Interactive Effects of Lubricant Type and Sliding Distance on the Tribological Behavior of Aluminium 6061 Against SKD11 Steel

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Abstract : This study investigated the effects of lubricant formulation and sliding distance on the tribological behavior of Aluminum 6061 coupled with SKD11 steel under a constant normal load of 10 N. Sliding distances of 100, 1000, and 5000 m were tested under three lubrication regimes: dry contact, waste cooking oil (WCO)-based biolubricant, and WCO-based biolubricant containing 0.15 wt% TiO_2 nanoparticles. Tribological performance was evaluated using the coefficient of friction (COF) and wear rate, while Two-Way ANOVA assessed the significance of the main factors and their interaction. The TiO_2-enriched biolubricant produced the lowest COF (0.1081–0.1311), corresponding to a maximum reduction of 73.1% compared with dry friction, and reduced the wear rate to 1.48×10^{-3} $mm^3/N{\cdot}m$ at 5000 m, indicating approximately 95% improvement in wear resistance. ANOVA confirmed that lubricant type significantly affected tribological performance ($p < 0.05$). These improvements were attributed to a more persistent boundary lubrication layer and protective tribofilm formation promoted by TiO_2 nanoparticles, demonstrating its potential as an environmentally friendly lubricant for aluminum-based manufacturing applications.

Keywords : Biolubricant; Waste Cooking Oil; TiO_2; Tribology; Coefficient of Friction.

Abstrak: *Penelitian ini menyelidiki pengaruh formulasi pelumas dan jarak luncur terhadap perilaku tribologi Aluminium 6061 yang berpasangan dengan baja SKD11 pada beban normal konstan sebesar 10 N. Jarak luncur 100, 1000, dan 5000 m diuji pada tiga kondisi pelumasan: kontak kering, biopelumas berbasis minyak jelantah (WCO), dan biopelumas berbasis WCO yang mengandung nanopartikel* TiO_2 *0,15 wt%. Kinerja tribologi dievaluasi menggunakan koefisien gesek (COF) dan laju keausan, sedangkan ANOVA Dua Arah digunakan untuk menilai signifikansi faktor utama dan interaksinya. Biopelumas yang diperkaya* TiO_2 *menghasilkan COF terendah (0,1081–0,1311), setara dengan penurunan maksimum 73,1% dibandingkan gesekan kering, serta menurunkan laju keausan menjadi* $1{,}48 \times 10^{-3}$ $mm^3/N{\cdot}m$ *pada 5000 m, yang menunjukkan peningkatan ketahanan aus sekitar 95%. ANOVA mengonfirmasi bahwa jenis pelumas secara signifikan memengaruhi kinerja tribologi secara keseluruhan dalam penelitian ini (p < 0,05).*

Peningkatan ini dikaitkan dengan lapisan pelumasan batas yang lebih persisten dan pembentukan tribofilm pelindung yang dipromosikan oleh nanopartikel TiO_2, sehingga menunjukkan potensinya sebagai pelumas ramah lingkungan untuk aplikasi manufaktur berbasis aluminium yang beroperasi pada kondisi layanan sedang.

Kata kunci: *Biopelumas; Minyak Jelantah; TiO_2; Tribologi; Koefisien Gesek.*

INTRODUCTION

Tribology is the science of friction, wear, and lubrication between interacting surfaces in relative motion. This discipline holds a pivotal role in enhancing the efficiency, reliability, and service life of mechanical components subjected to sliding movement (Uniyal et al., 2024). Petroleum-derived lubricants continue to be predominantly employed across various societal and industrial activities, however, concerns regarding environmental impact, biodegradability, and resource depletion have driven research towards sustainable alternatives such as bio-based lubricants (biolubricants) (Rahmani et al., 2024; Singh et al., 2022). Vegetable oil-based lubricants are considered promising due to their high lubricity, viscosity index, flash point, renewability, and biodegradability, with the potential to replace a large proportion of conventional lubricants worldwide (Hussein et al., 2021).

Waste cooking oil (WCO) has emerged as a compelling raw material for biolubricant synthesis, owing to its low procurement cost, wide availability, and ecological advantage as a resource valorized from discarded waste (Joshi et al., 2023). Previous studies have demonstrated that WCO can be converted into high-performance biolubricants through transesterification processes and suitable additive incorporation (Hussein et al., 2021; Pawar et al., 2022). Among the diverse additive candidates, nanoparticles have garnered considerable scholarly interest because of their capacity to attenuate friction and wear through the development of tribofilms, surface-restorative actions, and nano-rolling phenomena (Hamisa et al., 2023; Uniyal et al., 2024). Titanium dioxide (TiO_2) nanoparticles, specifically, have been documented to improve lubricating efficacy by diminishing both the coefficient of friction and the wear rate in a range of oil-based lubricant systems (Choudhury et al., 2024). In addition, biolubricants fortified with TiO_2 tend to demonstrate more favorable rheological behavior, dispersion stability, and tribological response, primarily through the reinforcement of boundary film development and the minimization of direct metal-to-metal interaction (Hamisa et al., 2023; Neta et al., 2026; Uniyal et al., 2024).

In metal forming processes such as stamping, direct contact between tooling and workpiece materials often causes severe tribological problems, including adhesion, abrasion, and surface defects resulting from high contact pressure and friction (A. Y. et al., 2023) Aluminium 6061 and SKD11 tool steel constitute a frequently encountered tribological pairing in manufacturing processes. In this configuration, Al6061 is commonly employed as the workpiece material because of its advantageous strength-to-weight characteristics and resistance to corrosion, whereas SKD11 is extensively utilized for punches and dies owing to its elevated hardness and strong wear-resistant properties (Kumar et al., 2026; Purba et al., 2025). Consequently, the enhancement of lubrication at the Al6061–SKD11 contact interface becomes indispensable for mitigating friction, wear progression, and surface deterioration during forming operations.

Accordingly, the improvement of lubricating conditions at the Al6061–SKD11 interfacial contact is regarded as crucial for suppressing frictional resistance, limiting wear development, and minimizing surface degradation throughout forming processes (Abhang et al., 2025; ASTM International, 2023). Although many studies have investigated vegetable oil-based lubricants and nanoparticle additives, available information regarding the combined effects of WCO-based TiO_2 biolubricants and their application on Al6061–SKD11 is still limited. Furthermore, statistical evaluation of the interaction between lubrication condition and sliding distance using factorial analysis remains limited.

To address that issue, this study was conducted by examining the tribological response of Al6061 rubbing against SKD11 under three lubrication regimes, namely dry contact, WCO-derived biolubricant, and TiO_2-enriched WCO biolubricant. The evaluation was conducted across varying sliding distances through a pin-on-disc configuration in accordance with ASTM G99-23. ANOVA was employed to evaluate the significance of lubrication type, sliding distance, and their interaction on friction and wear responses (García-León et al., 2024; Kolawole et al., 2024). This study is expected to contribute to the combined contribution of used cooking oil-based biolubricant and TiO_2 nanoparticles in enhancing tribofilm development and inhibiting wear development under prolonged friction conditions. Then the use of ANOVA in this study is also expected to provide a more comprehensive and valid analysis in spreading the effectiveness of biolubricant with TiO_2 additives on Aluminum 6061 and SKD11 steel.

RESEARCH METHOD

The test process was carried out by adding a biolubricant based on WCO and also a biolubricant with the addition of TiO_2 nanoparticle additives. Aluminum 6061 was used as the disc material and SKD11 steel was used as the pin material in the pin-on-disc tribology test. Disc and pin material prepared with diameter and thickness as in the Figure 1.

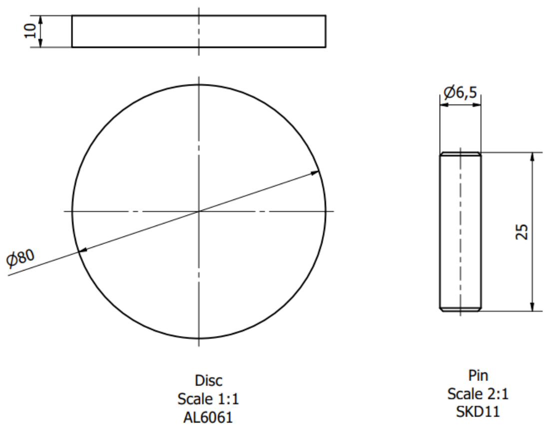


Figure 1. Material Specimen Aluminum 6061 and SKD11

The density of Al 6061 used for wear volume calculation was $\rho = 2.70$ g/cm³. Mass measurements were conducted using an analytical balance with ±0.1 mg resolution in accordance with ASTM G99-13 (ASTM International, 2023). This research was an experimental study. The process of making bio lubricant based on used waste cooking oil(WCO) uses the transesterification method on Fatty Acid Methyl Ester (FAME) that has been produced with Ethylene glycol with a molar ratio of 6:1 and CaO catalyst 1.2% of the mass of FAME used (Puspitasari et al., 2024). The transesterification temperature used was 130° for 120 minutes at 1000rpm. After that, the catalyst separation process was carried out on the transesterification results by letting it stand for 24 hours and continued with the first filtration process of filter paper and the second filtration with filter paper (Degfie et al., 2019).

Biolubricant was added with TiO2 nanoparticle additives with concentrations of 0.15wt%. The concentration of 0.15 wt% employed in this study was adopted as a reference-guided dosage, drawing upon insights from previous literature as well as the authors' earlier experimental investigations (Nurhidayat et al., 2025; A. Singh et al., 2020; Y. Singh et al., 2020). The TiO_2 nanopowder used in this study was a commercial product (Sigma-Aldrich), size < 25 nm and purity 99,7%. The dispersion was first agitated using a magnetic stirrer at 1250 rpm for 20 min, after which it was subjected to ultrasonic homogenization for 30 min to promote more uniform nanoparticle distribution. The experimental design was structured using a full factorial design (3

× 3) to evaluate the individual and interactive effects of lubrication condition and sliding distance on the tribological behavior of Aluminium 6061 against SKD11 steel. The full factorial design generated nine experimental combinations, each repeated five times, as presented in Table 1.

Table 1. Experimental combinations

Run	Lubrication Type	Sliding Distance (m)
1	Dry	100
2	Dry	1000
3	Dry	5000
4	Biolubricant	100
5	Biolubricant	1000
6	Biolubricant	5000
7	Biolubricant + TiO_2	100
8	Biolubricant + TiO_2	1000
9	Biolubricant + TiO_2	5000

Thus, the total number of treatment combinations: n = 9. The pin on disc parameters is shown in Table 2 and pin on disc scheme in figure 2. The pin on disc testing parameter also to be a variable control on this experiment.

Table 2. Experimental parameters for the pin-on-disc test

Parameters	Value
Force (N)	10
Sliding Speed (m/s)	0.1
Track Diameter (mm)	35
Temperature (°C)	23

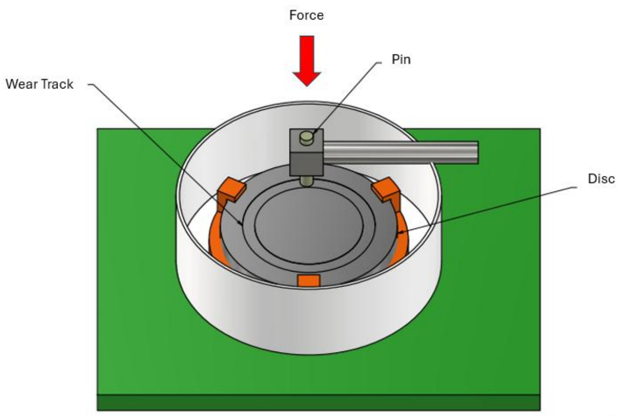


Figure 2. Pin on Disc Scheme

Wear and Coefficient of Friction Determination

Wear evaluation was conducted using the gravimetric method, which is widely accepted for metallic tribo-pairs due to its accuracy in quantifying material loss (Zhang et al., 2021). The mass loss (Δm) was calculated as:

$$\Delta m = mi - mf \quad (1)$$

Where mi and mf represent the initial and final mass, respectively.

Wear volume (V) was calculated using

$$V = \Delta m / \rho \quad (2)$$

Where ρ is the material density.

The density of Aluminium 6061 used for wear volume calculation was ρ = 2.70 g/cm³, which is consistent with the standard physical properties reported for AA6061 alloy (Rajeshshyam et al., 2023). The calculated volume was converted into mm³ for consistency with tribological reporting standards. Gravimetric wear analysis is widely accepted for metallic materials due to its accuracy and compatibility with Archard-based modeling. The specific wear rate *(k)* was calculated by referring to the Archard wear law formulation. Within the mild wear regime, the generated wear volume is considered to vary proportionally with the applied normal load and the corresponding sliding distance:

$$V = k\,F\,L \quad (3)$$

Rearranging gives

$$k = \frac{V}{(F \; x \; L)} \quad (4)$$

where:
k = the specific wear rate (mm³/N·m)
V = the resulting wear volume (mm³)
F = the imposed normal load (N)
L = the total sliding distance (m)

Archard's model assumes adhesive wear dominated by asperity contact and plastic deformatio. This formulation enables normalization of wear performance across varying test parameters and is widely used in tribological research for comparative analysis (Hamisa et al., 2023). For completeness, the dimensionless wear coefficient (K) can also be expressed as :

$$K = \frac{V\,H}{F\;L} \quad (5)$$

Where H denotes the hardness value of the softer material involved in the contact pair. However, in this study, wear rate is reported in mm³/N·m for consistency with recent nanolubricant tribology literature (Hamisa et al., 2023). To determine the statistical significance of lubrication condition and sliding distance on wear rate, ANOVA was employed. The statistical model evaluates main effect of lubrication type, main effect of sliding distance and interaction effect between both factors. The ANOVA methodology used was a two-way ANOVA following the principles of factorial experimental design as described by Montgomery (Kolawole et al., 2024). Statistical significance was evaluated at a 95% confidence interval with α set at 0.05; accordingly, a p-value lower than 0.05 was regarded as indicating a meaningful statistical influence on the wear rate response.

RESULT AND DISCUSSION

Wear Rate Analysis

The wear rate was derived from the pin-on-disc tribometer test results by utilizing the corresponding mass loss data. Each testing condition was replicated five times, and the resulting mean value was subsequently employed for statistical analysis *(n = 5)*. From the mass loss data, wear rate analysis was carried out and is displayed in table 3. There are summarizes the calculated wear coefficient values under different lubrication conditions and sliding distances.

Table 3. Wear Rate analysis

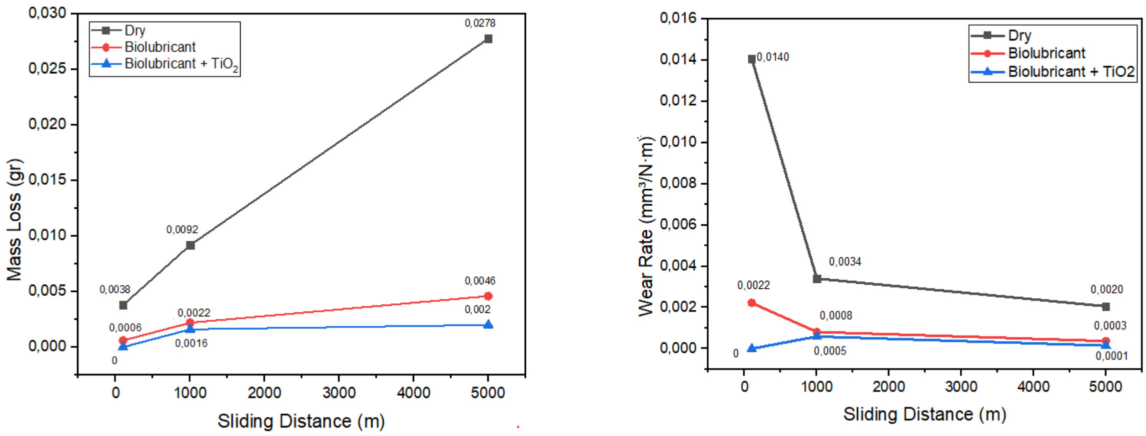
Lubrication Type	Sliding Distance (m)	Mass Loss (kg) (n=5)	Volume Loss (mm³)	Wear Coefficient (mm³/N·m)
Dry	100	3.8×10^{-6}	1.4074	1.41×10^{-3}
Dry	1000	9.2×10^{-6}	3.4074	3.41×10^{-4}
Dry	5000	2.78×10^{-5}	10.2963	2.06×10^{-4}

Biolubricant	100	6.0×10^{-7}	0.2222	2.22×10^{-4}
Biolubricant	1000	2.2×10^{-6}	0.8148	8.15×10^{-5}
Biolubricant	5000	5.0×10^{-6}	1.8518	3.70×10^{-5}
Biolubricant + TiO_2	100	$<1.0 \times 10^{-7}$	<0.0001	$<1.00 \times 10^{-5}$
Biolubricant + TiO_2	1000	1.6×10^{-6}	0.5925	5.93×10^{-5}
Biolubricant + TiO_2	5000	2.0×10^{-6}	0.7407	1.48×10^{-5}

The highest wear rate was observed under dry sliding at 100 m (1.41×10^{-3} mm³/N·m), indicating severe material removal during the initial running-in stage. As the sliding distance was extended to 1000 m and 5000 m, the wear rate was progressively reduced to 3.4×10^{-4} mm³/N·m and 2.1×10^{-4} mm³/N·m, respectively. This reduction suggests stabilization of the contact interface due to surface adaptation and debris compaction during prolonged sliding.

In contrast, the WCO-based biolubricant significantly reduced wear rate across all sliding distances. At a sliding distance of 100 m, the wear rate was diminished by approximately 84% relative to the dry sliding condition. A further decline was observed as the sliding distance increased, with the value reaching 3.0×10^{-5} mm³/N·m at 5000 m. This tendency suggests the establishment of a more effective boundary film, accompanied by the attenuation of direct asperity-to-asperity interaction. The most minimal wear response was obtained under the TiO_2-fortified biolubricant condition. At 100 m, wear was almost imperceptible (≈ 0 mm³/N·m), whereas at 5000 m, the wear rate was suppressed to 1.0×10^{-5} mm³/N·m. Compared to dry sliding at 5000 m, the nanolubricant reduced wear rate by approximately 95%. This demonstrates the strong anti-wear capability of TiO_2 nanoparticles.

The findings indicate that the application of biolubricant substantially suppresses the wear rate compared to the unlubricated condition. In dry contact, the wear rate tends to increase with increasing sliding distance. This trend is consistent with previous studies showing that Aluminum 6061 exhibits significant wear in dry friction, while the use of lubricants can significantly reduce wear through the formation of a protective tribofilm at the friction interface (Al-Qutub et al., 2024). In addition, the addition of TiO_2 to Al6061 significantly improves wear resistance and reduces material loss compared to unreinforced specimens. This improvement is due to the ability of TiO_2 nanoparticles to increase surface hardness and produce a protective layer, thereby restraining plastic deformation during sliding contact (Ali, 2021).



(a) (b)

Figure 3. Interaction graph Mass loss and sliding distance (a) Wear rate and sliding distance (b)

The quantitative mass loss results presented in Figure 3a show that dry friction produces the highest mass loss and wear rate compared to all other lubrication conditions. The use of used cooking oil-based biolubricant significantly reduces mass loss and wear rate across all friction distance variations. Figure 3b shows that the greatest reduction in specific wear rate was observed when using the biolubricant with added TiO_2 nanoparticles (Birleanu et al., 2022). Analysis of variance (two way ANOVA) was performed to determine the effect of lubrication conditions and sliding distance on the wear rate response. As presented in Table 4, both main factors, along with their interaction effects, are statistically significant at the 95% confidence level, as indicated by a p-value below 0.05.

Table 4. Two-way ANOVA results for wear rate

Source of Variation	SS	df	MS	F-value	p-value	Contribution (%)	Partial Eta Squared (ηp^2)
Lubrication	1.82×10^{-6}	2	9.10×10^{-7}	195.4	<0.0001	50.70	0.916
Sliding Distance	8.27×10^{-7}	2	4.14×10^{-7}	88.7	<0.0001	23.04	0.831
Interaction (A×B)	7.70×10^{-7}	4	1.93×10^{-7}	41.2	<0.0001	21.45	0.821
Error	1.68×10^{-7}	36	4.67×10^{-9}	–	–	4.68	–
Total	3.59×10^{-6}	44	–	–	–	100	–

Two-way ANOVA analysis in Table 4 revealed that lubrication conditions, sliding distance, and their interaction significantly affected the wear rate ($p < 0.0001$). Lubrication was identified as the most dominant factor, accounting for 50.70% of the total variance, followed by sliding distance (23.04%) and the interaction of lubrication with sliding distance (21.45%). High partial eta-squared values ($\eta p^2 > 0.80$) for all factors indicated strong effect sizes. Furthermore, a significant interaction term confirmed that lubrication effectiveness varied with sliding distance. The low residual error (4.68%) indicated good reproducibility of the experimental data and validated the statistical model.

Coefiicient of friction Analysis

The results of tribological testing using the pin-on-disc method show that lubrication conditions and sliding distance affect the friction coefficient value of aluminum 6061 against SKD11 steel. Each test was repeated five times (n=5) for the treatment combinations shown in Table 5.

Table 5. Coefiicient of friction Analysis

Lubrication Type	Sliding Distance (m)	Mean COF (n = 5)	Standard Deviation of COF
Dry	100	0.2818	0.0931
Dry	1000	0.4126	0.0159
Dry	5000	0.4715	0.0673
Biolubricant	100	0.1670	0.0746
Biolubricant	1000	0.2124	0.0755
Biolubricant	5000	0.2314	0.0288
Biolubricant + TiO_2	100	0.1081	0.0612
Biolubricant + TiO_2	1000	0.1110	0.0789
Biolubricant + TiO_2	5000	0.1311	0.0191

Table 5 shows that the dry friction regime produces the highest COF values for each friction distance condition examined. The average COF increases from 0.2818 at 100 m to 0.4715 at 5000 m. Conversely, when the used cooking oil-based biolubricant is applied, lower COF values are obtained across all friction distance variations compared to the unlubricated condition, which is in accordance with previous research (A. Singh et al., 2020). The minimum COF was recorded in the TiO_2 nanoparticle-enriched biolubricant condition, reaching 0.1081 at a friction distance of 100 m. The corresponding friction reduction behavior is illustrated in Figure 4.

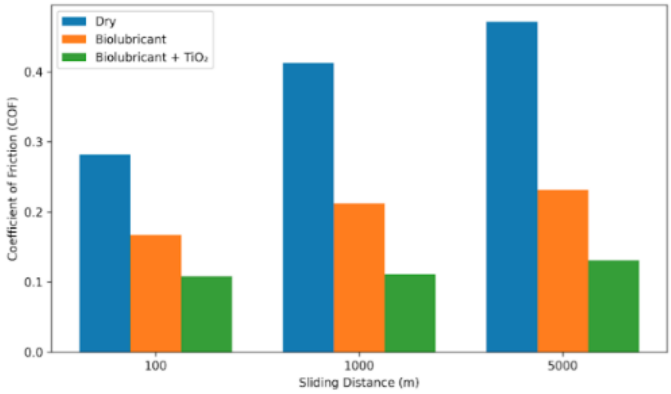


Figure 4. Graph mean COF

Figure 4 show that the use of lubricants reduces the COF value compared to conditions without lubricants. Under dry sliding conditions, an increase in sliding distance causes the COF value to rise from 0.2818 to 0.4715. When using biolubricants, the COF values ranged from 0.1670 to 0.2314. Meanwhile, the application of TiO_2 nanoparticle-fortified biolubricant produced the most diminished COF values relative to the other lubrication regimes, with values spanning from 0.1081 to 0.1311.

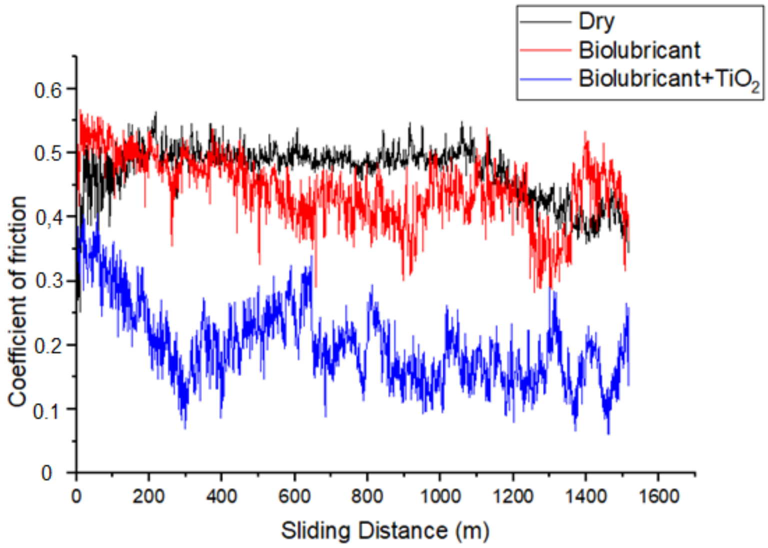


Figure 5. Graph COF evolution vs time

The COF variation curve indicates that the dry sliding condition generated more pronounced fluctuations in the coefficient of friction than the lubricant-assisted conditions. The use of biolubricants and biolubricants with the addition of TiO_2 resulted in more stable COF values during the testing process. In addition, the percentage decrease in COF values was calculated for dry sliding conditions as shown in Table 7.

Table 7. Percentage reduction in COF compared to dry sliding conditions

Lubrication Type	Sliding Distance (m)	COF Dry	COF Biolubricant	COF Reduction (%)
Biolubricant	100	0.2818	0.167	40.7
Biolubricant	1000	0.4126	0.2124	48.5
Biolubricant	5000	0.4715	0.2314	50.9
Biolubricant + TiO_2	100	0.2818	0.1081	61.6
Biolubricant + TiO_2	1000	0.4126	0.1110	73.1
Biolubricant + TiO_2	5000	0.4715	0.1311	72.2

The results indicate that waste cooking oil-derived biolubricants were capable of lowering the COF by as much as 50.9% relative to the dry sliding condition. A more substantial diminution was achieved when TiO_2 nanoparticles were incorporated into the biolubricant, with the highest COF reduction reaching 73.1% at a sliding distance of 1000 m. To further examine the influence of lubricant type, sliding distance, and the conjoint effect of both variables on the COF response, statistical testing was performed using the Two-Way ANOVA approach. The outcomes of this ANOVA evaluation are presented in Table 8.

Table 8. Two-way ANOVA results for Coefficient of Friction

Source of Variation	SS	df	MS	F-value	p-value	Contribution (%)	Partial Eta Squared (ηp^2)
Lubrication	0.2513	2	0.1257	72.58	<0.0001	69.81	0.801
Sliding Distance	0.0286	2	0.0143	8.26	0.0011	7.94	0.315
Interaction (A×B)	0.0178	4	0.0044	2.57	0.054	4.94	0.222
Error	0.0623	36	0.00173	–	–	17.31	–
Total	0.3600	44	–	–	–	100	–

The ANOVA results indicate that lubrication condition is the dominant factor affecting the coefficient of friction, contributing 69.81% of the total variation and exhibiting a very large effect size ($\eta p^2 = 0.801$). Sliding distance also significantly influences COF, accounting for 7.94% of the total variation with a large effect size ($\eta p^2 = 0.315$). Although the interaction effect between lubrication regime and sliding distance did not attain statistical significance at the 95% confidence threshold ($p = 0.054$), the observed effect size ($\eta p^2 = 0.222$) suggests a substantial practical influence, indicating that lubricant performance may vary with sliding distance. Comparable tendencies have also been documented in recent tribological investigations, in which lubrication conditions contributed more strongly to friction behavior than operating parameters such as sliding distance and load (Kolawole et al., 2024).

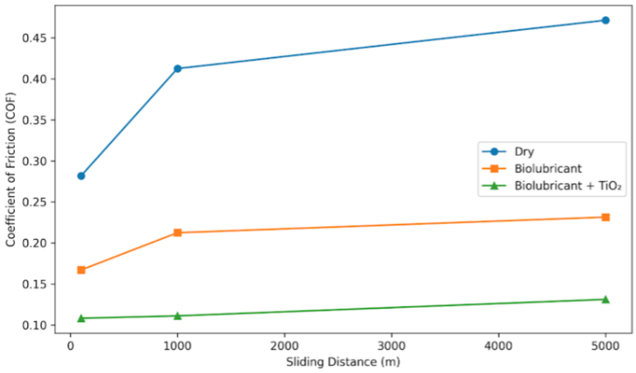


Figure 6. Interaction plot of lubricant type and sliding distance vs COF.

The results of the interaction plot show that the dry sliding condition produced the highest COF values across all sliding distance variations. The use of biolubricants and biolubricants with added TiO_2 nanoparticles resulted in lower COF values compared to the unlubricated condition across all test parameters.

Wear Track Morphology of Aluminium 6061

Morphological characterization of the worn surface was performed using SEM on AL6061 aluminum after pin-on-disc testing against SKD11 steel is shown in Figure 7. Figure 7 observed that the wear mechanism undergoes significant changes with increasing sliding distance and changes in lubrication conditions. In general, dry conditions (Figures 7a and 7d) show the most severe surface damage, dominated by adhesive wear, severe plastic deformation, delamination, and debris transfer.

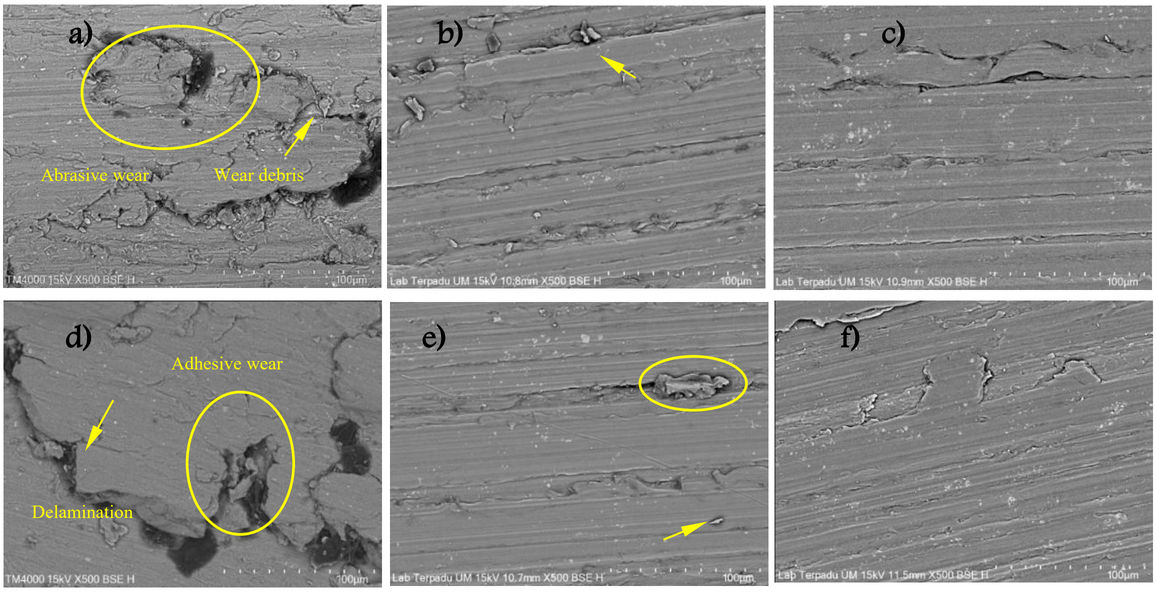


Figure 7. Disc morphology under a sliding distance of 1000 m (7a,7b,7d) and 5000 m (7d,7e,7f) under dry test conditions (7a,7d), biolubricant (7b,7e), and biolubricant+TiO_2(7c,7f)

At a sliding distance of 1000 m under dry sliding conditions, as depicted in Figure 7a, the surface damage is more obvious, where extensive delamination, transfer layer, crack propagation, and material removal are observed on the disc surface. These phenomena indicate severe adhesive wear due to the increase in contact temperature and accumulation of shear stress during the sliding process (Ali, 2021). Figure 7d shows the dry condition with a sliding distance of 5000 m, where the surface is most severely damaged. Severe delamination, surface peeling, a network of cracks, the formation of large debris, and a plastically deformed layer are clearly visible. The wear mechanism progresses towards a more severe adhesive wear regime, along with fatigue wear, as a consequence of the accumulation of repeated contact cycles and increasing interfacial temperatures.

Meanwhile, the application of biolubricant derived from used cooking oil (Figures 7b and 7e) was able to significantly reduce surface damage through the formation of a lubricating tribofilm layer that limits direct interaction between surface protrusions. Surface morphology under biolubricated conditions at a distance of 1000m, as shown in Figure 7b. The Aluminum surface still shows grooves and some adhesive spots; however, the degree of damage is lower than in dry conditions. The lubricant layer formed by the biolubricated is able to maintain surface stability and reduce the possibility of significant cracks and delamination. At sliding distance of 5000m (Figure 7e), the effectiveness of the lubricant layer decreases due to the increase in temperature and degradation of the lubricant layer during the test (Ayyadevara et al., 2026). However, some microploughing and adhesive patches begin to appear due to a decrease in lubricant film stability during long-term testing. Nevertheless, the biolubricant remains effective in reducing wear rates compared to unlubricated conditions (Ali, 2021; Teh et al., 2025).

The addition of TiO_2 nanoparticles to the biolubricant is shown in Figures 7c and 7f where the addition of TiO_2 nanoparticles improves the tribological response by inducing rolling and surface repair mechanisms, as well as the possible formation of a protective tribofilm, resulting in a smoother and more stable wear surface (Dassenoy et al., 2021). The biolubricant + TiO_2 testing condition with a sliding distance of 1000 m in Figure 7c shows the most stable and smooth morphological surface compared to all other testing conditions. Then, at a distance of 5000 m, as seen in Figure 7f, the dominant wear mechanism switches to a mild abrasive wear mode, with adhesive wear only occurring at minimal intensity. This indicates that TiO_2 nanoparticles exhibit a stable protective layer at long sliding distances. In addition, this indicates that the synergistic combination of used cooking oil and TiO_2 effectively improves the tribological response of AL6061 by suppressing direct interfacial contact, increasing load-bearing capacity, and forming a protective transfer layer on the contact surface (Xue et al., 2023). Limitation of this study was limited to a single TiO_2 concentration (0.15 wt%) and room-temperature conditions. Future work should investigate different nanoparticle concentrations and validate tribofilm formation using SEM-EDS and surface chemistry analyses.

CONCLUSIONS

This study demonstrated that the incorporation of 0.15 wt% TiO_2 nanoparticles into a waste cooking oil (WCO)-based biolubricant significantly improved the tribological performance of the Al6061–SKD11 tribosystem under varying sliding distances. The TiO_2-enhanced biolubricant achieved the lowest coefficient of friction (0.1081–0.1311), corresponding to a maximum reduction of 73.1% compared with dry sliding, and reduced the wear rate to 1.48 × 10^{-3} $mm^3/N.m$ at 5000 m sliding distance, representing an approximately 95% improvement in wear resistance. Two-way ANOVA substantiated that the lubrication condition acted as the principal determinant influencing both wear rate and coefficient of friction, accounting for 50.70% and 69.81% of the overall variance, respectively. Meanwhile, sliding distance was also shown to exert a significant contribution to the resulting tribological behavior. SEM observations revealed a transition from severe adhesive wear, delamination, and plastic deformation under dry conditions to a smoother and more stable wear surface under TiO_2-enhanced lubrication, thereby indicating the development of a protective interfacial layer capable of suppressing direct asperity-to-asperity interaction. These findings demonstrate the potential of TiO_2-reinforced WCO biolubricants as a sustainable and environmentally friendly lubrication solution for aluminum forming and other manufacturing applications requiring improved friction and wear performance.

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