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RESEARCH

Optimization of Palm Oil Ester-Based Bio-lubricant Composition as Automotive Engine Oil by WASPAS Method

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A B S T R A C T

The growing demand for sustainable alternatives to petroleum-based lubricants has accelerated interest in bio-lubricants derived from renewable resources. Palm oil has emerged as a promising bio-lubricant alternative due to its renewable sourcing, biodegradability, and advantageous physicochemical properties. Although palm oil esters are suitable for automotive engine oil applications, they have constraints and limitations that can be improved with appropriate additives. This study aims to identify the optimal composition of palm oil ester-based oil blended with lubricating additive oil (OA) for automotive engine oil using the Weighted Aggregated Sum Product Assessment (WASPAS) method. The palm oil ester base oil used in this study is trimethylolpropane trioleate (TMPTO), with an OA and ethylene-vinyl acetate copolymer (EVA). The kinematic viscosity results were determined using a Cannon-Fenske viscometer at temperatures ranging from 40°C to 100°C. The coefficients of friction (COF) and wear scar diameter (WSD) were measured using a four-ball tribometer. From the WASPAS method, TMPTO with 8 wt.% OA provided the optimum performance with the lowest COF and WSD. The sample was further improved by EVA with additives range from 0.5 wt.% to 3.0 wt.% concentration. The composition of 8 wt.% OA and 1 wt.% EVA was identified as the optimal formulation of the blended palm oil ester with additives, as it complies with the Engine Oil Viscosity Classification (SAE J300) standard.

1. INTRODUCTION

The global push toward environmental sustainability has intensified research into renewable and eco-friendly alternatives to petroleum-derived products, particularly in the lubricant industry. Most of the lubricants on the market today are mineral oils that come from

petroleum. Although these conventional oils are effective, their poor biodegradability and reliance on finite fossil resources highlight the necessity of pursuing sustainable, renewable, and commercially viable substitutes [1]. These limitations have driven research efforts toward renewable alternatives, with vegetable-based oils developing as particularly promising options for sustainable lubrication applications.

Vegetable oils are increasingly recognized as promising substitutes for petroleum-based lubricants due to their renewable, non-toxic, economic, and environmentally friendly nature. Their advantageous physicochemical properties, including high viscosity index, excellent lubricity, low volatility, high flash point, low coefficient of friction, and superior shear stability, make them highly suitable for lubrication compared to conventional mineral oils. Furthermore, their structural similarity to the long-chain hydrocarbons in mineral oils enhances their potential as sustainable feedstocks for lubricant production [2]. Vegetable oils have demonstrated superior biodegradability as lubricants, as reported in numerous studies on coconut oil [3], soybean [4], sunflower [5, 6], jatropha [7], castor oil [8], palm oil [9, 10], etc.

Palm oil demonstrates excellent lubrication characteristics and is widely recognized for its potential to serve as a substitute for mineral oil lubricants. Despite these advantages, palm oil encounters major limitations as a lubricant. Its thermal oxidative stability is relatively poor due to the presence of unsaturated bonds in the fatty acid structure and the hydrogen atoms located at the β position of the glycerol backbone [11]. In addition, palm oil exhibits poor low-temperature fluidity, which further restricts its lubrication applications [12, 13]. To address this issue, the oxidative stability of palm oil can be enhanced by modifying its molecular structure through the chemical modification of the transesterification and esterification processes [14].

Trimethylolpropane trioleate (TMPTO), synthesized through the esterification of polyol esters of trimethylolpropane (TMP) and oleic acid (OA), has significant potential as a base stock to produce bio-lubricants due to its low melting point [15]. Several studies have demonstrated improved lubrication performance for chemically modified palm oil-based TMP esters. Palm oil-based Trimethylolpropane Trioleate (TMPTO) offers advantageous properties such as high lubricity, good viscosity-temperature behaviour, and oxidative stability due to its branched ester structure [16].

Rahman et al. [17] highlight the potential of palm oil esters as alternative engine oils, demonstrating their ability to provide competitive tribological performance. Palm esters exhibited good viscosity behaviour at temperature and, when blended with additives, effectively reduced friction and wear, indicating their suitability as sustainable substitutes for petroleum-based lubricants in engine oil applications. Mustaffha et al. [18] study the palm oil esters blended with mineral oil as alternative engine lubricants. Results showed that incorporating palm esters improved friction and wear performance, with PE exhibiting favourable low-temperature properties, demonstrating their potential as eco-friendly engine oil base stocks. Norazman et al. [9] evaluated oleic acid-based bio-lubricants with different antioxidants to enhance lubrication performance. The results showed that additives greatly reduced friction and wear, with TBHQ being the most effective. This shows that palm-derived esters could be used as sustainable and efficient lubricant base oils. Yunus et al. [19] demonstrate that blending palm oil and TMP ester with semi-synthetic engine oil improves lubrication performance. Palm ester blends reduced friction and wear, with further enhancement from nano-glass additives, highlighting their effectiveness and potential as eco-friendly lubricants for engine oil applications.

The selection of appropriate base oils and suitable lubricating oil additives is essential for minimizing wear and friction, as these represent the key performance criteria for automotive engine lubricants. Multi-Attribute Decision-Making (MADM) techniques and mathematical modelling have been applied to assess and identify the most appropriate base lubricants [20]. More than 200 MCDM methods have been developed and commonly used. Among the methods, the Weighted Aggregated Sum Product Assessment method (WASPAS) is one of the modern MADM techniques that integrates the Weighted Sum Model (WSM) and Weighted Product Model (WPM). This combined approach has shown that it makes decisions more accurately than using just one WSM or WPM method [21].

The WASPAS method enables flexible weighting and averaging of criteria, providing comprehensive evaluations that support effective decision-making between objectives required [21, 22]. Several studies have applied the WASPAS method as a decision-making tool in lubricant formulation and process optimization, which demonstrates its versatility as a multi-criteria optimization approach for selecting the best alternatives across various industrial applications [16, 23-26].

Several studies have applied the WASPAS method as a decision-making tool in lubrication and process optimization. Kathamore and Bachchhav [20] identify the most suitable bio-based lubricants for metal cutting operations, particularly tapping challenging materials, by evaluating fourteen vegetable oils based on nine key performance criteria using MADM techniques. The WASPAS method confirms that coconut oil, palm oil, and Jatropha oil are the most suitable bio-based lubricants, with coconut oil demonstrating the highest performance ranking. Kandi et al. [23] used the WASPAS method to optimize heat treatment conditions for steel, showing that temperature had the greatest effect on improving its mechanical properties. Sahoo et al. [24] applied the Taguchi-based WASPAS method to improve the tribological performance of industrial ceramic coatings, showing that pressure was the key factor in reducing wear and friction.

Zalas [25] demonstrated that the WASPAS method is an effective tool for optimizing technological process parameters, enabling accurate selection of optimal conditions to improve overall performance and efficiency. Perec and Zalas [26] showed that the WASPAS method is a useful tool for optimizing machining parameters and improving process performance in advanced manufacturing. From previous research, it indicates that the WASPAS method is widely used as an optimization approach for systematically ranking and selecting the best alternatives among multiple competing criteria in diverse industrial decision-making applications, including lubricant selection, heat treatment, and process parameter optimization.

This study aims to identify the optimal composition of palm oil ester-based oil blended with lubricating additive oil for automotive engine oil using the WASPAS method. The optimization results obtained from the WASPAS analysis were validated through experimental findings.

2. EXPERIMENTAL PROCEDURE

2.1 Materials and sample preparation

Palm oil ester used in this study, Trimethylolpropane Trioleate (TMPTO) was supplied by KLK OLEO (Malaysia). The lubricating oil additives (OA) and the viscosity modifier of ethylene–vinyl acetate copolymer (EVA) were supplied by Chevron Oronite (Malaysia) and Sigma-Aldrich (Malaysia), respectively. The OA consists of barium (B), calcium (Ca), magnesium (Mg), molybdenum (Mo), phosphorus (P), silicon (Si), strontium (Sr), and zinc (Zn). The benchmark engine oil used was Shell Helix HX5 15W-40. The properties of the lubricating oils and EVA are presented in Table 1 and Table 2.

Table 1. Properties of lubricating oils.

Parameter	TMPTO	15W-40
Kinematic Viscosity (mm^2/s)		
40°C	57.76	109.78
100°C	11.41	14.46
Flash Point C.O.C (°C)	321.33	231.33
Pour Point (°C)	-39	-45
Viscosity Index	195.92	134.564

Table 2. Properties of EVA.

Parameter	EVA
Density (g/cm)	0.941
Autoignition temp (°C)	340
Melting point (°C)	75
Composition Vinyl acetate (wt. %)	40

The first step is to obtain the optimum percentage of OA through the WASPAS method. The TMPTO was mixed with OA at compositions of 2 wt.%, 4 wt.%, 6 wt.%, 8 wt.%, and 10 wt.%. The mixtures were stirred for 45 minutes at a temperature of 50-60°C using an overhead stirrer equipped with a rotary motor at 200 rpm. The summary of the blend composition of TMPTO with OA is shown in Table 3. Each sample was tested for kinematic viscosity using a viscometer and for wear preventive (WP) performance using a four-ball tribometer. Data obtained from the process were tabulated and optimized through WASPAS to obtain the best percentage ratio.

Table 3. Blend composition of TMPTO with OA.

Sample	Material
A1	TMPTO + OA 2 wt.%
A2	TMPTO + OA 4 wt.%
A3	TMPTO + OA 6 wt.%
A4	TMPTO + OA 8 wt.%
A5	TMPTO + OA 10 wt.%

In the next step, the optimum percentage ratio was subsequently blended with EVA at compositions of 0.5 wt.%, 1.0 wt.%, 1.5 wt.%, 2.0 wt.%, 2.5 wt.%, and 3.0 wt.%. The blending process involved 2 hours of continuous stirring at a temperature of 110–120°C. The optimum TMPTO:OA:EVA ratio was selected with reference to the Engine Oil Viscosity Classification (SAE J300) standard, based on kinematic viscosity, COF, and WSD parameters.

2.2 WASPAS method

The process flow of the WASPAS method is illustrated in Fig. 1.

The first step of the WASPAS method is to identify and create the decision matrix, *X* by equation (1),

$$X = [x_{i,j}]_{mxn} \quad (1)$$

Where $x_{i,j}$is the performance of the i^{th} variant with respect to the j^{th} criterion, *i* is the number of compared variants, *j* is the number of evaluation criteria, *m* is the number of variants, and *n* is the number of evaluation criteria.

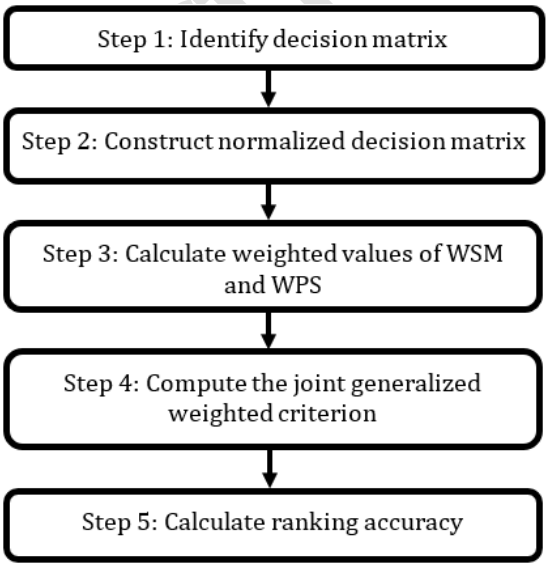

Fig. 1. Flowchart of WASPAS method.

For the next step, a normalized decision matrix was constructed by equations (2) and (3).

$$\bar{X}_{i,j(1)} = \frac{X_{i,j}}{max(X_{i,j})} \quad (2)$$

$$\bar{X}_{i,j(2)} = \frac{\min(X_{ij})}{X_{i,j}} \quad (3)$$

Where $\bar{X}_{i,j(1)}$ is the beneficial criteria, and $\bar{X}_{i,j(2)}$ is the unbeneficial criteria.

From the normalized values, the WSM and WPM methods were calculated by equations (4) and (5).

$$Q_i^{(1)} = \sum_{j=1}^{n} X_{ij} * W_j \quad (4)$$

$$Q_i^{(2)} = \prod_{j=1}^{n} (r_{ij})^{w_j} \quad (5)$$

Where $Q_i^{(1)}$ is the relative importance of the i^{th} alternative of the WSM method, $Q_i^{(2)}$ is the relative importance of the i^{th} alternative of the WPM method, and W_j is the weight of relative significance of the j^{th} criterion.

The total importance of each alternative is determined by using a joint generalized criterion, Q_i by equation (6).

$$Q_i = \left(Q_i^{(1)}\right) + \left(Q_i^{(2)}\right) \quad (6)$$

Equation (7) was used to enhance the accuracy and reliability of the decision-making process.

$$Q_i = \lambda * Q_i^{(1)} + \left((1-\lambda) * Q_i^{(2)}\right) \quad (7)$$

Where λ is the value of 0, 0.1,..., 1.

λ represents the weighting coefficient that controls the balance between the two components from WSM and WPM methods and the highest Q_i is selected as the best option.

2.3 Kinematic viscosity, COF and WSD

Kinematic viscosity was measured using a Cannon–Fenske viscometer in accordance with ASTM D445 (Fig. 2). In this method, the oil sample is placed in a capillary viscometer immersed in a constant temperature bath, where the time required for the fluid to flow under gravity from the start mark to the stop mark is measured. Readings were taken at each 10°C temperature increment from 40°C to 100°C. The kinematic

viscosity, expressed in centistokes (cSt) or mm^2/s in SI units, is calculated by multiplying the measured flow time by the calibration constant specific to each viscometer tube.

Fig. 2. Schematic diagram of a viscometer.

The four-ball tribometer was used to determine the wear preventive (WP) characteristics using the standard test procedures described in ASTM D4172. The coefficient of friction (COF) was recorded during testing. The device consists of three alloy steel balls that are held stationary in a spherical cup. Approximately 10 mL of the oil sample was placed in the spherical cup. One ball is mounted on a rotating spindle within the four-ball tribometer chamber (Fig. 3). The wear scar diameter (WSD) of the three stationary balls was measured using an optical microscope. The test parameters used for the four-ball tribometer are presented in Table 4.

Fig. 3. Schematic diagram of the four-ball operation.

Table 4. Four-ball test parameters.

Parameter	Value
Rotating speed	1200±60 rpm
Load	40±0.2 kg
Duration	60±1 min
Temperature	75±2°C

3. RESULTS AND DISCUSSION

3.1 Optimization by WASPAS method

Kinematic viscosity, COF, and WSD were selected as the main parameters. The data obtained are presented in Table 5, where v represents the kinematic viscosity at 100°C.

Table 5. Kinematic viscosity, COF and WSD results.

Sample	v (mm^2/s)	COF	WSD (mm)
A1	10.76	0.082	443.3
A2	11.08	0.0864	220.8
A3	11.5	0.0820	204.3
A4	11.31	0.0626	200.8
A5	12.24	0.0741	206.9

The data obtained from Table 5 were arranged into a decision matrix according to Equation (1).

From the decision matrix values, the normalized matrix values were calculated using Equations (2) and (3) and are presented in Matrix 2, which combines both beneficial and nonbeneficial attributes.

Beneficial attribute (max): v at 100°C
Max (x_1) = 12.24 mm^2/s

Non-beneficial attribute (min): WSD and COF
Min (x_2) = 0.0626
Min (x_3) = 200.8 μm

Matrix 1. Decision matrix.

$$X_{ij} = \begin{matrix} Sample \\ A1 \\ A2 \\ A3 \\ A4 \\ A5 \end{matrix} \begin{bmatrix} v & COF & WSD \\ 10.76 & 0.082 & 443.3 \\ 11.08 & 0.0864 & 220.8 \\ 11.5 & 0.0820 & 204.3 \\ 11.31 & 0.0626 & 200.8 \\ 12.24 & 0.0741 & 206.9 \end{bmatrix}$$

Matrix 2. Normalized decision matrix.

$$X_{ij} = \begin{matrix} Sample \\ A1 \\ A2 \\ A3 \\ A4 \\ A5 \end{matrix} \begin{bmatrix} \bar{X}_{i,1}(v) & \bar{X}_{i,2}(COF) & \bar{X}_{i,3}(WSD) \\ 0.8791 & 0.7634 & 0.4530 \\ 0.9052 & 0.7245 & 0.9094 \\ 0.9395 & 0.7634 & 0.9829 \\ 0.9240 & 1.0000 & 1.0000 \\ 1.0000 & 0.8448 & 0.9705 \end{bmatrix}$$

Total additive relative importance for each alternative based on the WSM and WPM was calculated from the formula (4) and (5) and shown in Table 6.

Table 6. Total relative of alternative.

Sample	$Q_i^{(1)}$	$Q_i^{(2)}$
A1	0.6985	0.6724
A2	0.8464	0.8418
A3	0.8953	0.8900
A4	0.9747	0.9740
A5	0.9384	0.9360

By using the equation (6), WSM and WPM were generalized as an overall weighted criterion and shown in Table 7.

A comprehensive equation was developed to rank the alternatives more accurately and enhance the decision-making process by equation (7). Based on the results, the effect of the λ parameter on the joint generalized criterion was calculated and presented in Matrix 3, while the realistic ranking of the alternatives was determined according to the ranking accuracy value illustrated in Fig. 4.

Table 7. Total importance of each alternative.

Sample	Q_i
A1	0.6854
A2	0.8441
A3	0.8926
A4	0.9743
A5	0.9372

Matrix 3. Effect of λ value on joint generalized criterion.

Alt	$\lambda=0$	$\lambda=0.1$	$\lambda=0.2$	$\lambda=0.3$	$\lambda=0.4$	$\lambda=0.5$	$\lambda=0.6$	$\lambda=0.7$	$\lambda=0.8$	$\lambda=0.9$	$\lambda=1.0$
$A1$	0.6724	0.6750	0.6776	0.6802	0.6828	0.6855	0.6881	0.6907	0.6933	0.6959	0.6724
$A2$	0.8418	0.8423	0.8427	0.8432	0.8436	0.8441	0.8446	0.8450	0.8455	0.8459	0.8464
$A3$	0.8900	0.8905	0.8911	0.8916	0.8921	0.8927	0.8932	0.8937	0.8942	0.8948	0.8953
$A4$	0.9740	0.9741	0.9741	0.9742	0.9743	0.9744	0.9744	0.9745	0.9746	0.9746	0.9747
$A5$	0.9360	0.9362	0.9365	0.9367	0.9370	0.9372	0.9374	0.9377	0.9379	0.9382	0.9384

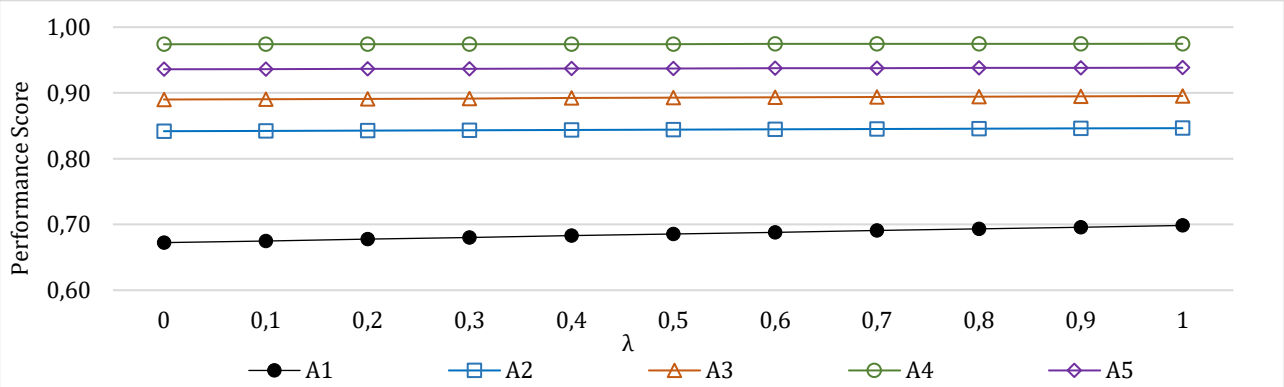

Fig. 4. Ranking of the alternative.

It can be observed that the line representing sample A4 remains consistently at the top, indicating the highest performance score and confirming it as the optimal selection. In contrast, the line for sample A1 remains consistently at the bottom, identifying it as the least preferred alternative. The results indicated that the mixture of TMPTO with 8 wt.% OA (sample A4) is selected based on the performance score.

Another method of optimization involves plotting each parameter and identifying the best performance for each. Fig. 5 shows the kinematic viscosity of each sample measured from 40°C to 100°C. Sample A4 was identified as optimal based on its lowest COF and WSD values. However, its kinematic viscosity requires modification with EVA to comply with the Engine Oil Viscosity Classification (SAE J300) standard [27].

It can be observed that 15W-40, as a commercial benchmark engine oil, has the highest kinematic viscosity of all samples compared to TMPTO and blended TMPTO with OA. The kinematic viscosity of samples A3 to A5 increased by 1.00% to 12.70% at 40°C, whereas samples A1 and A2 showed decreases of 5.59% to 8.34% compared to TMPTO.

Samples A1 and A2 show lower kinematic viscosity than TMPTO because, as reported by Lee et al. [28], the viscosity of vegetable-oil-derived TMP esters is influenced by molecular

structure and intermolecular interactions. Therefore, at low additive composition, the additives modify ester molecular interactions without increasing viscosity. Similar results were reported by Rahman et al. [17] and Azman et al. [9], where the base oil blended with additives had a lower kinematic viscosity value than the base oil alone. As for samples A3 to A5, the higher additive composition enhances intermolecular interactions and increases internal resistance to flow, resulting in a higher kinematic viscosity.

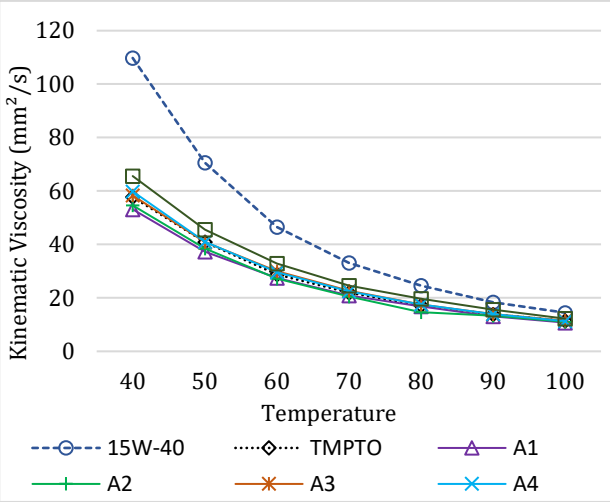

Fig. 5. Kinematic viscosity of 15W-40, TMPTO and samples A1 to A5.

In terms of COF mapping as shown in Fig. 6, sample A4 demonstrates the best performance. This finding aligns with the WASPAS results, which also selected sample A4 as optimal. The results show that sample A4 shows the lowest COF among all samples, demonstrating a reduction of 43.9% and 6.34% compared to 15W-40 and pure TMPTO, respectively.

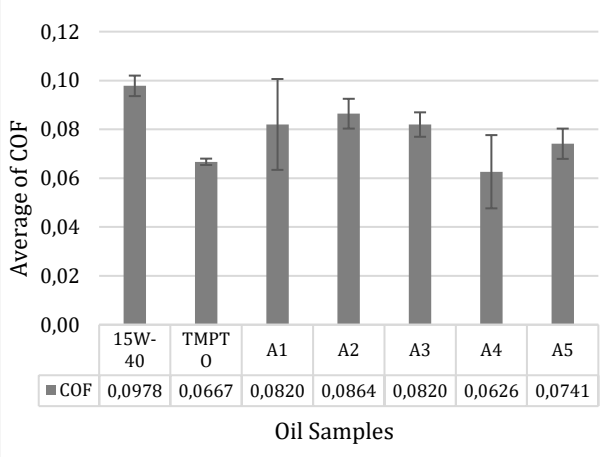

Fig. 6. The average COF of 15W-40, TMPTO and samples A1 to A5.

There is a similar finding in the study conducted by Rahman et al. [17], where the addition of approximately 8 wt.% OA to palm oil ester resulted in the lowest COF among all samples. TMPTO exhibits a lower COF than the other samples. This indicates that, although vegetable oil-based lubricants generally provide low friction, friction behaviour is strongly influenced by additive composition. The addition of OA containing B, Ca, Mg, Mo, P, Si, Sr and Zn to TMPTO affects the tribological behaviour of the oil samples. At 2 wt.% OA in TMPTO, the COF is higher than that of pure TMPTO due to insufficient additive content, which limits the formation of a continuous and stable boundary layer on the metal surface. As a result, incomplete surface protection and increased asperity interaction occur during sliding [29,30]. Increasing the OA composition causes the COF to decrease. At 6 wt.% OA, the additives become fully functional, resulting in improved friction performance.

Similarly, the WSD results presented in Fig. 7 show that sample A4 demonstrates the best performance among all samples, which is consistent with the selection obtained from the W ASPAS method.

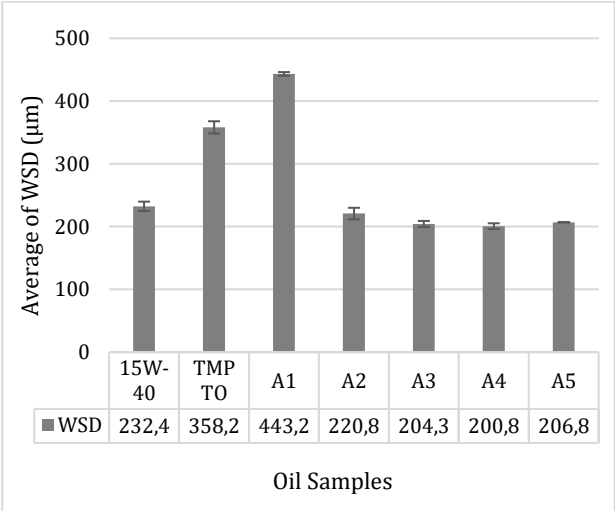

Fig. 7. The average WSD of 15W-40, TMPTO and samples A1 to A5.

The commercial 15W-40, which serves as the benchmark, shows a WSD of 232.44 µm, whereas TMPTO exhibited a WSD of 358.21 µm. This indicates that the commercial 15W-40 has been formulated with suitable lubricating oil additives that more effectively protect the contact surfaces compared to pure TMPTO

without additional additives. Sample A1 exhibited the largest WSD, whereas sample A4 showed the smallest, with reductions of 14.6% and 56.36% compared to 15W-40 and pure TMPTO.

TMPTO shows a lower COF but a higher WSD compared to the other samples. This indicates that even though vegetable oil has a lower COF, it does not correspond to a low WSD due to the presence of fatty acids that chemically interact with metal surfaces under sliding conditions [31]. At 2 wt.% OA, the WSD is higher than that of pure TMPTO due to insufficient additive composition to form a protective tribo-film. As the OA composition increases from 4 wt.% to 10 wt.%, the WSD remains nearly constant, indicating stable wear scar diameters and consistent wear protection. As reported by Spikes [32], Zn acts effectively as an anti-wear additive by forming a protective layer that limits direct surface contact, leading to reduced wear and smaller WSD values.

Analysis of the individual results for kinematic viscosity, COF, and WSD aligns with the WASPAS findings. These experimental outcomes confirm the WASPAS analysis, which identified sample A4 as the optimal composition.

3.2 Kinematic viscosity improvement using EVA

Based on the WASPAS (Weighted Aggregated Sum Product Assessment) results, sample A4 containing 8 wt.% OA (oleic acid) was selected as the optimum composition. To meet the Engine Oil Viscosity Classification (SAE J300) standard for kinematic viscosity, sample A4 was subsequently modified with EVA, as presented in Table 8. The kinematic viscosity results of samples B1 to B6 are presented in Fig. 8.

Table 8. Final blend composition of sample A4 with EVA.

Sample	Material
B1	A4 + EVA 0.5 wt.%
B2	A4 + EVA 1.0 wt.%
B3	A4 + EVA 1.5 wt.%
B4	A4 + EVA 2.0 wt.%
B5	A4 + EVA 2.5 wt.%
B6	A4 + EVA 3.0 wt.%

Kinematic viscosity of samples B1 to B6 shows in Fig. 8 increases consistently with increasing additive composition. This trend indicates that the addition of EVA effectively enhances the viscosity of all samples. Compared to sample A4, the addition of EVA increased the kinematic viscosity of samples B1 to B6 by 26.52% to 94.39% at 40°C and by 22.10% to 80.27% at 100°C.

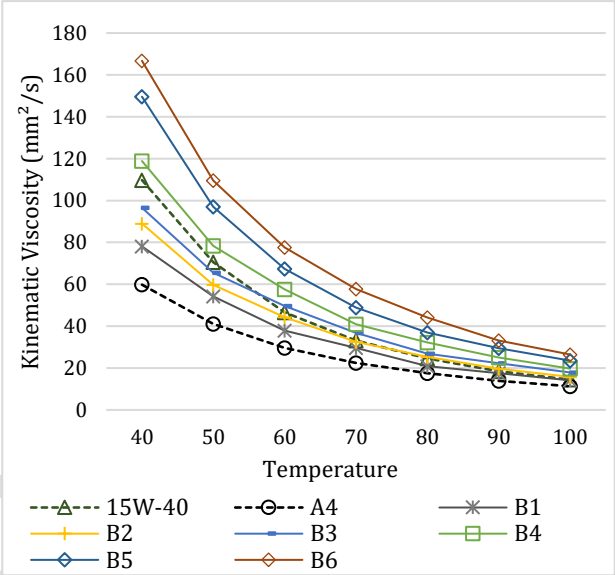

Fig. 8. Kinematic viscosity of 15W-40, sample A4 and samples B1 to B6.

Among the samples, samples B1 (0.5 wt.%) and B2 (1.0 wt.%) met the required kinematic viscosity values of 14.12 mm^2/s and 15.77 mm^2/s, respectively, according to the standard.

There are similar outcomes from the studies by Dandan et al. [33] and Norazman et al. [9], which use EVA as a viscosity improver in palm oil. They found that the dispersed EVA molecules strengthen intermolecular interactions and form thicker boundary films, reducing friction, wear, and metal-to-metal contact, thereby improving anti-wear performance under high load and extreme pressure conditions.

According to Alothman [34], the increase in viscosity is due to the introduction of long-chain polymer molecules. EVA polymer chains interact with the oil molecules and physically entangle within the fluid, forming a structure that makes it harder for the molecules to move around. This constraint of molecular mobility and reduction of free volume within the system makes the mixture more resistant to flow, thus

increasing its viscosity. A higher vinyl acetate percentage makes the EVA copolymer more polar, enhancing its interaction with polar components in the oil and further contributing to viscosity increase [35].

Sample A4 with EVA at varying concentration percentages was presented in Fig. 9. Sample A4 exhibits the lowest COF, while commercial 15W-40 shows the highest COF among all samples. Although the addition of EVA increased the COF in samples B1 to B4 compared to sample A4, these samples still outperformed the 15W-40 lubricant, with reductions ranging from 16.25% to 26.18%. COF for samples B5 and B6 was excluded from further testing, as its kinematic viscosity exceeded the limits specified by the Engine Oil Viscosity Classification (SAE J300) standard.

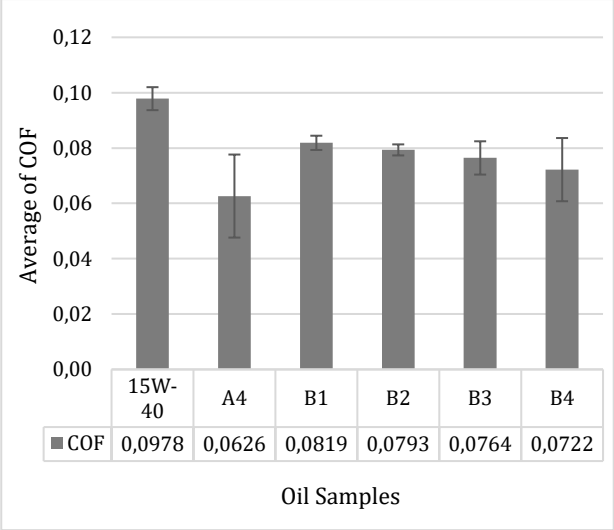

Fig. 9. The average COF of 15W-40, sample A4 and samples B1 to B4.

A similar outcome was reported by Dandan & Samion [33], who found that the addition of 1% EVA to palm kernel methyl ester effectively reduced friction compared to commercial mineral oil. This reduction in the coefficient of friction is attributed to the ability of viscosity modifier additives to adsorb onto metal surfaces and form thick, viscous boundary films, thereby enhancing lubrication when EVA copolymer is incorporated into PKME.

From the observations, the mixture of OA and EVA in TMPTO increases the COF compared to TMPTO blended with OA alone. This increase is due to the higher viscosity of the blended samples, which elevates viscous shear stress during the slide. Although EVA is effective as a viscosity improver, higher viscosity also raises shear stress, thereby increasing the friction [36, 37].

The lower WSD observed in sample A4 is consistent with its COF results. Samples B1 to B4 in Fig. 10 show a consistently smaller average of WSD compared to 15W-40. From the figure, samples B1 to B4 show a stable smaller average of WSD compared to 15W-40 and TMPTO. Sample B1 recorded the smallest WSD at 196.30 μm, followed closely by B4, B2, and B3, with values of 198.53 μm, 205.90 μm, and 207.98 μm, respectively. Dandan and Samion [33], similarly reported that adding EVA reduced WSD and improved lubricant performance.

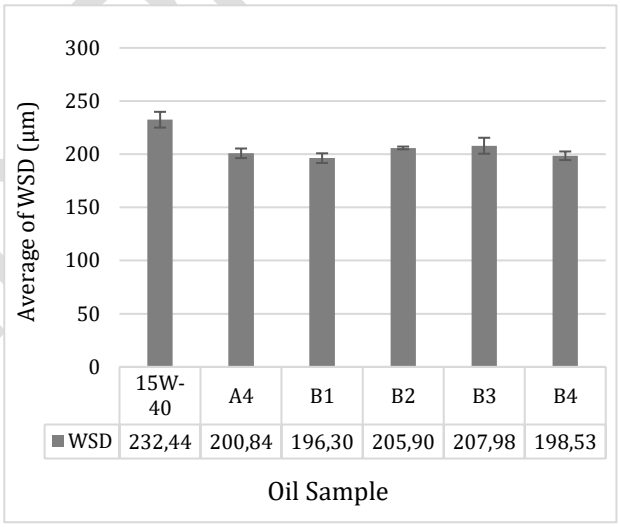

Fig. 10. The average WSD of 15W-40, sample A4 and samples B1 to B4.

Fig. 11 illustrates the WSD on the steel ball surface, measured using an optical microscope. The parallel grooves observed on the worn surfaces show depth variations indicated by colour contrast, where darker regions represent deeper grooves and brighter areas correspond to shallower wear. According to Norazman et al. [9], these grooves were caused by wear debris of the oxide layer or worn-off adhesion of rigid particles. 15W-40 demonstrated the darkest wear scar morphology, signifying the formation of deeper wear tracks among the tested lubricants. Sample A1 exhibited the largest WSD at 456 μm, followed by pure TMPTO at 356.5 μm, consistent with its highest average WSD. In

contrast, sample A4 displayed the smallest WSD with a brighter scar.

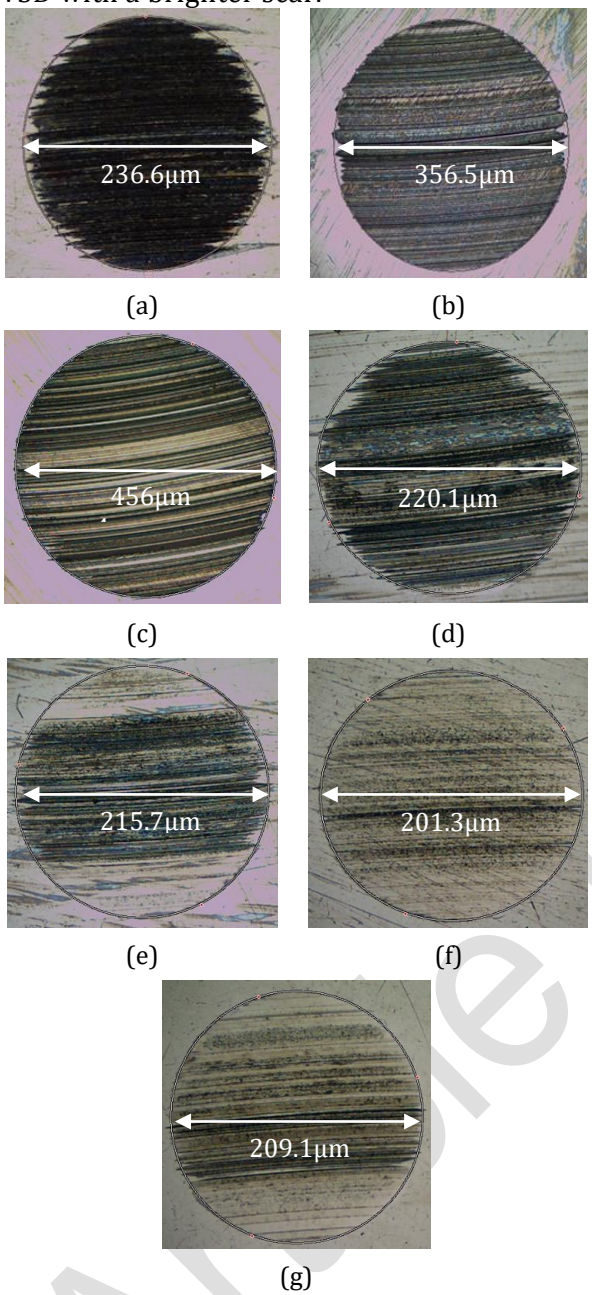

Fig. 11. Optical micrograph of wear scars for oil samples of (a) 15W-40 (b) TMPTO, (c) A1, (d) A2, (e) A3, (f) A4 and (g) A5.

According to the results of COF and WSD, samples B1 (0.5 wt.% EVA) and B2 (1.0 wt.% EVA) met the kinematic viscosity requirements for engine oil specifications. Although samples B3 (1.5 wt.% EVA) and B4 (2.0 wt.% EVA) present lower COF, its kinematic viscosity exceeded the acceptable standard range. Sample B2 was identified as the optimal blended palm oil ester with additives due to its kinematic viscosity being within the required range of 12.5 to 16.3 mm^2/s at 100°C.

4. CONCLUSION

Palm oil ester demonstrates significant potential as a sustainable alternative to 15W-40 for engine lubricant applications, and its performance can be further improved through the addition of suitable additives. In this study, the WASPAS method was used as an optimization tool to determine the most suitable composition of palm oil ester with additives for engine oil applications. The main findings are summarized as follows:

(a) From the WASPAS method, TMPTO with 8 wt.% OA (sample A4) is selected based on the performance score.
(b) Sample A4 provided the optimum performance with 43.9% lower COF and a 14.6% smaller WSD compared to 15W-40.
(c) Sample A4 was subsequently improved with EVA to meet the Engine Oil Viscosity Classification (SAE J300) standard for kinematic viscosity.
(d) The addition of EVA in sample A4 increased the kinematic viscosity of samples B1 to B6 by 26.52% to 94.39% at 40°C and by 22.10% to 80.27% at 100°C.
(e) For samples B1 to B4, the COF decreased as the EVA composition increased, showing improvements with reductions ranging from 16.25% to 26.18% compared to 15W-40.
(f) The composition of 8 wt.% OA and 1 wt.% EVA was identified as the optimal formulation of the blended palm oil ester with additives, as it complies with the Engine Oil Viscosity Classification (SAE J300) standard.
(g) Analysis of the individual results for kinematic viscosity, COF, and WSD aligns with the WASPAS findings. These experimental outcomes confirm the WASPAS analysis, which identified sample A4 as the optimal composition.

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