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Tribological performance analysis of palm oil esters as alternative automotive engine oil

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ABSTRACT

Petroleum-based lubricants are non-renewable and environmentally hazardous, contributing to significant ecosystem contamination. In contrast, plant-based lubricants offer renewable, biodegradable, and less toxic alternatives, though palm oil-based esters face challenges in oxidative stability and thermal performance, which can be improved with appropriate additives. This paper studies the use of palm oil esters as a base oil blended with additives as a potential alternative for automotive engine oils. These palm esters (PE2088 and PE3971) were blended with additives in varying percentages of 1%, 2.5%, 5%, 7.5%, and 10% by weight. The kinematic viscosity results were measured using a viscometer at 40°C and 100°C. The results present a consistent pattern in all tested oil samples where they decrease as the temperature increases. The coefficient of friction (COF) and wear scar diameter (WSD) were measured using a four-ball tribotester. Pure PE2088 without additives showed the lowest COF, approximately 25% lower than that of the engine oil, while blended PE2088 with 7.5 wt% additives exhibited the lowest WSD of 0.34 mm, about 31% lower than that of the engine oil. These results indicated that PE2088 with 7.5 wt% additives, may serve as viable alternatives to conventional engine oil.

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1.0 INTRODUCTION

The automotive industry is experiencing rapid growth in the development of sustainable and environmentally friendly alternatives to conventional lubricants. The shift towards electrification and the reduction of reliance on fossil fuels have increased the demand for sustainable lubricants. Plant-based lubricants are emerging as viable alternatives, particularly in terms of their performance under the extreme operating conditions typical of automotive applications. It has gained significant attention as an eco-friendly alternative to conventional petroleum-derived lubricants due to its inherent advantages, including renewability, biodegradability, and reduced toxicity (Menon and Rajasekaran, 2023).

The primary function of lubricants is to optimize tribological interactions between opposing surfaces by minimizing friction and wear through the reduction of the coefficient of friction (COF). This enables the development of high-performance lubricants capable of maximizing system efficiency and minimizing component degradation. The development of high-performance lubricants leverages the correlation between optimized lubricant rheological properties and the minimization of the COF at the contact interface, resulting in enhanced system efficiency and reduced component degradation (Panchal et al. 2017; Singh et al. 2017). Mineral oils, such as petroleum oil, are the most common and least expensive oils due to their availability in the market. Petroleum-based lubricants are non-renewable and inevitably unsafe for the environment and human beings, as they lead to severe contamination of the plants, soil, air, surface, and groundwater systems. According to Ahmad et al. (2022), high demand for lubricants in the global market contributes to increased carbon dioxide emissions and affects marine pollution. The development of alternative high-performance lubricants that are environmentally friendly is essential for providing standard options in various industries.

Lubricants are composed of two primary components: base oil and additives. Base oils, typically constituting over 90% of the volume of lubricants, are derived from crude oil through refining processes. The remaining 10% contain various chemical additives that enhance the performance of the lubricant (Woma et al. 2019). Vegetable oils are increasingly recognized as potential alternatives to mineral oils as lubricant base oils due to their long-chain fatty acids and polar groups of the molecule structure (Shaari et al. 2015). It can be categorized into two groups: edible and non-edible oils. Non-edible oils are particularly environmentally friendly and have been extensively used as lubricants in engine fuels and automotive applications. Common vegetable oils used as lubricants are sunflower (Kiran et al. 2022; Noble et al. 2023), jatropha (Sabri et al. 2023; Sani et al. 2024; Talib et al. 2022), castor oil (Roberto et al. 2023), soybean (Parente et al. 2021; Rios et al. 2019), palm oil (Amminuddin et al. 2024; Ojaomo et al. 2023; Paiman et al. 2024; Rahman et al. 2023), etc.

Palm oil is recognized for its good lubrication performance and the possibility of reducing reliance on mineral-based oil lubricants. Many researchers have studied the development of lubricants from palm oil esters. Trimethylolpropane (TMP) esters have been widely used in lubricant production due to its high sustainability characteristics that enhance the performance and reliability of lubricants in many applications. Yunus et al. (2020) have investigated the tribological properties of semi-synthetic engine oil (SSEO) blended with palm oil (PO) and palm oil-based TMP ester. The optimal blend, containing 2 wt.% TMP, achieved a COF of 0.075 and a wear scar diameter (WSD) of 485.7 μm, indicating enhanced performance. Further addition of 0.5 wt.% nano-glass powder reduced the COF to 0.057 and WSD to 295.53 μm, demonstrating significant improvements in lubrication efficiency. Alias et al. (2011) use palm oil-based methyl ester (POME) ester as a base fluid in order to study the lubrication properties of the formulated

TMPE. From the finding, the point was measured at 10°C, significantly higher than the -30°C of commercial hydraulic fluids and slightly lower than the unformulated TMP ester at 12°C.

Zulkifli et al. (2013) found that using palm oil-based TMP ester can reduce the WSD and COF by up to 30%. At 220 kg load, the 3% TMP blend exhibited optimal performance, while 7% TMP in hydrodynamic lubrication reduced friction by 50%. These findings support the development of efficient, environmentally friendly lubricants as alternatives to petroleum-based options for automotive applications. The authors (Zulkifli et al. 2014) continued the research using the same palm oil-based TMP ester blended with paraffin oil for extreme pressure characteristics. The results demonstrate that the blend of TMP ester and paraffin provides superior surface protection by approximately 70%.

While vegetable oils, such as palm oil-based TMP ester, demonstrate superior lubricating properties, they cannot entirely substitute mineral oils due to limitations in oxidative stability, thermal performance, and higher pour points. This issue can be resolved by implementing proper additives to enhance the overall performance and expand the applications of vegetable oil-based lubricants. Tertiary-Butyl-Hydroquinone (TBHQ) is recognized as an antioxidant used to modify the wear and friction caused by oxidation at higher operating temperatures (Ojaomo et al. 2022). Research by Zulhanafi and Syahrullail (2019) demonstrated the effectiveness of TBHQ in palm olein using a four-ball tribometer to assess the coefficient of friction, wear scar diameter, and surface roughness. The results indicated that TBHQ addition significantly improved performance, resulting in smoother surface roughness. Similarly, Dandan et al. (2019) found that incorporating TBHQ into palm kernel oil reduced the coefficient of friction compared to both commercial mineral and semi-synthetic engine oils.

This paper investigates the palm oil ester as a base oil blended with additives as a potential alternative for automotive engine oils. The kinematic viscosity, viscosity index, COF, and WSD blended palm esters with package additives were evaluated using a viscometer and four-ball tribometer.

2.0 EXPERIMENTAL PROCEDURE

2.1 Sample Preparation

Two types of palm oil esters, Palmester 2088 (PE2088) and Palmester 3971 (PE3971), were purchased from KLK OLEO (Malaysia), while the package additives (calcium, magnesium, phosphorus, zinc) were obtained from Brightstar Oils Sdn Bhd (Malaysia). The commercial engine oil (Petronas) was purchased from the authorized supplier for use as a benchmark test. Both palm esters were blended with additives in varying percentages of 1 wt.%, 2.5 wt.%, 5 wt.%, 7.5 wt.%, and 10 wt.% by volume using a magnetic stirrer. The mixtures were heated and stirred at a constant velocity of 700 rpm for 30 minutes to enhance the effective mixing. The properties of engine oil and palm esters extracted from the Product Data Sheet (PDS) are summarized in Table 1.

Table 1: Physicochemical properties of engine oil and palm esters

Parameter	Engine Oil	Palmester 2088	Palmester 3971
Acid Value (mg KOH/g)	-	0.2	1.0
Kinematic Viscosity 40°C (mm^2/s)	112	53	31
Flash Point C.O.C (°C)	>200	300	275
Pour Point (°C)	< -30	-39	3
Viscosity Index	-	-	-

2.2 Determination of Kinematic Viscosity and Viscosity Index

The most common method for determining kinematic viscosity is by using a Cannon-Fenske viscometer, as shown in Figure 1, according to the ASTM D445 standard. Kinematic viscosity is typically reported in centistokes (cSt), which is equivalent to mm^2/s in SI units and is calculated based on the time it takes for the oil to flow from the starting point to the stopping point, using a calibration constant supplied for each tube. Based on the measured kinematic viscosity, the viscosity index is determined in accordance with the ASTM D2270 standard.

In this study, the kinematic viscosity is reported at 40°C and 100°C temperatures. The kinematic viscosity (ν) is determined using Equation (1), which involves multiplying the time (t) by the viscometer constant (C).

$$v = Ct \tag{1}$$

where;

v = kinematic viscosity, mm^2/s

C = viscometer calibration constant, mm^2/s

t = outflow time, s

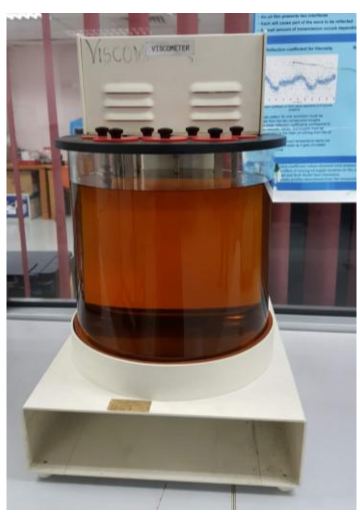


Figure 1: Viscometer.

2.3 Tribological Test Using Four-Ball Tribometer

The four-ball tribometer (Ducom) was used to determine the COF and WSD, following the standard testing procedures outlined in ASTM D4172. The machine consists of three alloy steel balls that are held immovably in a ball pot with one ball in a rotating spindle positioned against them, located in the four-ball tribometer chamber (Figure 2). A thin layer of lubricant was applied to the balls, enabling smooth contact between the balls. The four-ball tribometer testing parameters are exhibited in Table 2. Each of the tests was applied with a 40±0.2 kg load at the rotational speed of 1200±10 rpm for 60 minutes of duration and approximately at 75±2°C temperature until the balls were welded together. The sample volume of the lubricant oil was approximately 10 ml. It is important to ensure that all three steel balls are completely immersed and that the lubricant oil adequately covers its contact surfaces. The three stationary assembly balls were then taken to measure its WSD under the optical microscope.

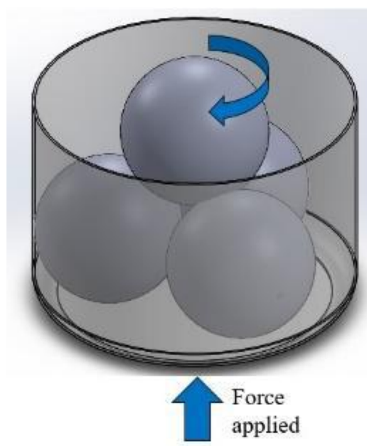


Figure 2: Schematic diagram of the four-ball operation. Adapted after Hamimi et al., 2019.

Table 2: Four-ball tester testing parameters.

ASTM	Test method	Rotating speed	Load	Duration	Temperature
D4172	Wear preventive characteristics	1200±60 rpm	40±0.2 kg	60±1 min	75±2 °C

3.0 RESULTS AND DISCUSSION

3.1 Kinematic Viscosity and Viscosity Index (VI)

The kinematic viscosity and viscosity index (VI) of the palm esters with additives at varying percentages of 1 wt.%, 2.5 wt.%, 5 wt.%, 7.5 wt.%, and 10 wt.% by volume were measured at temperatures of 40°C and 100°C. The engine oil, which acted as a benchmark test, was also measured. Table 3 presents the recorded kinematic viscosity of the engine oil, as well as pure and blended palmester samples.

Table 3: Kinematic viscosity and viscosity index of engine oil, pure and blended palm esters samples.

Samples	Kinematic Viscosity at 40⁰C (mm²/s)	Kinematic Viscosity at 100⁰C (mm²/s)	Viscosity Index
Engine Oil	111.96	17.71	175.166
Pure PE2088	57.76	11.41	195.919
PE2088 + 1 wt.%	49.2	9.89	192.524
PE2088 + 2.5 wt.%	51.12	10.04	187.997
PE2088 + 5 wt.%	54.21	10.17	178.553
PE2088 + 7.5 wt.%	55.49	10.84	190.859
PE2088 + 10 wt.%	59.14	11.19	185.598
Pure PE3971	35.41	7.17	171.268
PE3971 + 1 wt.%	29.65	6.08	158.375
PE3971 + 2.5 wt.%	30.52	6.21	158.385
PE3971 + 5 wt.%	32.14	6.49	160.718
PE3971 + 7.5 wt.%	32.34	6.18	142.856
PE3971 + 10 wt.%	32.01	7.19	198.72

As shown in Table 3, the kinematic viscosity presents a consistent pattern in all tested oil samples where it decreases as the temperature increases. The values in Table 3 indicate that the engine oil exhibited a kinematic viscosity of 111.96 mm^2/s at 40°C, decreasing to 17.71 mm^2/s at 100°C. Similarly, pure PE2088 decreased from 57.76 mm^2/s at 40°C to 11.41 mm^2/s at 100°C, while pure PE3971 decreased from 35.41 mm^2/s at 40°C to 7.17 mm^2/s at 100°C. A similar pattern is observed for blended oil samples, with the oils becoming thinner at high temperatures and thicker at low temperatures. These results have the same findings reported by Opia et al. (2023) and Dandan et al. (2019) on the decrease in viscosity as temperature increases.

The viscosity of a lubricant must be sufficiently high to maintain a film thickness between interacting components, especially under extreme temperature and pressure conditions. It is shown that engine oil presents the highest viscosity compared to pure palm esters (PE2088 and PE3971) and blended oil. According to Masjuki and Maleque (1997) and Reddy et al. (2014), engine oil sustains its high viscosity over a broad temperature range due to the inclusion of specialized additives, such as viscosity improvers and modifiers. These additives are designed to prevent the loss of viscosity at elevated temperatures, ensuring consistent performance under varying thermal conditions.

Of the samples tested, pure PE2088 at the highest concentration of 10 wt.% at 40°C contributed to a viscosity improvement of approximately 2.39% compared to pure palm esters. In contrast, the other blended additives at concentrations of 1 wt.%, 2.5 wt.%, 5 wt.%, and 7.5 wt.% present a lower viscosity than pure palm esters. This indicates that there was no significant improvement from blending, with only slight variations observed across the additive blend ratios, which are believed to be due to the lack of viscosity improver additives that could enhance viscosity performance. To address this issue, Pathmasiri and Perera (2020) suggested that one method to enhance the viscosity while maintaining its lubricating properties is by using a viscosity booster such as oxidized polyethylene (OPE).

The VI, which measures the rate of change in oil viscosity with temperature, adheres to the ASTM D2270 standard. A higher VI indicates a more stable viscosity over a range of temperatures and less dependence on temperature variations (Stanciu 2023). It is shown that PE2088 presents the highest VI among all blended concentrations compared to engine oil, with similar results reported in the studies by Dandan et al. (2019) and Pathmasiri et al. (2022). Pure PE2088 without additives contributed to the highest VI increment of 11.85%, while PE2088 with a 5 wt.% concentration contributed to the lowest VI increment of 1.93%, compared to engine oil. This improvement is due to the higher VI of vegetable oils, which results from their molecular structure. The long-chain triglycerides in vegetable oils maintain stronger intermolecular connections as temperature increases, resulting in greater resistance to changes in viscosity under varying thermal conditions.

On the other hand, PE3971 shows inconsistent results. At a 10 wt.% additive concentration, it exhibits the highest VI increment of 13.45%. In contrast, at concentrations between 1 wt.% and 7.5 wt.%, VI decreases by approximately 2.23% to 18.44% compared to that of the engine oil. This inconsistency may be attributed to the higher oxidative stability of PE3971, which could lead to lower VI results (Agboola et al. 2015). Almeida et al. (2014) suggested that this issue can be overcome by mixing with VI improver additives, as higher concentrations of these additives tend to increase the VI value.

3.2 Coefficient of Friction

The mean COF results for engine oil and palm esters (PE2088 and PE3971) blended with additive concentrations in percentages of 1 wt.%, 2.5 wt.%, 5 wt.%, 7.5 wt.%, and 10 wt.% by volume are presented in Figure 3. Each test was conducted in triplicate, with the results representing the averages of the three values. The engine oil that acted as a benchmark test shows a constant COF of 0.0914. As baseline oils, pure PE2088 and PE3971 without additives demonstrated COFs of 0.0710 and 0.0918, respectively. Bhowmik et al. (2024) suggested that the inconsistencies in COF when oils are blended with varying concentrations of additives are influenced by the individual compositions of fatty acids. This is supported by the varying outcomes observed for PE2088 and PE3971 in Figure 3, which are due to differences in their molecular structures and interaction strengths with metal surfaces. Similar results were also reported by Alias et al. (2011) and Zulhanafi et al. (2021).

PE2088 initially exhibits lower friction but spikes to 0.0934 at a 1 wt.% additive concentration, which corresponds to the run-in period. According to Mujtaba et al. (2021), this spike is due to the limited ability of the additives to form a consistent protective barrier on metal surfaces during this run-in period. Subsequently, PE2088 demonstrates a downward trend, with pure PE2088 without additives reaching its lowest COF of 0.0710, which is approximately 25% lower than that of the engine oil. As for PE3971, pure PE3971 without additives starts with a higher COF and then shows a decreasing trend, reaching the lowest COF of 0.0769 at a 5 wt.% concentration. However, the COF then increases at 7.5 wt.% and 10 wt.% concentrations, yet it still significantly outperforms engine oil. This decreasing trend is believed to be because of the presence of long-chain fatty acid and esters, which are recognized as surface-active materials (Hassan et al. 2016). The friction characteristics of the lubricant oil improve as the COF value decreases. This indicates they have a good lubricity ability in friction and wear due to the longer fatty acids chain presenting high strength lubricating films that exhibited a strong contact surface between the material (Syahrullail et al. 2013).

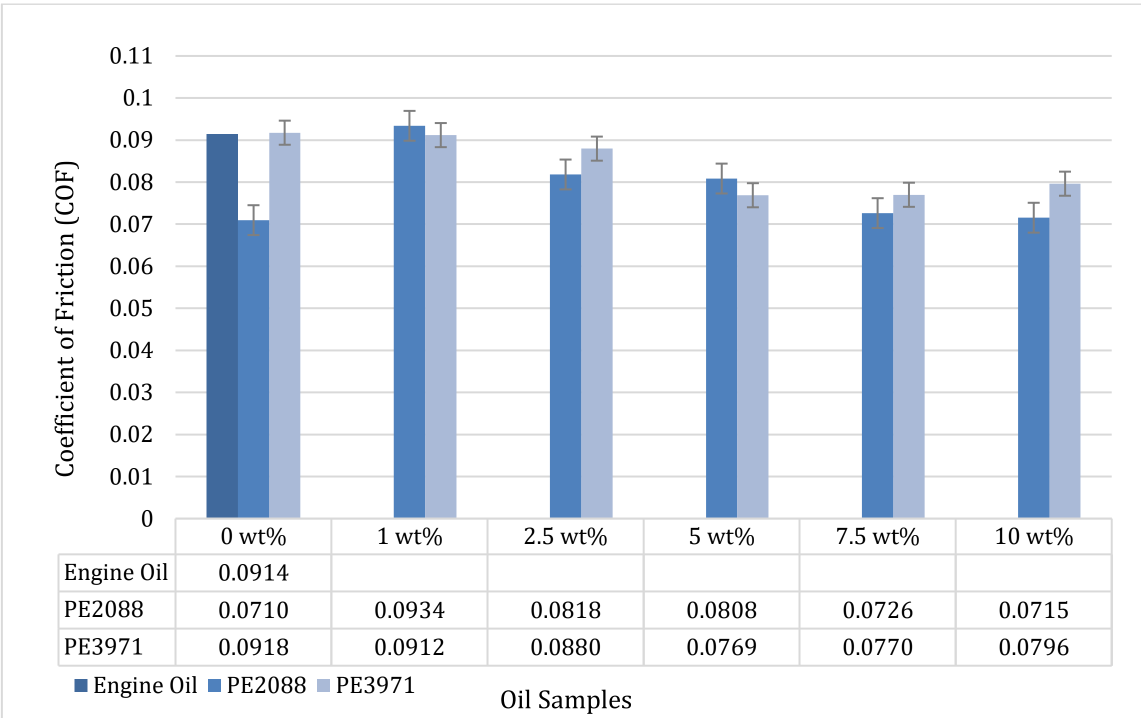
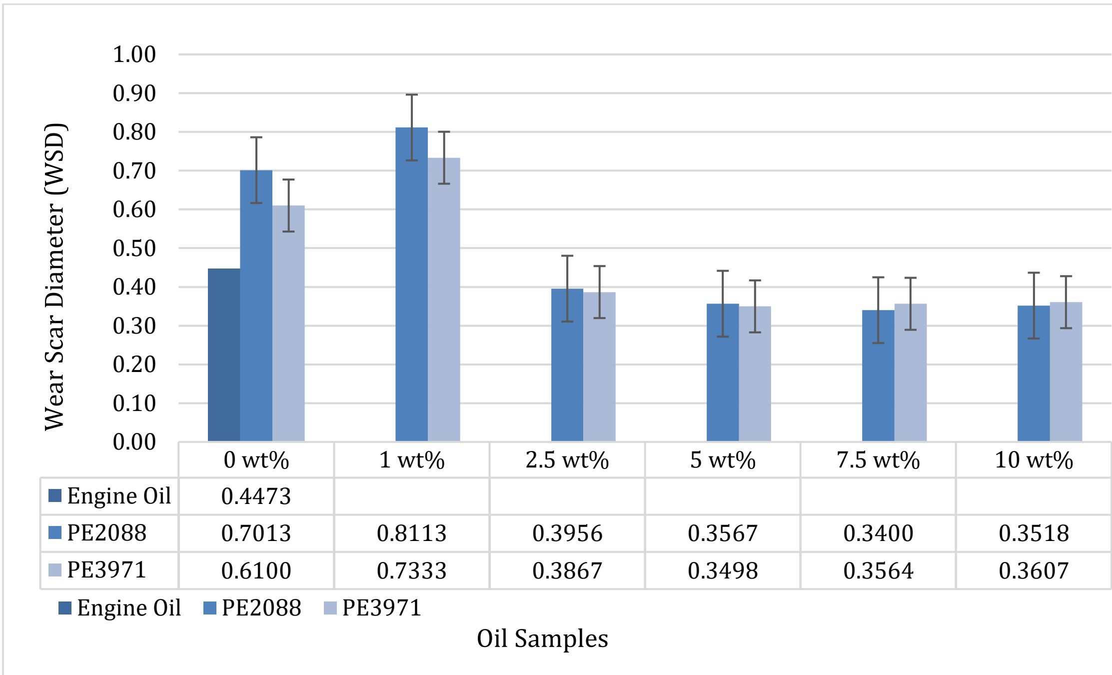


Figure 3: The average COF for engine oil, pure and blended palm esters samples.

3.3 Wear scar diameter

The WSD on the surface of steel balls was captured by an optical microscope. The WSD values for blended palmester samples with additive concentrations in percentages of 1 wt.%, 2.5 wt.%, 5 wt.%, 7.5 wt.%, and 10 wt.% by volume were measured and are presented in Figure 4. As can be seen, it can be concluded that the WSD of blended palm esters (PE2088 and PE3971) was lower than the WSD of engine oil and pure palm esters. The engine oil that serves as a benchmark test presents the WSD at 0.4473 mm, and pure palm esters exhibit the WSD of 0.7013 mm and 0.6100 mm, respectively. At 1 wt.% additive concentration, the WSD values for both PE2088 and PE3971 increased by approximately 16% and 20%, respectively, suggesting that low concentrations of additives initially reduce lubrication performance. Analysis of the data reveals that the 1 wt.% concentration blended palm esters present the highest values for both COF and WSD, as illustrated in Figures 3 and 4, respectively. This suggests that as the COF value increases, the wear scar diameter WSD value also increases. A similar trend was also reported by Shaari et al. (2015) and Hamimi et al. (2019). For additive concentrations ranging from 2.5 wt.% to 10 wt.%, both PE2088 and PE3971 consistently exhibited lower WSD values than the engine oil benchmark, falling between 0.34 and 0.40 mm. This indicates superior wear resistance properties of palm esters with additives compared to engine oil. PE2088 at 7.5 wt.% additive concentration demonstrated the best result for WSD, with a value that is 31% lower than that of engine oil, indicating optimal wear protection among the tested samples.



	0 wt%	1 wt%	2.5 wt%	5 wt%	7.5 wt%	10 wt%
Engine Oil	0.4473					
PE2088	0.7013	0.8113	0.3956	0.3567	0.3400	0.3518
PE3971	0.6100	0.7333	0.3867	0.3498	0.3564	0.3607

Figure 4: The average WSD for engine oil, pure and blended palm esters samples

3.4 Wear Scar Observation

The wear scar micrographs presented in Figure 5 and Figure 6 illustrate the tribological behavior of engine oil, pure PE3971, pure PE2088, and blended palm esters with additive concentrations in percentages of 1 wt.%, 2.5 wt.%, 5 wt.%, 7.5 wt.%, and 10 wt.% by volume. Both palm esters demonstrated similar appearances of parallel grooves on the worn surfaces, with the wear scar reducing as additive concentrations increased. According to Zulhanafi et al. (2023), these parallel grooves show the presence of abrasive wear. The grooves were caused by wear debris of the oxide layer or worn-off adhesion of rigid particles. The depth of these grooves can be observed through color variation in the micrographs, with darker regions indicating deeper grooves and brighter areas representing shallower surface wear (Maheswari et al. 2014).

In Figure 5, pure PE2088 shows the largest wear scar diameter, measuring 0.345 mm^2, compared to engine oil and pure PE3971, which measure 0.172 mm^2 and 0.286 mm^2, respectively. Pure palm esters have smaller scar diameters because no additives are present in their composition, which leads to a higher wear impact.

From Figure 6, for PE3971, the highest WSD value was observed at a 1 wt.% additive concentration, with a WSD of 0.448 mm^2. In contrast, the lowest values were found at 2.5 wt.%, with a WSD of 0.094 mm^2. For palmester PE2088, the highest WSD also occurred at 1 wt.%, with a WSD of 0.584 mm^2, while the lowest WSD of 0.075 mm^2 was observed at a 7.5 wt.% concentration. This is shown in Figure 6(a), where the darker appearance of both palm esters (PE3971 and PE2088) indicates deeper grooves and larger wear scars compared to the smaller diameter scars in Figure 6(b) for PE3971 and Figure 6(d) for PE2088. It is believed that the lowest additive concentration of 1 wt.% results from insufficient additive concentration, which affects the wear scar on the ball surfaces. In addition, Figure 6(e) for PE3971 presents a deeper adhesive region in the center of the wear scar diameter, resulting from the interaction of fatty acids with the rubbing surfaces (Aiman et al. 2017). These findings indicate that the ideal additive concentration for minimizing wear and friction varies between PE3971 and PE2088.

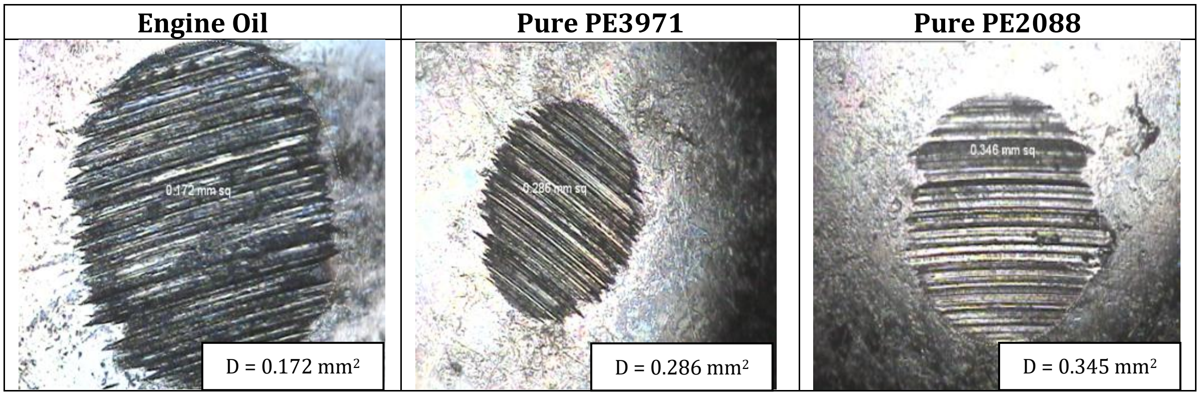
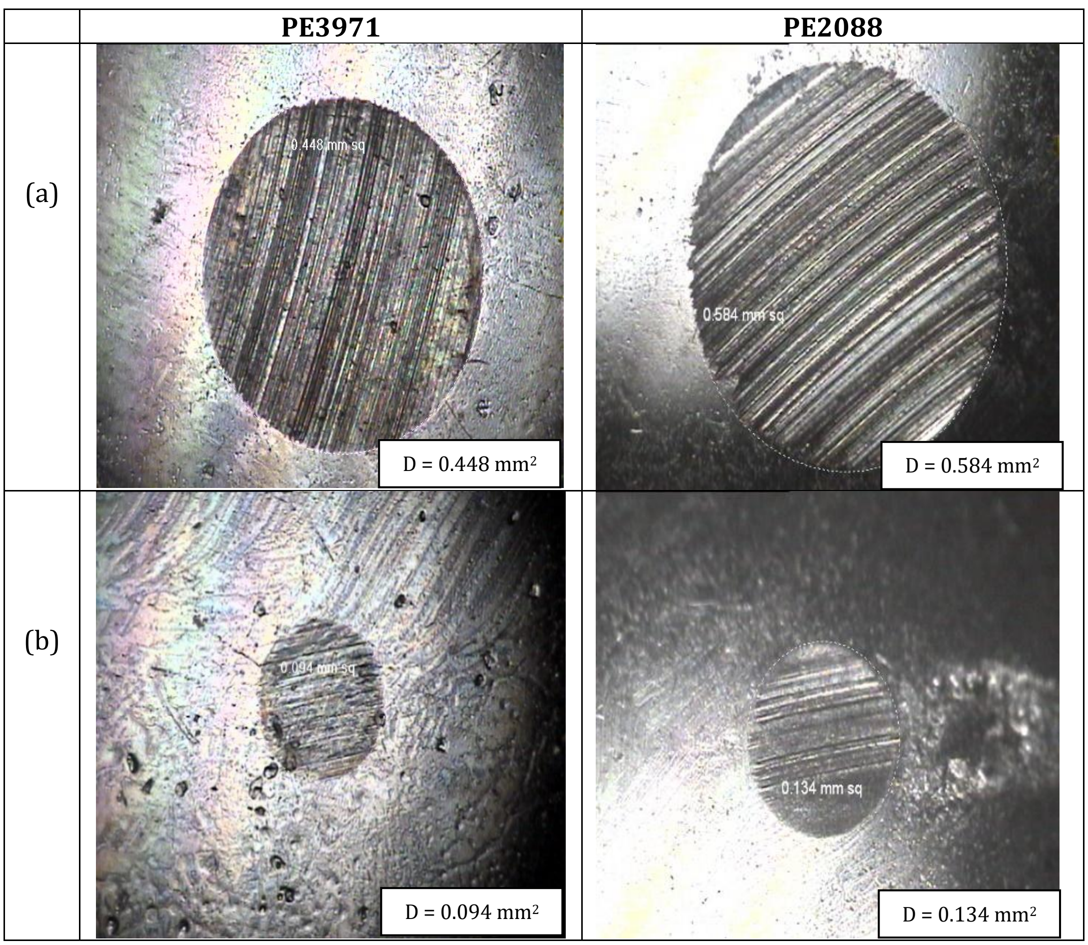


Figure 5: Optical micrograph of wear scars for engine oil, pure PE3971 and pure PE2088.



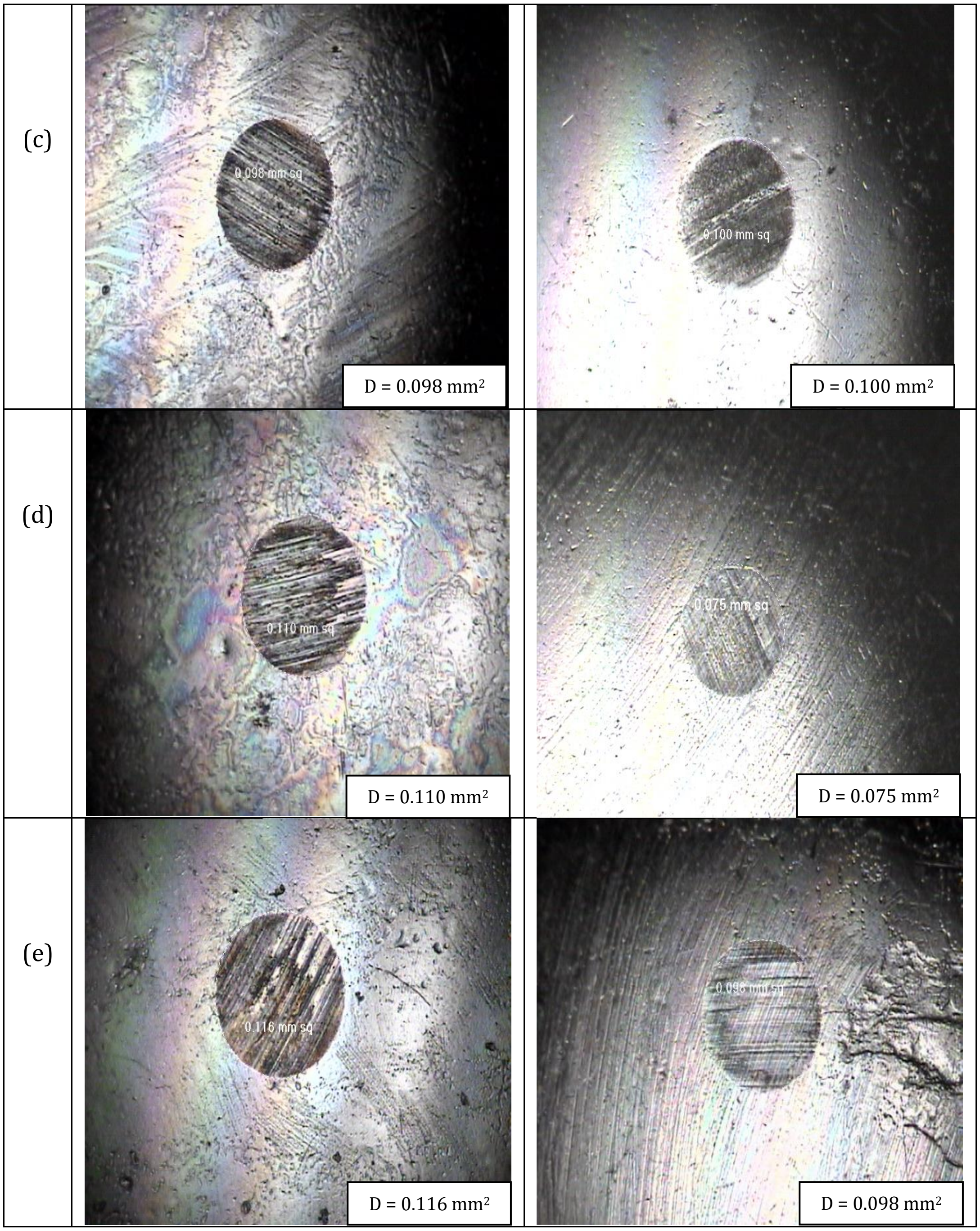


Figure 6: Optical micrograph of wear scars for blended palm esters with additives of (a) 1 wt.%, (b) 2.5 wt.%, (c) 5 wt.%, (d) 7.5 wt.%, and (e) 10 wt.% concentration.

CONCLUSIONS

In this study, the kinematic viscosity, COF, and WSD of PE2088 and PE3971 blended with additives were investigated and compared to a benchmark engine oil. The significant findings of the study are summarized as follows:

(a) The viscosity presents a consistent pattern in all tested oil samples where it decreases as the temperature increases.
(b) PE2088 shows the highest VI among all blended concentrations, with pure PE2088 without additives contributing to the highest VI increments, while PE2088 with a 5 wt.% concentration contributed to the lowest VI increments compared to engine oil.
(c) PE3971 presents inconsistent VI results; at a 10 wt.% additive concentration, it exhibits the highest VI increment, while at concentrations between 1 wt.% and 7.5 wt.%, it presents a lower VI increment compared to engine oil.
(d) The highest value of COF and WSD for both blended palmester (PE2088 and PE3971) samples were at 1 wt.% of additives concentration.
(e) Pure PE2088 without additives presents the lowest COF of 0.0710, approximately 25% lower than that of the engine oil.
(f) PE2088 blended with 7.5 wt.% concentration additives showed the lowest WSD of 0.34 mm which is about 31% lower than engine oil.
(g) The PE3971 and PE2088 at 1 wt.% of additives concentration showed darker appearances with deeper grooves and larger wear scars in their wear scar micrographs.
(h) The lighter and smaller scars were observed in the micrographs of PE3971 at 2.5 wt.% and PE2088 at 7.5 wt.% additives concentration.

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