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Experimental Study of Biolubricant Performance Based on Palm Oil and Aloe Vera (60:40) on the Tribological Properties of Aluminium 6061 Using Pin on Disk Testing

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ABSTRACT
The current use of petroleum-based lubricants has significant environmental impacts and relies on non-renewable resources, highlighting the need for more eco-friendly alternatives. This study aims to develop a biolubricant derived from palm oil and aloe vera with a 60:40 ratio and evaluate its tribological performance on Aluminium 6061. The testing was conducted using a pin-on-disk apparatus under 5 N and 10 N loads for 10 minutes at 1000 rpm. Evaluated parameters included viscosity, friction coefficient, wear rate, surface roughness, and microstructural observations. The results indicated that the biolubricant yielded lower friction coefficients and wear rates compared to conventional and non-lubricated specimens. Furthermore, the biolubricant demonstrated effective lubrication and thermal stability during testing. Thus, the formulated biolubricant appears to be a viable green substitute for mechanical engineering purposes.
Keyword: Biolubricant, Tribology, Palm Oil, Aloe Vera, Pin on Disk

1. Introduction

Environmental ecosystem degradation caused by waste from petroleum-based lubricants has become a serious concern in recent decades [1]. Conventional lubricants are generally non-biodegradable and produce toxic compounds that contaminate soil, water, and air, disrupting ecological balance [2]. Amid this sustainability crisis, biolubricants derived from renewable resources have emerged as an environmentally friendly alternative. As the world's largest producer of palm oil, Indonesia holds significant potential in developing sustainable plant-based lubricants. Palm oil is rich in saturated fatty acids that support the formation of a stable lubricating film, while aloe vera contains polysaccharides and antioxidants that enhance oxidative stability and lubrication efficiency. This study aims to develop a biolubricant based on a combination of palm oil and aloe vera and to evaluate its tribological performance on Aluminium 6061 material.

Lubricants play a crucial role in reducing friction and wear in mechanical systems. Traditionally, petroleum-based lubricants are widely used, but they pose environmental hazards due to their non-biodegradable nature and toxic by-products. In response, biolubricants—derived from renewable natural resources—have emerged as a promising alternative [3].

Biolubricants offer advantages such as biodegradability, low toxicity, and good lubrication properties. However, challenges remain, particularly regarding their oxidative stability and viscosity performance under high-temperature conditions. This study explores the formulation of a biolubricant using palm oil and aloe vera. Palm oil contributes excellent thermal stability due to its high saturated fatty acid content, while aloe vera introduces polysaccharides and antioxidants that may improve oxidative stability and lubrication efficiency [4]

The primary goal of this research is to evaluate the tribological behavior of Aluminium 6061 under biolubrication conditions using a pin-on-disk test setup [5]. This study is expected to support the development of sustainable lubrication technologies and reduce dependence on petroleum-based lubricants.

2. Method

The research was conducted experimentally using a pin-on-disk tribometer to test Aluminium 6061 samples under three lubrication conditions: dry (no lubricant), conventional lubricant, and biolubricant (60:40 palm oil and aloe vera). The tests were performed under two normal loads (5 N and 10 N) for 10 minutes at a rotation speed of 1000 rpm.

The main tools and instruments used included: Pin-on-Disk Machine: for friction and wear testing. Microscope: for surface defect observationSurface Roughness Tester: for Ra measurements. Polishing machine: for preparing smooth sample surfaces.

The measured parameters were: Friction coefficient (μ), Wear (ΔW), calculated from mass loss. Surface roughness (Ra), microstructural changes, evaluated qualitatively using microscopy.

Table 1. Material Codefication

Independent Variable			Material Codefication
Load (N)	Types of Lubricant	Lubricant Code	
5	Non-Lubricant	a	5a
5	Conventional Lubricant	b	5b
5	Biolubricant	c	5c
10	Non-Lubricant	a	10a
10	Conventional Lubricant	b	10b
10	Biolubricant	c	10c

2.1 Biolubricant

The biolubricant used in this study was formulated using a 60:40 ratio of palm oil and aloe vera extract. Palm oil was selected due to its high content of saturated fatty acids, which improve lubricating film formation and thermal stability. Aloe vera was incorporated for its polysaccharides and antioxidant components, which enhance viscosity and reduce oxidative degradation [6].

The aloe vera extract was prepared through gel separation and filtration, while palm oil was processed via transesterification. Both components were mixed thoroughly until a homogeneous solution was achieved. The final biolubricant exhibited a kinematic viscosity of 2.57 cSt at 40°C and 2.36 cSt at 100°C, with a density of 1.1905 g/cm³ at 40°C.

Figure 1. Biolubricant Palm Oil + Aloe Vera (60:40)

2.2 Aluminium 6061

Aluminium 6061 was chosen as the test material for its widespread use in mechanical and structural applications. It offers a good balance of strength, machinability. With a density of 2.7 g/cm³ and a melting point of 588°C, this alloy is suitable for tribological testing [7]. Its composition includes elements such as Mg, Si, and Cu, which contribute to its strength and thermal performance. The test specimens were cylindrical pins machined to match the pin-on-disk apparatus dimensions.

Table 2. Mechanical Properties Al 6061

Properties	Materials
	Al 6061
Density ($\mathbf{g/cm^3}$)	2,7
Thermal Conductivity (W/mK)	167
Melting Point (℃)	590
Tensile Strength (Mpa)	310
Shear Strength (Mpa)	207
Impact Toughness Strength (J)	39
Hardness ($\boldsymbol{H_v}$)	107

2.3 Wear Testing

Wear testing was conducted using a pin-on-disk tribometer under ASTM G99-17 standard. The Aluminium 6061 pin was pressed against a rotating steel disk under two load conditions: 5 N and 10 N, for a duration of 10 minutes at a constant speed of 1000 rpm.

Three lubrication conditions were evaluated:
Dry (no lubricant)
Conventional lubricant (Castrol Aircol 68)
Biolubricant (Palm Oil–Aloe Vera 60:40)

The average friction force ($\dot{F}$) during testing was obtained by averaging recorded friction data over time:

$$\dot{F} = \frac{F_1 + F_{..}}{F_n} \quad (1)$$

During testing, the tribometer recorded friction force, from which the coefficient of friction (μ) was calculated using:

$$\mu = \frac{F}{N} \quad (2)$$

Where:
μ = coefficient of friction
F = friction force (N)

N = normal load (N)

The wear (mass loss) was obtained from:

$$(\Delta W) = M_1 - M_2\ (gr) \qquad (3)$$

Where:
M_1= initial pin mass (g)
M_2= final pin mass (g)
ΔW = wear (g)

Then, the volume loss was calculated using:

$$V_{loss} = \frac{\Delta W}{\rho} \qquad (4)$$

Where:
ρ = density of Aluminium 6061 = 2.7 g/cm³

The sliding distance (X) was obtained from:

$$X = r \times N \qquad (5)$$

Where:
r= track radius (m)

Finally, the specific wear rate (K) was calculated by:

$$K = \frac{V_{loss}}{F \times X} \qquad (6)$$

This method provides quantitative insight into the material's resistance to friction and wear under each lubrication condition. Lower values of μ, ΔW, and K represent better performance [8-11].

2.4 Surface Roughness

Surface roughness testing was conducted to assess the effect of lubrication on surface quality after wear testing. The Ra (Roughness Average) value, which represents the arithmetic average of absolute deviations from the mean surface line, was used as the primary indicator [12].

Measurements were taken before and after pin-on-disk testing using a Mitutoyo surface roughness tester. The roughness tester provided values in micrometers (µm), and each specimen was measured at three different positions, with the average taken as the final value. [13]

Smaller ΔRa values indicate less surface damage, suggesting that the lubricant provided effective protection during sliding contact. This parameter is essential for evaluating the quality of tribological contact and lubricant performance [14].

2.5 Microstructural Observation

Microstructural analysis was performed to examine the surface morphology of the Aluminium 6061 specimens before and after wear testing under different lubrication conditions. Observations were carried out using a optical microscope at 50x and 100x magnification.

This qualitative evaluation focused on identifying wear mechanisms and surface damage such as: Grooves or scratches, plastic deformation, pitting Surface delamination [15]. Samples were grouped based on lubrication conditions: dry, conventional, and biolubricant. The dry condition showed the most severe surface damage, including deep scratches and plastic flow. In contrast, biolubricated samples exhibited fewer defects, with smoother worn surfaces and minimal groove formation. This difference indicates the biolubricant's ability to form a protective boundary layer, preventing direct metal-to-metal contact during sliding. The aloe vera component likely contributed to improved oxidative resistance, while palm oil enhanced film strength and surface coverage.

Microstructural observation complemented the wear and friction data, confirming the superior protective performance of the palm-aloe biolubricant.

2.6 Experiment Set Up

The experimental setup utilized a pin-on-disk tribometer configured in accordance with ASTM G99-17 standards. In this setup, a cylindrical Aluminium 6061 pin was held vertically and pressed against a horizontally rotating steel disk [16]. The contact was maintained under constant normal loads of 5 N and 10 N, with the disk rotating at a fixed speed of 1000 rpm for a total testing time of 10 minutes per sample. The pin specimens had polished, flat-end surfaces and were mounted securely in the tribometer holder to prevent movement during sliding. Lubrication conditions varied among three categories: dry (no lubricant), conventional lubricant (Castrol Aircol 68), and biolubricant (palm oil and aloe vera in a 60:40 ratio).

For the lubricated tests, a few drops of lubricant were applied directly to the contact area before each test began to ensure boundary lubrication. The tribometer was equipped with a load cell to continuously record friction force throughout the test duration. After each run, the pins were carefully removed, cleaned, and weighed to determine mass loss due to wear. Surface roughness measurements and optical microstructure observations were performed on the worn surfaces to further assess the effectiveness of each lubrication condition. The schematic of the experimental setup is illustrated in Figure X (optional if you have a diagram), showing the pin orientation, rotating disk, and direction of frictional force

3. Results and discussion

3.1 Wear Result

Table 3. Wear Result at 5N Load

Variable	Material Testing		
	5a	5b	5c
$\dot{F}$ (N)	3,21	0,61	0,044
Coefficient of Friction (μ)	0,64	0,122	0,088
Wear (ΔW)	0,011	0,006	0,006
Vloss(mm^3)	4,074	2,22	2,22
Wear rate $10^{-7} mm^2/N$	8,306	4,55	4,55

At a load of 5 N, the experimental results reveal clear distinctions among the three lubrication conditions: dry (5a), conventional (5b), and biolubricant (5c). The highest friction force was recorded under dry conditions at 3.21 N, followed by 0.61 N in the conventional, and only 0.044 N in the biolubricant condition. Correspondingly, the coefficient of friction (μ) dropped significantly from 0.640 (dry) to 0.122 (conventional), and the lowest was 0.088 for the biolubricant. This indicates that the biolubricant reduced interfacial shear resistance most effectively.

For wear performance, both conventional and biolubricant conditions showed identical mass loss values of 0.006 g, while dry testing led to a higher mass loss of 0.011 g

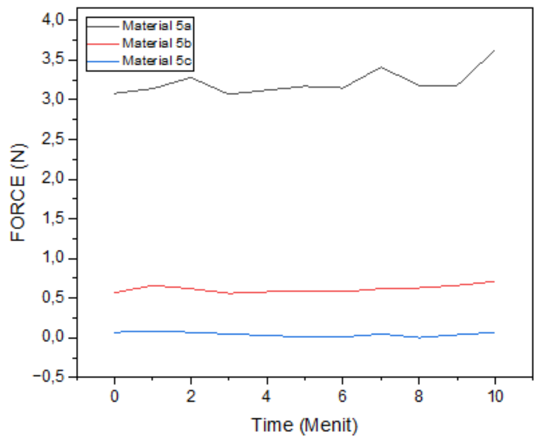

Figure 2. Graphic Friction Coefficient at 5 N Load

Table 4. Wear result at 10 N Load

Variable	Material Testing		
	10a	10b	10c
$\dot{F}$ (N)	3,55	0,43	0,085
Coefficient of Friction (μ)	0,35	0,043	0,0085
Wear (ΔW)	0,017	0,008	0,007
Vloss(mm^3)	6,29	2,96	2,59
Wear Rate$10^{-7} mm^2/N$	12,8	6,03	5,28

Table 4 shows the tribological performance of Aluminium 6061 under a 10 N load across three lubrication conditions: dry (10a), conventional (10b), and biolubricant (10c). The highest friction force was recorded in the dry condition (3.55 N), while the lowest was observed in the biolubricant condition (0.085 N). Correspondingly, the coefficient of friction decreased significantly from 0.35 (dry) to 0.043 (conventional) and reached the lowest at 0.0085 with biolubricant. Wear data followed a similar trend, with the dry condition showing the highest mass loss (ΔW = 0.017 g) and volume loss (Vloss = 6.29 mm^3), while the biolubricant produced the lowest values at 0.007 g and 2.59 mm^3, respectively. Furthermore, the specific wear rate under biolubrication was 5.28 × 10^{-7} mm^2/N, demonstrating better wear resistance compared to 6.03 for conventional and 12.8 for dry conditions. These results confirm the effectiveness of the palm-aloe biolubricant in minimizing friction and material loss under higher load conditions [17].

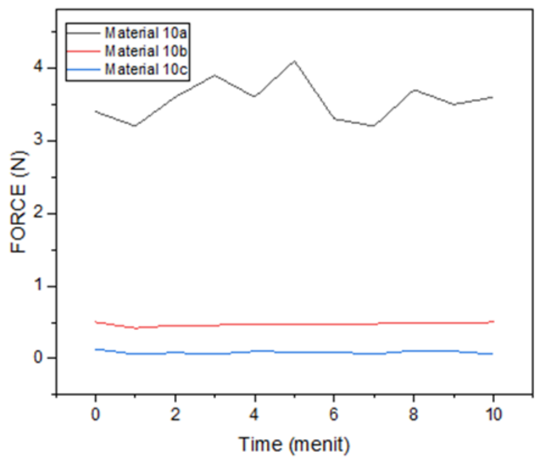

Figure 3. Graphic Friction Coefficient at 10 N Load

Based on the obtained data, it is shown that the biolubricant is capable of performing under heavy load conditions. The data also indicate that as the applied load on the pin-on-disk wear testing apparatus increases, the wear rate correspondingly becomes higher. [18]

3.2 Temperature Performance Based on Linear Regression Analysis

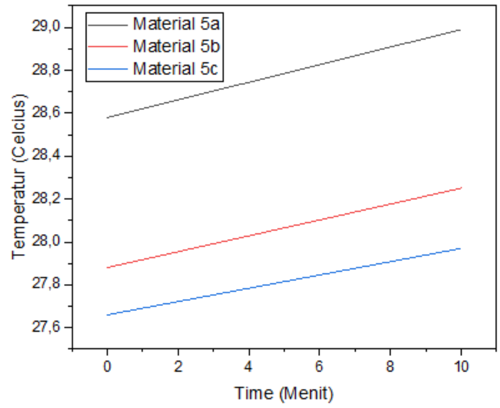

Figure 4. Temperature Performance at 5 N Load

At a load of 5 N, the temperature increased gradually and consistently over the 10-minute testing period for all lubrication conditions. Among them, the biolubricant showed the slowest rise in temperature, indicating effective thermal control. Compared to dry and conventional lubricants, the biolubricant maintained a more stable surface temperature, which suggests that it minimized frictional heat generation. The trend observed in the biolubricant condition followed a clear linear pattern, confirming predictable thermal performance and reduced energy loss due to friction.

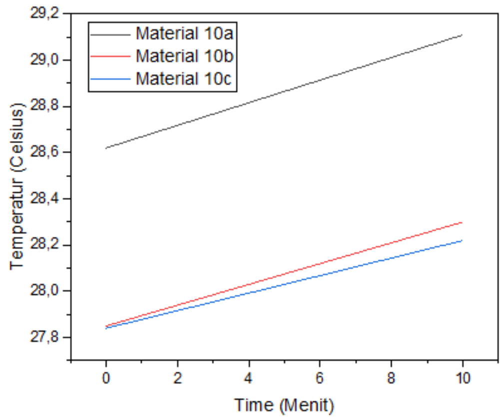

Figure 5. Temperature Performance at 10 N Load

Under the 10 N load, temperature rose more rapidly in all conditions due to the higher contact pressure and frictional forces. However, the biolubricant still outperformed the other lubricants by limiting the temperature increase more effectively. The temperature growth remained linear and stable, reflecting the biolubricant's ability to form a durable lubricating film even under heavier loads. This behavior highlights the biolubricant's excellent heat resistance and film stability, further supporting its effectiveness in demanding tribological environments.

3.3 Surface Roughness Result

Surface roughness (Ra) was measured before and after the pin-on-disk tests to evaluate the extent of surface damage caused by friction under different lubrication conditions. At both 5 N and 10 N loads, dry testing resulted in the highest increase in surface roughness, indicating severe abrasion and plastic deformation on the Aluminium 6061 surface. In contrast, the biolubricant condition produced the lowest surface roughness values after testing, suggesting effective surface protection.

At 5 N, the increase in Ra (ΔRa) was 2.541 µm for dry, 1.499 µm for conventional lubricant, and 0.634 µm for biolubricant. Under 10 N loading, ΔRa increased overall due to higher contact pressure: 3.964 µm (dry), 3.066 µm (conventional), and 2.127 µm (biolubricant). These results indicate that the biolubricant consistently minimized surface deterioration, even under heavier loads. The combination of aloe vera and palm oil provided both viscosity and film strength, reducing direct asperity contact and limiting surface roughening. This further supports the biolubricant's superior tribological performance in terms of wear resistance and surface preservation [19].

The surface roughness analysis reveals that lubrication significantly affects the wear behavior of Aluminium 6061 during pin-on-disk testing. Specimens without lubricant experienced the most severe increase in roughness, indicating high friction and material removal. Conventional lubricants provided moderate protection, reducing surface damage compared to dry conditions. However, specimens lubricated with the palm oil and aloe vera-based biolubricant consistently showed the smallest change in surface roughness. This indicates that the biolubricant offers better film formation and wear resistance, maintaining smoother surfaces even under increased load, and demonstrates its potential as an effective and eco-friendly alternative to conventional lubricants.

3.4 Microstructure Observation

Before the tribological testing, the microstructure of the Aluminium 6061 specimen was carefully observed to assess its initial surface condition. At 50x magnification, the surface appeared relatively uniform with fine, evenly distributed grains. The grain boundaries were visible, and the surface showed no significant wear marks, deformation, or irregularities. This condition indicates that the specimen was properly polished and prepared, ensuring a clean and smooth surface that would be sensitive to any changes occurring after friction and wear testing.

At a higher magnification of 100x, more detailed microstructural features were evident. The grain structure was more pronounced, with clearly defined boundaries and minimal surface defects such as microcracks or voids. The absence of abrasive marks or plastic deformation confirmed that the material had not undergone any mechanical interaction prior to testing. This initial microstructure served as the baseline reference for evaluating changes in surface morphology caused by the application of different lubricants and test loads during the pin-on-disk experiments.

a b

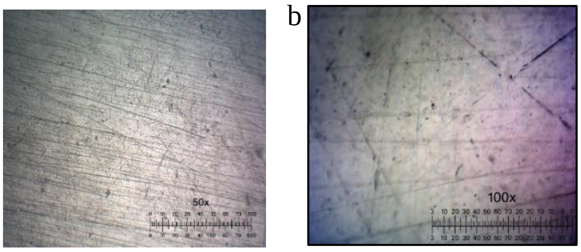

Figure 6 Microstructure Condition before wear testing

Prior to testing, the microstructure of the Aluminium 6061 specimen exhibited a clean and uniform surface, with fine grain boundaries visible at both 50x and 100x magnification. There were no signs of wear, deformation, or surface defects, confirming that the specimen was well-polished and suitable as a baseline reference for evaluating tribological effects.

After testing under a 5 N load, noticeable differences appeared between the three lubrication conditions. In specimen 5a (without lubricant), the microstructure showed severe surface damage characterized by deep scratches, plowing marks, and clear signs of plastic deformation, indicating high friction and material removal due to direct metal-to-metal contact. In specimen 5b (with conventional lubricant), the surface condition was moderately improved.

Wear marks were still present but less intense, and the grain structure remained partially visible, suggesting that the lubricant provided a protective layer that reduced friction and wear to a certain extent. In contrast, specimen 5c (with biolubricant) showed the smoothest surface among the three. Only minor wear traces were observed, and the original grain structure was well-preserved, indicating effective lubrication performance and thermal stability of the biolubricant under the same testing conditions.

a b c

Figure 7. Microstructure Condition of the material under 5N testing at 50x magnification (a) without Lubricant (b) with conventional Lubricant (c) Biolubricant

Before testing, the Aluminium 6061 specimen displayed a smooth and homogeneous microstructure, with well-defined grain boundaries observed at 50x and 100x magnifications. The absence of scratches, deformation, or surface irregularities confirmed that the specimen was properly polished and had not undergone any mechanical stress, making it ideal for comparative analysis after wear testing.

Under the higher load of 10 N, more pronounced surface degradation was observed across all lubrication conditions. In specimen 10a (without lubricant), the surface suffered severe wear damage, with extensive grooves, deep abrasive marks, and grain boundary distortion, indicating high friction and significant material loss. Specimen 10b (with conventional lubricant) exhibited reduced but still considerable wear. Although some surface protection was evident, the microstructure showed signs of moderate scuffing and micro-pitting, suggesting limited effectiveness under higher load. Specimen 10c (with biolubricant) demonstrated the best performance among the three. The surface maintained a relatively intact structure, with only slight polishing marks and minimal deformation. This suggests that the biolubricant provided superior film strength and thermal resistance, effectively protecting the material even under elevated load conditions [20-21].

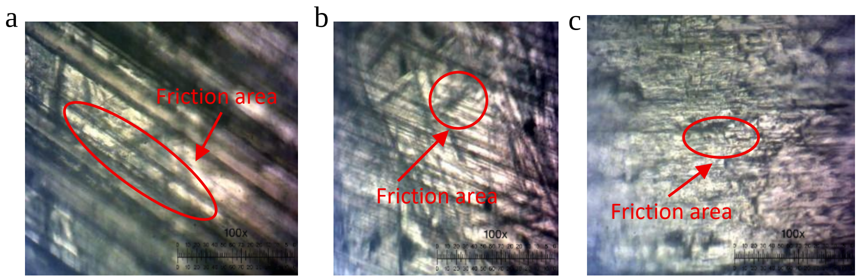

Figure 8. Microstructure Condition of the material under 10 N testing at 50x magnification (a) without lubricant (b) with conventional lubricant (c) Biolubricant

Based on the microstructural observations before and after wear testing, it can be concluded that biolubricant made from palm oil and aloe vera provides the most effective surface protection for Aluminium 6061 under both 5 N and 10 N loads. Prior to testing, all specimens exhibited clean and uniform microstructures. After testing, the specimen without lubricant showed the most severe surface damage, especially under higher load. The use of conventional lubricant reduced wear to some extent, but significant surface degradation was still evident. In contrast, the biolubricant consistently minimized wear, preserved grain structures, and prevented deep scratches, indicating its superior tribological performance and potential as an environmentally friendly alternative to petroleum-based lubricants.

4. Conclusion

The experimental results demonstrated that the biolubricant composed of palm oil and aloe vera (60:40) consistently outperformed conventional lubricant and dry conditions in improving the tribological behavior of Aluminium 6061. Under both 5 N and 10 N loads, the biolubricant achieved the lowest wear volume and wear rate, indicating superior resistance to material loss. It also resulted in the lowest coefficient of friction, reducing interfacial resistance and energy dissipation. These findings confirm the biolubricant's effectiveness in forming a stable lubricating film that minimizes direct contact between sliding surfaces.

Surface roughness analysis further supported these results, as the biolubricant-treated specimens showed the smallest increase in Ra values after testing, indicating smoother surface retention. Microstructural observation at 50× magnification revealed that the biolubricant condition produced the most intact surface, with minimal scratches and no visible deformation or fatigue cracks, compared to the severe damage observed in dry testing and moderate wear under conventional lubrication. These results highlight the potential of palm-aloe biolubricant as an environmentally friendly and high-performance alternative for reducing wear, friction, and surface damage in mechanical systems.

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