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Evaluating palm oil ester base oils as eco-friendly alternatives in lubricant formulations

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ABSTRACT

Palm oil-based ester is a potential replacement of the conventional petroleum-based base oil for eco-friendly alternative with promising characteristics. This study aims to examine the impact of palm oil ester base oils characteristics and their behaviour on friction and wear. The formulation of lubricant was made by combining mineral base oil (MO) with two type of palm oil-based which are trimethylolpropane ester (TMPE) and polyol ester (PE) in a range of 0%wt to 100wt%. The tribological performance of the mixture base oils is discussed based on the engineering standard using four-ball tribometer according to ASTM D4172. The wear scar diameter was measured using digital microscope. The kinematic viscosity, density, acid number and pour point of each sample were also recorded. The result showed that PE has the lowest pour point, lower than -37 °C. However, the mix of 80%wt MO and 20%wt PE exhibit lowest coefficient of friction among others. As evidenced by the data, the combination of palm oil ester base oil with petroleum base oil can contribute to a better tribological performance. The outcome demonstrates that the incorporation of palm oil ester base oil and petroleum base oil significantly enhances tribological performance.

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1.0 INTRODUCTION

The research and development of bio-based lubricant has increased in recent years due to several factors. These include the growing awareness of environmental pollution caused by petroleum-based lubricant on ecosystems (Soni & Agarwal, 2014). The term “bio-based” on biolubricant itself attracts consumer to purchase this kind of environmentally friendly product which increase the demand on the market (Shah et al., 2019).

Due to their ability to biodegrade, renew and lack of toxicity, biolubricants are becoming a popular alternative to petroleum-based lubricants, drawing the interest of scientists worldwide (Kurre & Yadav, 2023). For example, plant oils possess several desirable characteristics such as high viscosity index and miscibility with other fluids (Erhan & Asadauskas, 2000). Another favourable lubricating properties exhibited by biolubricants is low volatility due to the molecular weight of triacylglycerol molecules (Brentin, 2020), which consisting of three lengthy chains of fatty acids. These attributes make plant oils an excellent substitute for mineral oil.

Among the vegetable oils used, palm oil has come to the limelight due to its sustainable and renewable resources of global food, oleochemical and biofuel industries (Basiron, 2007). Its availability and abundant production compared to other vegetable oils are also key factors in choosing palm oil as feedstock of biolubricant production as shown in Figure 1. Palm oil has favourable properties compared to mineral oil. Palm oil has been known for its biodegradability, exceptional lubricating characteristics, elevated viscosity indices, low volatility and high flash points (Durango-Giraldo et al., 2022). Palm oil has also shown promising tribological properties such as good lubricity, high viscosity index and has thermal stability (Md Alias et al., 2018). These properties make it a compelling choice for various applications, particularly in industrial machinery (Sapawe et al., 2019).

Many authors have focused on using palm oil derivatives to produce higher reliable base oils. Chemically modified palm oil through esterification can improve its oxidative stability, which is the main limitation for directly use of pure palm oil as biolubricant (Mohd Nor & Salimon, 2023). Juwita et al. (2021) has synthesized crude palm oil-based polyol ester as biolubricant and show promising results that palm oil derivatives can be used as potential replacement for petroleum-based lubricant. Previously Kotturu et al. (2020) blended up to 25% of palm oil polyol ester in commercial lubricant. The experiment showed that the blended lubricant with 15% of palm oil polyol ester has shown a significant reduction in wear rates and fuel consumption.

Previous researches has focused on using synthesized palm oil-based lubricants independently (Juwita et al., 2021.; Mohd Nor & Salimon, 2023). Palm olein which is a fraction of palm olein has also been discovered as lubricant (Aiman et al., 2022; Husnawan et al., 2011; Jumali et al., 2021; Loh & Muzzammil, 2022). Additionally, some studies have investigated the use of palm oil derivatives as additive in commercial lubricant (Alias et al., 2011; Yunus et al., 2020). However, studies on mixing mineral base oils with palm oil derivative base oils at various concentrations are lack reported.

Hence, this paper aims to examine the tribological performance of palm oil derivative base oils and their characteristics. The performance of the blend of different palm oil-based base oil compositions with mineral oil are also being recorded. The research result highlights the potential of palm oil derivative base oils to be mixed with mineral oil as new lubricant formulation as the demand for sustainable and high performance lubricants grow.

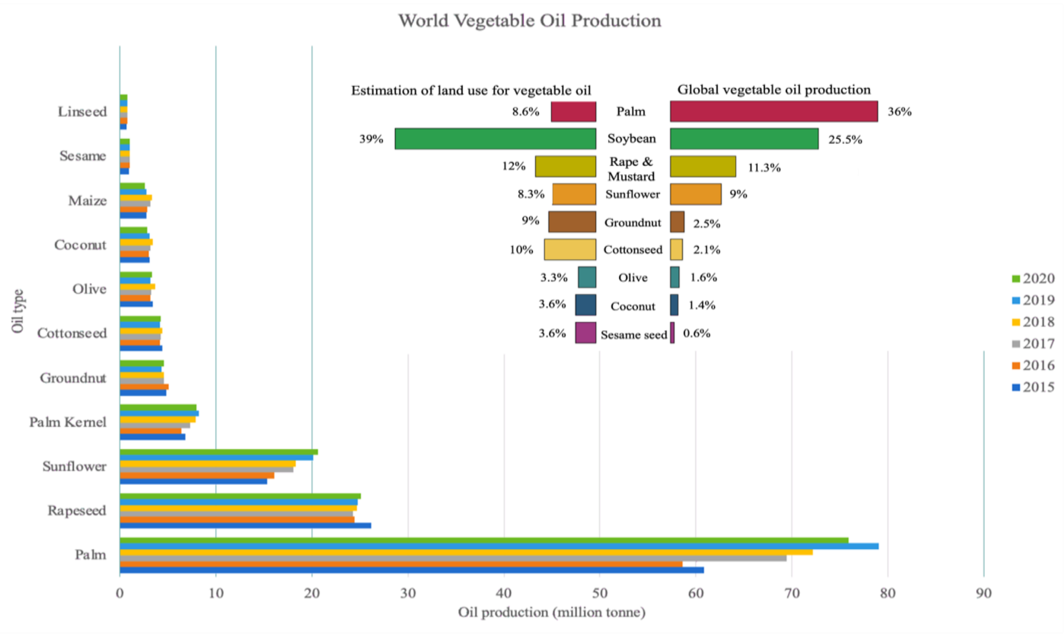


Figure 1: Total world vegetable oil production from 2015 to 2020 and the estimation of land use for vegetable oil planting and their oil production (Ritchie, 2021).

2.0 EXPERIMENTAL PROCEDURE

2.1 Lubricants

In the study, two type of base oils were used, which are Group III mineral-based base oil and palm oil-based base oils. Mineral base oil (MO) used was locally purchased without modification, while palm oil-based base oil used are palm oil trimethylolpropane ester (TMPE) and palm oil polyol ester (PE). The compositions of the blended base oils are detailed in Table 1.

Table 1: The composition of base oils and selected characteristics test.

Composition		Characteristics for screening
Mineral oil (% wt)	**Palm oil-based base oil (% wt)**	
0	100	Kinematic viscosity
20	80	Acid number
40	60	Density
60	40	Cloud Point
80	20	Pour Point
100	0	Density

The different sample composition of MO and TMP ester and PE were weighted according to wt% as shown in Table 1. The mixture was then heated to 65 °C to 70 °C using hotplate and stirred continuously at 400 rpm for 45 minutes until the blends were homogenous to the naked eyes without any separation, layers or visible particles. Then the stability of oil samples was observed by examining whether separation layers occurred.

The kinematic viscosity of the samples was measured using viscometer at temperature of 40 °C and 100 °C. The samples density was measured using potentiometer. While pour point of samples were determined using SETA Cloud and Pour Point. The minimum temperature set up for this equipment is -35 °C. Acid number of all samples was determine using titration method by adding isopropyl alcohol as titration solvent with oil samples, and then adding phenolphthalein and KOH neutralization. The acid number was calculated according to ASTMD974 using Equation (1).

$$Acid\ value = \frac{Volume\ of\ KOH\ (ml) \times Normality\ of\ KOH \times 56.1}{Mass\ of\ sample\ (g)} \qquad (1)$$

2.2 Apparatus

The tribological tests was performed via four ball tribotester which adhered to the ASTM D4172 – 94 Standard Test Method for Wear Preventive Characteristics of Lubricating Fluid (Four-Ball Method). Figure 2 shows the schematic diagram of the four ball tribometer. This test assessed the lubricant's ability to reduce wear and provide effective lubrication in applications where moderate loads and speeds are involved. Standard ball bearings that used are AISI E-52100 steel ball, with a diameter of 12.7 mm and HRC hardness of 64-66 Ra. The surfaces of balls and pot were cleaned before each test using n-Haptane to remove the trace of solvent remained when the test lubricant is introduced. The test was run under specified test conditions, as outlined in Table 2.

Table 2: Testing condition based on ASTM D4172 – 94.

Conditions	Details
Speed (rpm)	1200
Temperature (°C)	75
Duration (s)	3600
Load (kg)	40

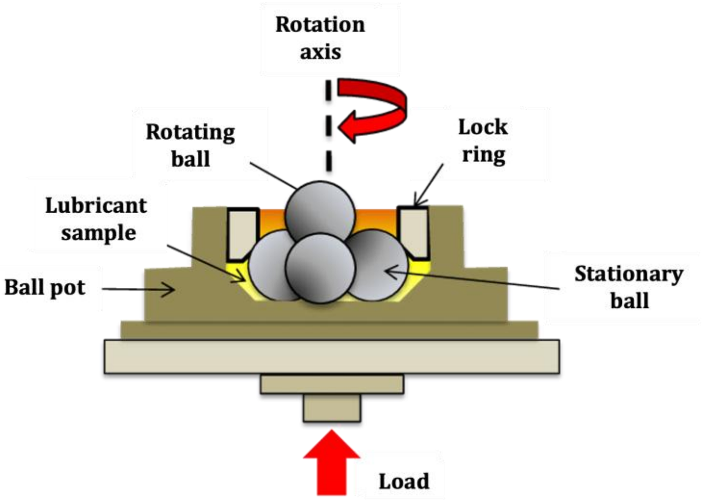


Figure 2: Schematic view of the four-ball assembly in the tribometer.

3.0 RESULTS AND DISCUSSION

3.1 Physicochemical Characteristics

The result of acid number, pour point and specific gravity of all samples are presented in Table 3. Mineral oils typically have lower acid numbers due to their refined nature, which removes most impurities and naturally occurring acids. In the contrary, bio-based base oils often have higher acid numbers because they contain natural fatty acids and other organic acids inherent to their biological origins. The feedstocks, processing methods and storage of palm oil-based base oil can contribute to the higher acid number of TMP ester and PE.

Table 3: Characteristics of base oils and their blends.

Type of Oil	Acid Number	Pour Point (°C)	Specific Gravity at 15 °C (kg/L)
MO	0.09	-19	0.8642
TMP Ester	0.264	-4	0.952
MO:TMP 20:80 (A1)	0.175	-6	0.932
MO:TMP 40:60 (A2)	0.173	-9.5	0.912
MO:TMP 60:40 (A3)	0.104	-15	0.892
MO:TMP 80:20 (A4)	0.099	-18	0.877
PE	0.18	< -37	0.932
MO:PE 20:80 (B1)	0.153	-34	0.917
MO:PE 40:60 (B2)	0.12	-31	0.902
MO:PE 60:40 (B3)	0.089	-23	0.887
MO:PE 80:20 (B4)	0.084	-20.5	0.872

However, for certain compositions, the acid values are lower than the MO itself. The composition of MO and PE at B3 and B4 are 0.089 and 0.084 respectively which are lower than acid value of MO (0.09). The neutralization of acids in TMP ester and PE reduced the overall acid number of the blends. This shows a synergistic interaction between MO and esters. The compositions of PE and MO showed lower acid number than TMP ester and MO.

The pour point of the lubricants indicates the lowest temperature that the lubricants remain at fluid state and pourable. This characteristic is important especially when the lubricants are used in cold climates. The pour point of TMP ester and PE derived from palm oil vary due to the differences in molecular structures and branching. TMP ester exhibits a higher pour point because it has more branches compared to PE, makes it has a higher pour point. In contrast, PE generally has less branching and more linear structure which results in a lower pour point. Generally, mineral-based base oil exhibits higher pour points compared to synthetic lubricants. In the result, mineral oil demonstrated higher pour point compared to PE which have pour point of lower than -37 °C. The pour point of TMP ester is higher than MO. This indicates that as the proportion of MO increases in the MO and TMP ester blends, the pour point decreases. Meanwhile, the composition of MO and PE indicate that the higher the percentage of PE in the blends, the better it can withstand low temperatures. For instance, B1 and B2 with the lowest pour points of -34 °C and -31 °C respectively, offer the best low-temperature fluidity. However, the pour point stand alone cannot be used as the benchmark in choosing the best blends for base oil.

Specific gravity has influence on the overall lubricant performance. In this assessment, the specific gravity results show that palm oil-based base oils (TMPE and PE) are denser compared to MO. This difference specific gravity can be caused by the molecular composition and the presence of heavier organic compound in both TMPE and PE. In the blended lubricants, an increase in the percentage of MO in the blends result in a reduction of base oil overall density. This occurs due to the lower specific gravity of MO compared to TMPE and PE.

Kinematic viscosity results show the influence of the lubricant on lubrication regime, friction and wear of two interacting surfaces. As can be seen in Table 4, the results indicate a clear trend of decreasing kinematic viscosity with increasing temperature for all pure lubricants and their various composition blends. Among the lubricants tested, MO exhibited the highest viscosity at all temperatures while pure PE showed the lowest viscosity at all temperature. The blended base oils of MO and PE showed lower viscosity compared to the blended base oil of MO and TMP. The different molecular structure of different base oils could influence the observed viscosity.

Table 4: Kinematic viscosity (cm^2/s).

Type of Oil Temp	MO	TMP	PE	A1	A2	A3	A4	B1	B2	B3	B4
40	1.179	0.341	0.209	0.385	0.455	0.581	0.778	0.281	0.360	0.468	0.701
100	0.124	0.068	0.049	0.076	0.081	0.091	0.106	0.062	0.067	0.079	0.097

3.2 Tribological Testing

The tribological testing was conducted three times for each pure oil and blend to observe any potential variation. The coefficient of friction for samples with different compositions of MO and TMPE and PE are illustrated in Figure 3. Numerous studies have demonstrated that palm oil-based lubricants have good friction coefficient and excellent performance against wear due to its chemical compositions (Amminuddin et al., 2024; Mohd Nor & Salimon, 2023; Yunus et al., 2020). In this study, B4 sample which consist of 80% MO and 20% PE has the lowest CoF among other samples. Second to this is the pure PE with CoF of 0.0745. For TMPE blends with MO, A2 and A3 blends have the lowest CoF values of 0.0749 and 0.0869 respectively, in the same group. Even, the CoF for these two blends are lower than the pure TMPE itself. When comparing the pure base oils, PE has the lowest CoF while TMPE itself has lower CoF than MO. TMPE and PE is said to attract to the metal surface due to ester polarity which form a lubricating film between the contacting surfaces (Rudrick, 2020). This polarity allows them to interact with metal surfaces and enhancing their adhesion.

Figure 4 shows the effect of different compositions on the wear scar diameter (WSD) for both palm oil-based base oil. The value of WSD was performed after the tribological test using digital microscope. Based on the figure, it is evident that the WSD for MO (1.184 mm) is greater in comparison to pure TMP ester (1.091 mm) and PE (1.176 mm). Nevertheless, the combination of TMPE and PE with various compositions show distinct outcomes. Sample B3 and B4 exhibit a considerable decrease in WSD, with compositions of 60wt% MO and 40wt% PE, and 80wt% MO and 20wt% PE, respectively. This can be caused by the chemical interactions between the molecules of different oils that may alter the physical characteristics of the resulting mixture (Zulkifli et al, 2014).

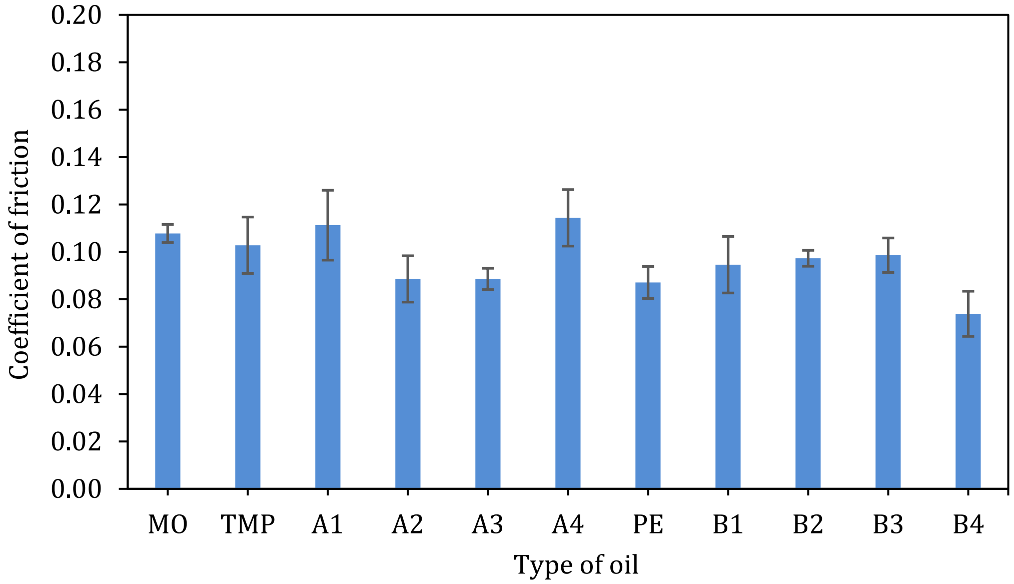


Figure 3: Coefficient of friction of different composition of base oils.

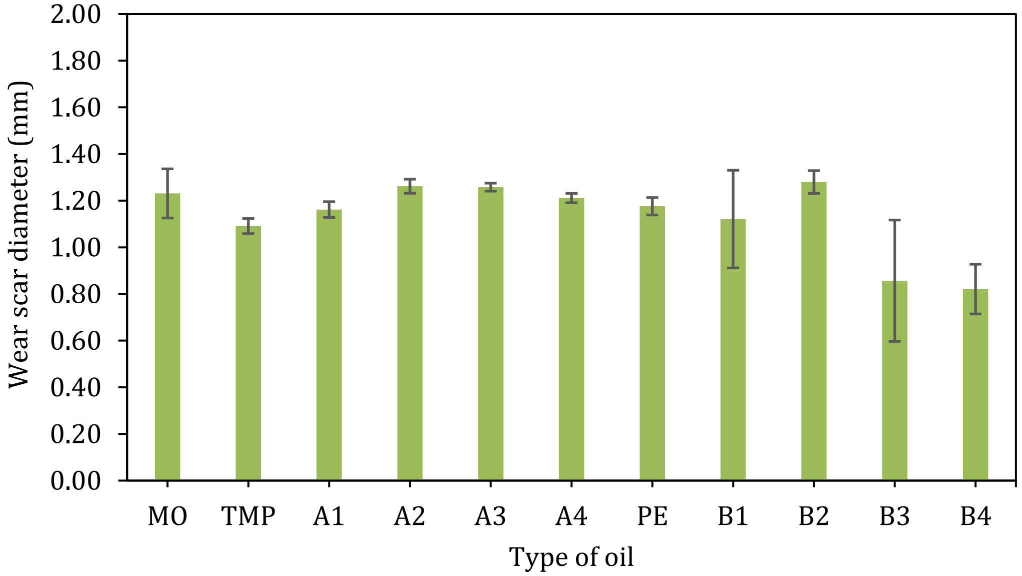


Figure 4: Average wear scar diameter tested for different base oil compositions.

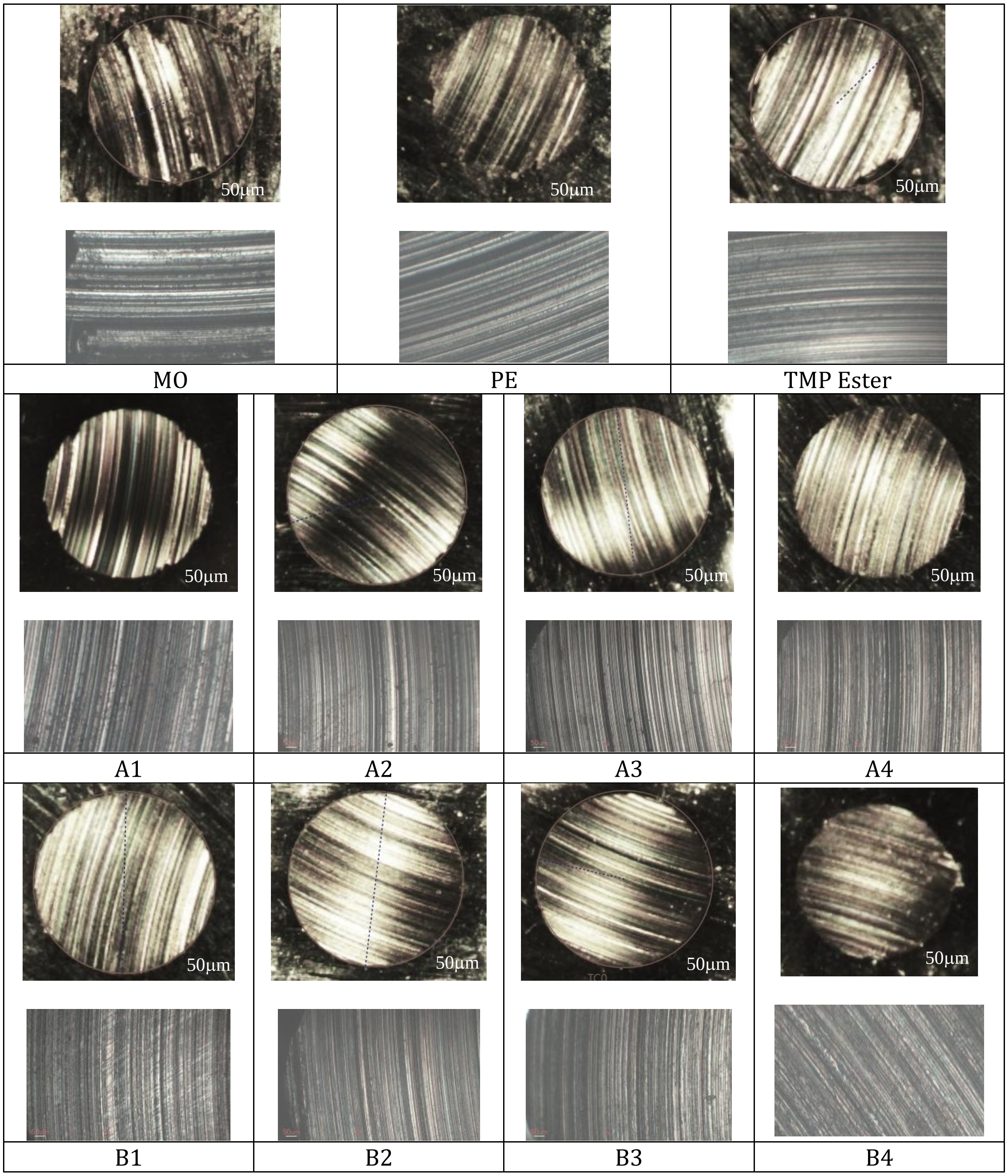
Lubricants with higher viscosity at elevated temperature may provide a better protection against wear and scuffing. However, in this study, TMP and PE showed better results in WSD compared to MO that has higher viscosity. This indicates that, despite their lower viscosity, TMP and PE provide superior anti-wear protection. This enhanced performance can be caused by the natural ester content in palm oil-based base oils which offers excellent lubricity and film strength

(Yunus et al., 2020). The ester in palm oil-based lubricant can form a stable lubricating film to reduce wear more effectively than MO.

The CoF and WSD results indicate that a higher CoF does not directly contribute to higher WSD. For instance, A4 exhibits a higher CoF compared to A2 and A3 yet has lower WSD compared to both. This situation suggests that the relationship between CoF and wear is not straightforward. While high friction implies a greater resistance to motion between two surfaces, it does not necessarily contribute to higher wear. The measured kinematic viscosity for A4 at 100 °C is 0.106 cm^2/s which is comparably higher than A2 and A3. Higher viscosity can contribute to thicker and more stable tribofilm, reducing direct surface contact, and thereby minimizing the wear. This results in a higher friction coefficient for A4 due to the resistance owing to the fluid friction causing greater energy losses. However, the higher viscosity offers improved wear inhibition compared to the lower viscosity of A2 and A3.

The B4 which contains 80 wt% of mineral oil and 20 wt% of PE has a lower COF and WSD compared to B1, B2 and B3. Notably, despite having higher CoF than B4, B3 has a slightly similar WSD with B4. The B4 is likely to achieve an optimum balance of viscosity, polarity and film stability. Palm oil-based PE has a longer and more complex structure with multiple hydroxyl and ester groups making it highly polar. This strong polarity promotes the formation of strong adhesive bonds with the metal surface which cause higher resistance during sliding. In B4, the high wt% of MO improves film stability and lubrication performance, while the small proportion of PE that provides adequate protection without significantly increase the friction. This combination results in lower friction and reduced WSD. A smaller wear scar indicates superior anti-wear properties of the lubricant formulation.

Figure 5 presents digital microscope images of the wear scar. The visible grooves and surface scratches illustrate that abrasive wear occurred on the balls. The wear scar for MO displays more clear wear groves with deeper channels compared to PE and TMP ester. The PE image displays finer wear tracks and smoother overall surface compared to MO and TMP. It reflects the PE's ability to minimize friction and wear on two contacting surfaces. The wear scar on A1 shows evidence of material removal, while wear scar on B1 displays a distinct patent of parallel grooves with minimal opposing scratches. The wear scar on B4 shows smoother grooves around the wear track, suggesting that this blend offers a better protection compared to other PE blends. As no additives were added in the blends, their ability to reduce surface wear relies on the properties of the base oils.



MO PE TMP Ester

A1 A2 A3 A4

B1 B2 B3 B4

Figure 5: Digital microscope images of wear scar of each pure base oils and their blends.

CONCLUSIONS

The findings of the study indicate that palm oil-based base oil has potential to improve wear and friction on the steel ball. PE base oil exhibits better lubrication characteristics than TMPE base oil and MO. Incorporating TMPE and PE in the mineral-based oil significantly improves physical characteristics of base oil and its tribological performance. Notably, although PE demonstrated the best performance and characteristics among the pure base oils, its incorporation into mineral base oils showed the best tribological performance. The B4 samples stand out as the best blends, exhibited the lowest WSD, lowest CoF and acceptable physical characteristics. However, performance trends suggest that a lower percentage of PE in mineral base oils might further enhance tribological performance. Further study should focus on this aspect as well and include additional additives to evaluate their impact on overall performance.

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