefficient of friction, suggesting that chemical modification can improve lubrication efficiency [22].

Jojoba oil, with its unique long-chain ester structure resembling synthetic oils, has also been studied both individually and in blends. Incorporating jojoba oil into conventional lubricants or mixing it with performance-enhancing additives has been shown to improve oxidation stability, reduce friction, and extend lubricant life [23, 24]. Subsequent optimization studies have demonstrated that chemical modifications of jojoba oil—such as epoxidation, polymerization, and esterification—enhance its thermal and oxidative stability while improving anti-wear behavior under standard tribological tests compared with unmodified jojoba [25].

Table 1 presents the experimentally measured parameter values (physical and chemical characteristics) for the raw palm and jojoba oils used in this study. The selection of these parameters was guided by references [19], [29], and [31], and the experimentally obtained values are found to closely match those reported in the cited references.

Table 1: Physical and chemical Properties of Jojoba and Palm Oil.

Properties	Palm	Jojoba
Density (kg/ m ³)	920	864
Viscosity at 40°C (cSt)	44.2	22.507
Viscosity at 100°C (cSt)	4.2	6.163
Viscosity Index	0.05	247
Pour point (°C)	15	+9
Flash point (°C)	182	150
Calorific value (MJ/kg)	38	42.1

From the Table 1, it is observed that jojoba oil is a suitable alternative to petroleum-based lubricants, particularly when thermal stability and cold-weather performance are key considerations. Jojoba oil maintains a more consistent viscosity over a wide range of temperatures, which makes it more advantageous when stable film formation and thermal performance are needed. Palm oil is more resistant to fire, but it has a higher pour point and is less stable in viscosity, so it has fewer uses. Modifying or blending these oils may help them perform better as a lubricant.

Based on the reviewed literature, this study primarily selected palm oil and jojoba oil because they represent two distinct classes of bio-oils with complementary properties—palm oil is abundant, cost-effective, and widely used in lubricant research. In contrast, jojoba oil is chemically unique, highly stable, has non-food-grade advantages, and is less explored in tribological applications. Also, jojoba oil was selected due to its non-competition with food production and its ability to be cultivated on marginal land. There has been no systematic study examining jojoba and palm oils combined performance as bio-lubricants; previous studies usually investigate these oils individually, typically in blends with mineral oils or after chemical modification. By focusing on palm and jojoba, our study aims to form an underexplored pairing with significant potential for developing sustainable and high-performance lubricants; thus, we have performed individual testing on palm and jojoba oils to establish a baseline with the aim of preparing data for future blend formulations. Despite the fact that the present study primarily focuses on bio-oils and their modifications, the use of conventional base oils as benchmarks is important for an adequate comparative analysis and will be addressed in future studies. The paper is presented in the following sequence: Section 1 provides a detailed introduction to lubricant oils. Section 2 outlines the testing arrangements, while Section 3 presents the results and discussion. Finally, the study is concluded in Section 4.

2. Testing Arrangement

2.1 Lubricant oil specimen processing

Two distinct lubricant samples were examined in this paper. Palm oil was used as the base lubricant and served as a reference for comparison, while the other sample consisted of jojoba oil.

Table 2: Specifications of DUCOM TR 30H IMTR Four Ball Tester Machine

Parameter	Value
Speed	300 to 4000 rpm
Load	200 to 10,000 N
Frictional Force	0 to 300 N
Frictional Torque	0 to 15 Nm
Temperature	Up to 95 °C

2.2 Friction and surface wear evaluation

The friction and wear evaluation was conducted using the DUCOM TR 30H IMTR Four Ball Tester Machine [26, 28]. This machine is configured to work with a computer equipped with a data collection system. The specifications of the DUCOM TR 30H IMTR Four Ball Tester Machine are provided in Table 2, and a block diagram illustrating the friction and surface wear measurement setup is exhibited in Fig. 1. During the measurement, a 40 kg load and 1200 RPM rotational speed were applied.

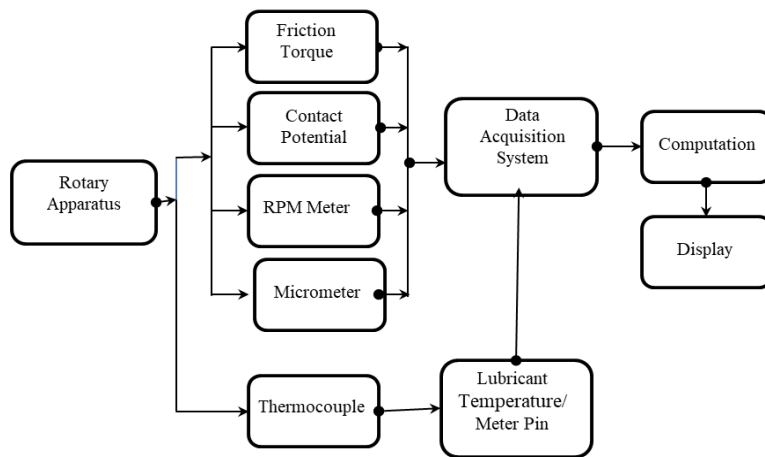


Fig.1. Visual Block Representation of Friction and Wear Testing.

2.3 Oil Sample Preparation

The lubricant samples, palm oil and jojoba oil, were prepared, and the construction geometry is illustrated in Fig. 2. The investigations were conducted using a Four-Ball Tester machine, in accordance with the IP239 standard[30]. This machine functions with a dynamic ball bearing pressing against three non-dynamic ball bearings, all submerged in the test lubricant. The dynamic ball is subjected to loads through weights connected to a load-actuating lever. The top non-dynamic ball is secured in a specialized fastener at the lower section of the upright rotating shaft, which is driven by an electric motor rotating at a constant speed. Meanwhile, the three non-dynamic balls are secured within a stationary cup using a clamping mechanism comprising a ring and a locking nut. Before performing the test, the surfaces of the balls were thoroughly cleaned to remove any dirt or debris. ACETONE LR (Propanone, $(CH_3)_2CO$) was used as the cleaning agent.

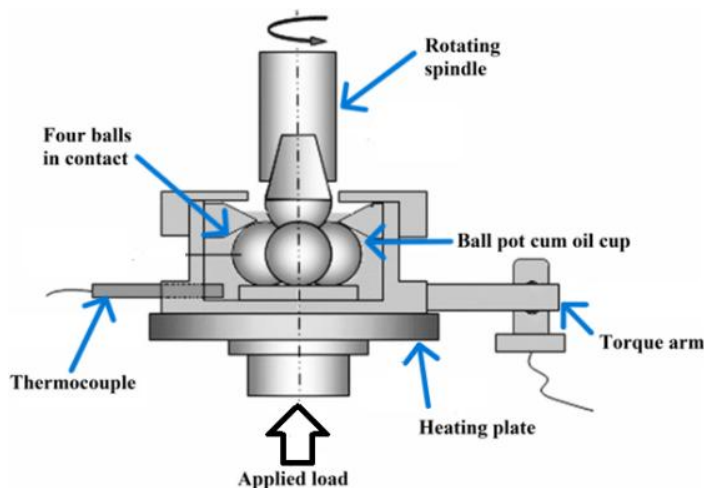


Fig. 2. Four-ball tester.

The standard test material for the balls was EN31 steel, with a surface finish of $0.1 \mu m$ CLA and a diameter of 12.7 mm [27]. Four fresh balls were employed in every test. Prior to testing, the balls underwent thorough cleaning with propanone and were subsequently dried using non-abrasive wipes. The material composition and rigidity of the balls are detailed in Table 3.

Table 3: Rigidity and Material Composition (Wt.%) of EN31 Steel Ball Material [14].

Material	EN31
Carbon	1.0
Silicon	0.35
Manganese	0.55
Sulfur	0.07
Phosphorous	0.07
Chromium	1.5
Iron	Balance
BHN	805

The steel balls and the cup used for testing the oil were carefully cleaned with toluene and then dried thoroughly. The ball-seat unit was fitted on the mounting plate, and three pre-cleaned balls were inserted into the ball seat. The retaining ring secured the assembly. Approximately 10 ml of the oil under test was poured into the cup to encase the balls placed to reach a minimum depth of 2.5–3 mm. The cup and the thrust bearing held a mounting disk between them. The test was performed at a load of 40 kg, with a speed of 1200 rpm and measurement intervals of 3600 seconds at 75°C, as outlined in Table 4.

Table 4: Outline of the Testing Arrangement using a four-ball tester

Operational specification	Condition
Load (kg)	40
Temperature (°C)	75
Speed (rpm)	1200
Measurement Intervals (sec)	3600

2.4 Lubricant analysis

The automatic ANTON PAARRheometer was used to measure viscosity, following the ASTM D 445 standard. Fluid thickness was determined at controlled bath temperatures of 40°C and 100°C for both samples.

3. Results and Discussion

3.1 Frictional Coefficient

Figs. 3 and 4 represent the variation of the frictional torque over time for palm oil and jojoba green lubricant. The frictional torque for each oil sample after three repeated tests of individual oil for a period of approximately 1 hour per sample is plotted. After each set of three consecutive tests, the wear scars on the steel balls were examined using a scar wear microscope. The individual graphs shown with three different colors obtained from each test for each of the oils are generated by the system of FBT in the same plot to demonstrate exactness. The three frictional coefficient values provided by FBT are at the top of each graph. This frictional coefficient is an output of the tests, based on the abscissa as the frictional torque and ordinate as the time period for which the tests have been carried out.

The results indicate that the lubrication regime in the course of the experiment was primarily boundary lubrication, as the film parameter λ ($\approx 2-3$) [Table 5] is below the full-film threshold ($\lambda \geq 3$), with friction coefficient values ranging from 0.001 to 0.2, except in the second experiment with palm oil biolubricant. In the FBT setup, high sliding and contact pressures further reduce film stability, so asperity interactions occur despite $\lambda > 1$, confirming that the test runs under boundary-dominated conditions. The three frictional coefficient values provided by FBT at the top of each graph (Fig. 3 and Fig. 4) lie well within the range. For palm oil, the frictional coefficient was highest in the second experiment, while jojoba oil exhibited the lowest friction coefficient in the first sample compared to all other tested samples. The palm oil biolubricant showed a tendency to stabilize after a certain time, with an almost constant frictional coefficient (μ). In contrast, the jojoba oil green lubricant demonstrated a lower frictional coefficient compared to palm oil throughout the entire operation time, but with greater variability, showing signs of crust and truffles.

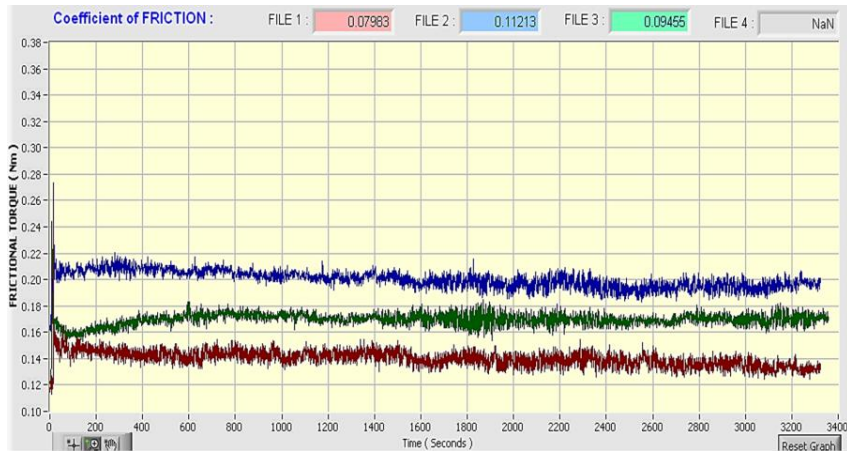


Fig. 3. The frictional torque during a one-hour test time for Palm oil.

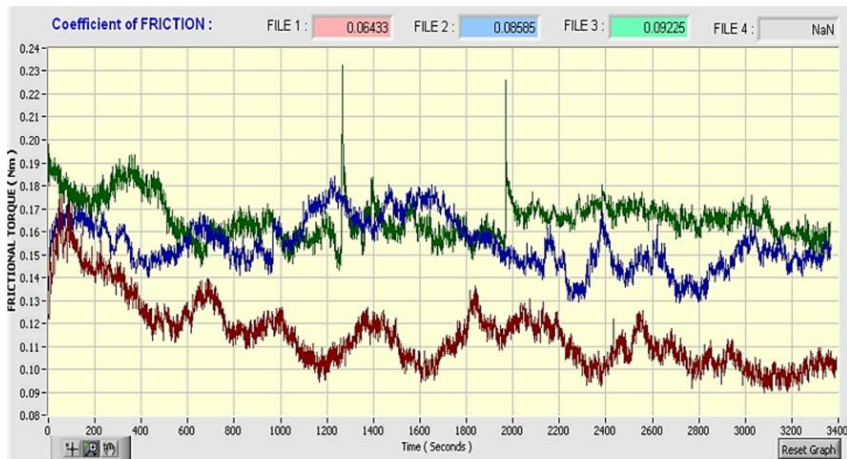


Fig. 4. The frictional torque during a one-hour test time for Jojoba oil.

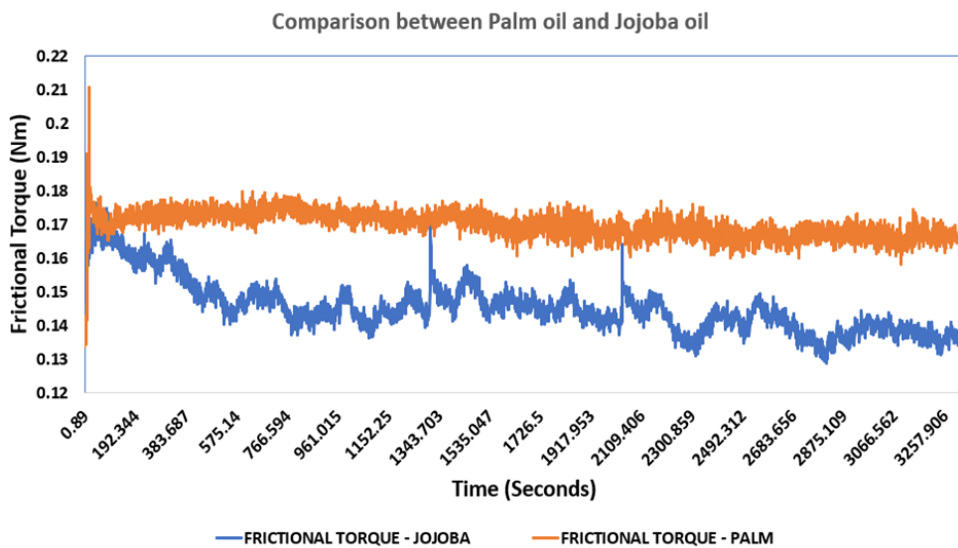


Fig.5. Comparison of the frictional torque during a one-hour test time.

Fig.5 shows the frictional torque comparison of jojoba and palm oil. It is clear through comparison that jojoba exhibits lower frictional torque, hence better lubrication. Jojoba oil thus represents superior lubricating ability under the given test conditions.

3.2 Viscosity

Fig. 6 shows the graph of various viscosity (Pa.s) values of jojoba oil and palmolein oil for tests performed on an ANTON PAAR rheometer.

Both palm oil (0.0713 Pa.s = 71.3 cP) and jojoba oil (0.0477 Pa.s = 47.7 cP), as measured in Fig. 6, fall within the viscosity ranges prescribed for ISO VG grades commonly used in industrial lubricants (VG 46–68). This demonstrates that both oils satisfy the ISO viscosity classification requirements. Both green lubricants were found to meet the full requirements of ISO VG 46, which classifies lubricants based on kinematic viscosity at 40 °C. Thus, both oils are considered suitable for applications such as hydraulic systems, bearings, and light-to-medium load gear operations. Moreover, the green lubricant exhibited a fluid thickness well above the prescribed standard limits.

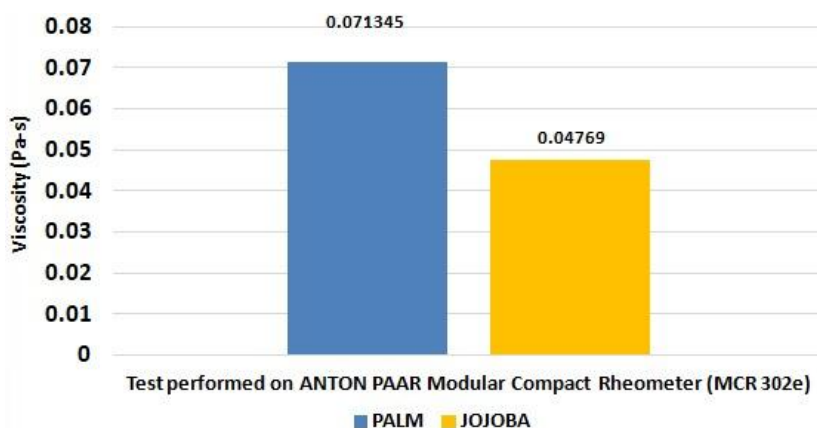


Fig. 6. The viscosity of Palm oil and Jojoba oil green lubricants.

The lubricating film properties of palm oil and jojoba oil are compared in Table 5 under conditions of temperature ($T = 75\text{ }^{\circ}\text{C}$), sliding motion ($U = 2.5\text{ m/s}$), and applied load ($W = 392\text{ N}$).

Table 5: Comparison of Palm oil and Jojoba oil lubricating film properties

Property	Palm Oil	Jojoba Oil
Viscosity η (Pa.s)	0.0713	0.0477
Film thickness $h_{\min}$ (μm)	0.43	0.33
Film parameter λ ($\sigma = 0.15\text{ }\mu\text{m}$)	2.8	2.1

This indicates that palm oil forms a film that is nearly 31% thicker ($h_{\min}$ ratio) and that both lubricants achieve a film parameter of $\lambda > 2$, which satisfies the full-film ISO lubrication requirements.

Figs. 7 and 8 illustrate the viscosity (fluid thickness) of the tested palm oil and jojoba oil biolubricant samples.

Temperature, shear rate, normal force, and speed are some of the variables that affect viscosity. Because of the decreased molecular friction, viscosity reduces with increasing temperature. Also, higher shear rates lower viscosity (shear thinning). With an increase in normal force or pressure, viscosity increases due to compression of the fluid's molecules. The operating speed affects lubricant viscosity by affecting the shear rate, whereby higher speeds lead to a reduction in viscosity in shear-thinning fluids.

It is indicated from the Figs.7 and 8, the shear-rate and viscosity-temperature responses of jojoba oil provide better rheological flexibility and thermal stability than palm oil, making them more viable options for demanding tribological applications.

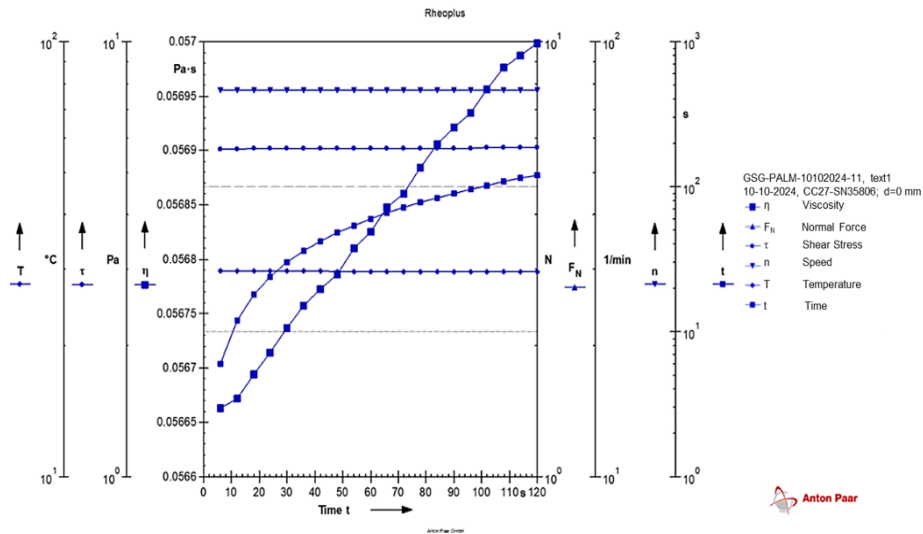


Fig. 7. The viscosity of Palm oil with load.

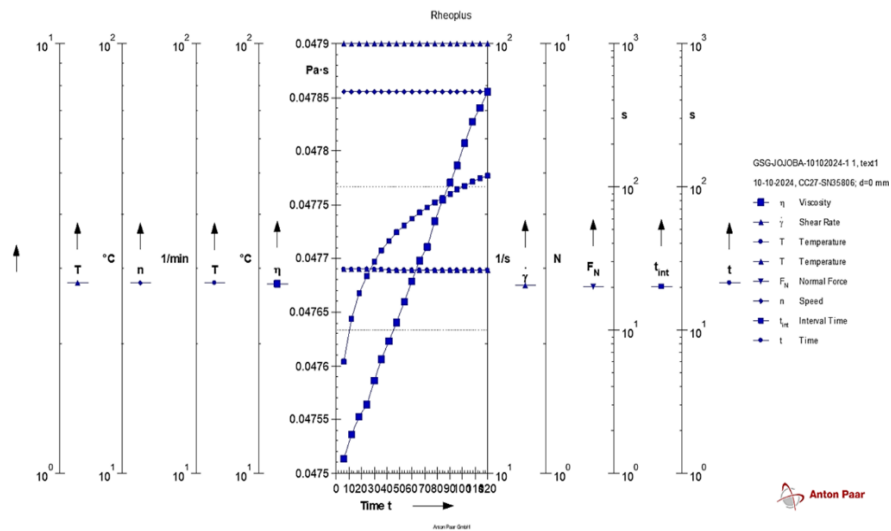


Fig. 8. The viscosity of Jojoba oil with load

3.3 Analysis of surface characteristics

Several types of surface damage occur in mechanical systems, such as localized adhesion damage, chemically assisted loss, grit-induced surface damage, and fatigue. Since contact-dominant lubrication prevailed in the experimental setup, all four types of surface damage were observed in the rubbing zone. While all four wear mechanisms were present during the experiment, adhesion damage and grit-induced surface damage were predominantly observed. The optical images of the tested steel balls using palm oil and jojoba oil biolubricants are shown in Figs. 9 and 10. The values of 'w' in Figs. 9 and 10 are the average CWD of nine balls from three experiments for each biolubricant.

CWD (Contact Wear Diameter) measures the extent of surface damage (wear scar) after a friction test performed on the Four-Ball Test apparatus. As seen in Fig. 10, the contact wear diameter (CWD), denoted by 'w', is larger for jojoba oil (0.679 mm) compared to palm oil (0.555 mm). From the obtained values of CWD, Palm oil shows less wear than Jojoba oil. Thus, palm oil provides better anti-wear performance under the specific test conditions used. Higher viscosity results for thicker lubricant film, which can better separate metal surfaces, reducing direct contact and wear.

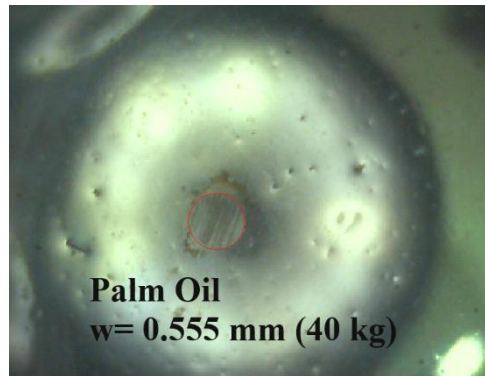


Fig.9. Surface micrograph of the steel balls for Palm oil (magnification30×)

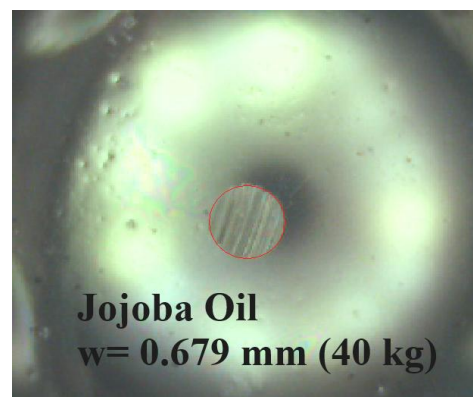


Fig.10. Surface micrograph of the steel balls for Jojoba oil (magnification30×)

This paper focuses on preliminary screening of oils and not an in-depth wear mechanism study, so only the contact wear diameter (CWD) was chosen as the parameter for evaluating wear behavior. Wear rate or volumetric wear analysis will be considered in future studies to complement the CWD data and provide a more comprehensive assessment of wear behavior.

3.4 Flash Temperature Characteristics

The Flash Temperature Characteristic, also known as Flash Temperature Parameter (FT), is a value that suggests the minimum thermal level at which a lubricant loses effectiveness for given specific requirements. For the requirements used in the four-ball machine measurement, the FT is defined under the ISO standard ISO 20623:2003, and its empirical expression is stated as:

Flash Temperature Parameter,

$$FT = \frac{P}{w^{1.4}} \quad (1)$$

Where, P = load in kg, w = mean contact wear diameter (CWD) in mm at this load.

Parameters such as sliding speed (velocity) and material properties (thermal conductivity, specific heat) are kept constant. The suggested equation aims to provide a quick and practical estimate of thermal stress as a function of load and wear scar.

Fig. 11 shows the graph of various percentages of jojoba oil and palmolein oil against the flash temperature characteristic (FT) for a load of 40 kg. It is observed that the FT increases as the applied load increases. In the 40 kg load test, the graph shows that palm oil has the highest FT value, indicating that palm oil is more effective as a fresh lubricant at 40°C for reducing wear. In contrast, jojoba oil shows a lower FT value, suggesting that it causes more surface damage on the bearing made of steel at 40°C compared to palm oil.

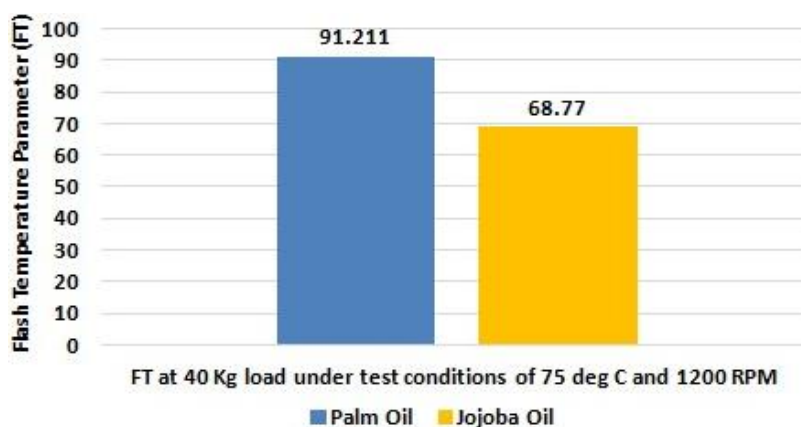


Fig. 11. Calculated Flash Temperature Parameter (FT).

4. Conclusion

The experimental investigation of palm oil and jojoba oil biolubricants revealed distinct differences in wear performance. Jojoba oil exhibited a larger contact wear diameter (CWD) of 0.679 mm compared to palm oil's 0.555 mm, indicating that jojoba oil caused more wear on the steel bearing surface. Furthermore, palm oil demonstrated a higher flash temperature parameter (FT), suggesting its superior effectiveness as a lubricant for reducing wear at 40°C. Throughout the operation, palm oil maintained a more stable performance with lower wear and a more consistent temperature rise, while jojoba oil showed higher wear and a less stable performance.

Both green lubricants met the ISO viscosity grade requirements, and the viscosity of both oils was significantly higher than standard requirements. Despite these promising characteristics, it is concluded that modifications are needed to improve the properties of palmolein oil and jojoba oil to match the operational performance of mineral oils more effectively.

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Nomenclature

w	mean contact wear diameter, mm
P	load, kg
FT	flash temperature parameter
CWD	contact wear diameter
ISO	International Organization for Standardization
T	temperature of the lubricant during the test, °C
U	entrainment speed, m/s
W	applied normal load, N
FBT	Four Ball Tester

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