FRICTION AND WEAR PERFORMANCE OF LUBRICANTS FORMULATED WITH PALM KERNEL METHYL ESTER AND POLYMERIC ADDITIVES IN HYDROGEN-FUELLED ENGINES

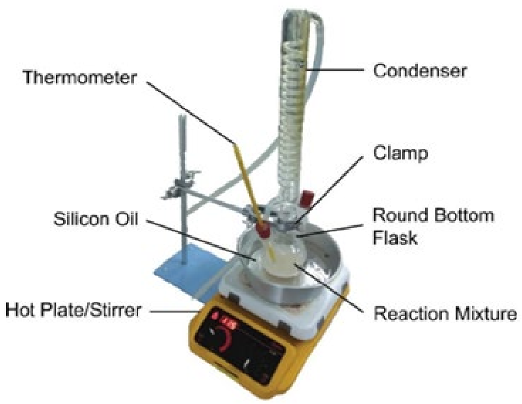
Article history
Received
25th January 2025
Received in revised form
10th April 2025
Accepted
19th June 2025
Published
26th June 2025

Aiman Yahaya[a,b]*, Syahrullail Samion[a,b], Zulhanafi Paiman[a,b], Arif Dandan[a], Zuraidah Rasep[a]

[a]Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[b]Institute for Sustainable Transport (IST), Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

*Corresponding author
wmaiman91@gmail.com

GRAPHICAL ABSTRACT



ABSTRACT

The transition to sustainable fuels and lubricants is critical in supporting the advancement of hydrogen internal combustion engines (H_2ICEs). Bio-lubricants derived from vegetable oils, such as palm kernel methyl ester (PKME), offer environmental advantages including renewability, biodegradability, and high lubricity. However, their inherently low viscosity poses challenges in demanding engine applications. This study investigates the use of ethylene-vinyl acetate (EVA) copolymer as a viscosity index improver (VII) in PKME-based lubricants for potential use in H_2ICEs. Tribological performance was evaluated using a four-ball tribotester and a modified pin-on-disc tester at varying EVA concentrations (2–4%), loads, and temperatures. The addition of 4% EVA enhanced the viscosity index of PKME by 61% and improved friction-reducing capabilities compared to SAE 40 mineral oil. While wear resistance remains slightly inferior, the frictional improvements indicate promising potential for PKME-EVA blends in hydrogen engine lubrication. Further formulation optimization is recommended to enhance anti-wear performance for reliable H_2ICE operation.

KEYWORDS

Palm kernel methyl ester, Hydrogen engine, Viscosity improver, Bio-lubricant.

INTRODUCTION

The development of alternative fuels and lubricants for internal combustion engines has increased due to the worldwide move towards environmentally friendly and sustainable technology. Because of its high energy density and lack of carbon dioxide emissions at the moment of use, hydrogen has become one of these alternatives' most promising clean energy carriers [1]. Using current engine technology, hydrogen-fueled internal combustion engines (H_2ICEs) provide a workable way to cut greenhouse gas emissions [2]. However, burning hydrogen is linked to greater flame temperatures and more water vapour, which might shorten the lifespan of engine parts and make lubrication more difficult [3].

The usage of eco-friendly lubricants is becoming more popular in this regard. Bio-lubricants based on vegetable oil, such palm kernel methyl ester (PKME), are appealing options for sustainable lubrication systems since they are biodegradable, renewable, and have a high flash point and good lubricity [4][5]. Despite these benefits, PKME's low viscosity at high temperatures and poor oxidative stability restrict its capacity to provide reliable lubrication in dynamic operating circumstances, which hinders its use in engines [6].

VIIs, or viscosity index improvers, are frequently used to get around these restrictions. By stabilising lubricant viscosity at different temperatures, these polymeric additives enhance internal combustion engine lubrication performance [7]. One such addition that has demonstrated potential in improving the rheological and tribological characteristics of synthetic and bio-based lubricants is ethylene-vinyl acetate (EVA) copolymer [8]. Although VIIs have been extensively researched for use in mineral oil applications, nothing is known about how they integrate with lubricants based on vegetable oil in hydrogen engine conditions.

Thus, with an emphasis on applications in hydrogen internal combustion engines, this research explores the use of EVA copolymer as a viscosity index improver in PKME-based bio-lubricants. The goal is to assess PKME-EVA blends' tribological performance, or more precisely, their wear and friction properties, in environments that simulate the functioning of hydrogen engines. It is anticipated that the results will aid in the creation of effective, biodegradable lubricants specifically designed for environmentally friendly hydrogen-powered automobile technology.

METHODOLOGY

Sample Lubricant Preparation

The vegetable oil employed in this investigation was refined, bleached, and deodorized palm kernel (PK) oil, supplied by Keck Seng (M) Sdn. Bhd., Malaysia. This oil displayed a pour point of 23 °C and looked semi-solid at ambient room temperature, which is consistent with its saturated fatty acid composition. To increase its rheological qualities, ethylene-vinyl acetate (EVA) copolymer was applied as a polymeric viscosity index improver. The EVA copolymer was purchased from Sigma-Aldrich and is classified as an inert, non-toxic, and thermally stable polymeric substance. Detailed parameters of the EVA copolymer are reported in Table 1.

Table 1: Properties of EVA copolymer

Properties	Information
Name	Ethylene-vinyl acetate copolymer
Vinyl acetate content	25%
Appearance	Colourless
Density, at 25°C	0.945 g/ml
Melt index	19 g/10min
Melting temperature	75°C

Palm kernel methyl ester (PKME) was manufactured by a transesterification procedure utilising 200 mL of refined palm kernel oil. A methanol-to-oil molar ratio of 6:1 was applied in the presence of 1.5 wt% calcium oxide (CaO) catalyst. The reaction mixture was put in a 500 mL three-necked round-bottom flask and kept at a constant reaction temperature of 65 °C (see Figure 1). Continuous stirring was given using a magnetic stirrer to guarantee optimum mixing and reaction homogeneity. Upon completion of the reaction, the PKME was extracted from the reaction products by filtering. The content of fatty acid methyl esters (FAMEs) in the resultant PKME was evaluated using gas chromatography (GC) equipped with flame ionization detection (FID). The full fatty acid profile is given in Table 2

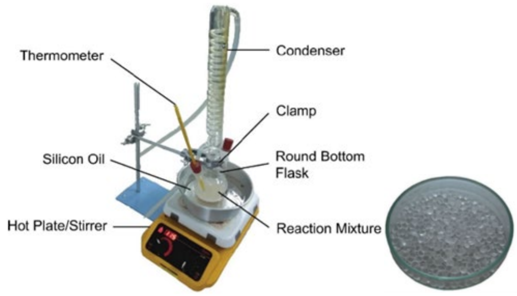


Figure 1: Transesterification setup and Ethylene-Vinyl-Acetate Copolymer (EVA)

Table 2: Fatty acid composition of PKME

Fatty acid	Composition (%)
Caprylic (C8:0)	4.8
Capric (C10:0)	4.6
Lauric (C12:0)	37.6
Myristic (C14:0)	22.0
Palmitic (C16:0)	10.9
Palmitoleic (C16:1)	0.1
Stearic (C18:0)	2.8
Oleic (C18:1)	16.0
Linoleic (C18:2)	1.1
Linolenic (C18:3)	0.1

Subsequently, PKME was mixed with different quantities of EVA copolymer at 2, 3, and 4 wt%. Each blend was made by mixing 200 mL of PKME with the relevant quantity of polymeric ingredient using a mechanical stirrer working at a constant speed of 300 rpm. The blending operation was carried out at a temperature of 120 °C for about 1 hour to guarantee full solubility of the EVA copolymer inside the base oil. Upon attaining full dissolution, the manufactured bio-lubricants were allowed to cool naturally to ambient temperature. Visual inspections showed that all blends created homogenous, single-phase mixtures, showing high compatibility between the PKME and the EVA copolymer at the studied concentrations.

Tribological Testing

The pin-on-disc machine utilised in this investigation was fitted with a load cell sensor to detect the friction caused between test specimens. The operational conditions for the test are detailed in Table 3. The equipment was adapted to imitate the sliding contact between the piston ring and cylinder liner of an internal combustion engine. While the system cannot fully imitate actual engine circumstances, such as excessive oil temperatures and high-speed reciprocating motion that provides a controlled setting to research wear mechanisms under lubricated conditions.

Table 3: Experiment condition

Parameter	Range
Volume (ml)	50
Load (kg)	1, 3 and 5
Speed (ms^{-1})	1.5
Temperature (°C)	Room temp ~23
Duration (hr)	1

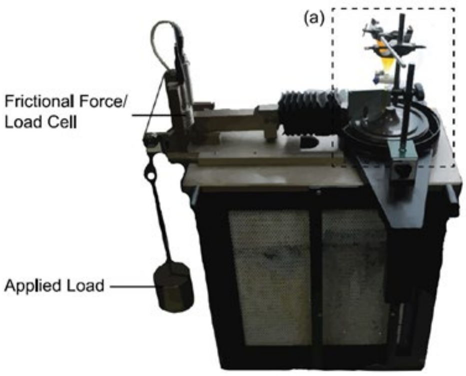


Figure 2: Pin-on-disc tester with modified piston ring-on-disc setup

This experiment aims to evaluate the tribological interaction between the piston ring and cylinder liner utilising the generated bio-lubricant samples. The pin-on-disc design duplicates the reciprocating action of a piston using a rotating contact device. In line with ASTM G99, the conventional arrangement commonly employs a metal pin against a flat spinning disc. However, in this study, the metal pin was substituted with an actual piston ring, while a curved spinning disc was employed instead of the conventional flat disc to better approximate engine geometry. Approximately 50 mL of oil was continually given throughout each test using a dropping funnel to maintain uniform lubrication throughout the experiment. The redesigned arrangement is represented in Figure 2.

Weight Loss and Worn Analysis

The initial and final weights of the piston ring will be measured using an electronic balance. The weight loss will be calculated using Equation (1). This parameter is critical for evaluating the anti-wear performance of the lubricant samples. Lower weight loss at the end of the test indicates better wear protection by the lubricant, as it reduces material removal from the piston ring surface.

$$Weight\ loss(g) = W_i - W_f \quad (1)$$

Where,
W_i= Initial weight (g)
W_f = Final weight (g)

An optical microscope was used to examine the worn surface of the piston ring in order to assess its condition and characterize the wear behaviour.

Result And Discussion

Analysis on Viscosity

Figure 3 illustrates the variation in kinematic viscosity for different lubricant samples, hydrogen engine oil (H_2EO), PK (palm kernel oil), PKME (palm kernel methyl ester), and PKME blended with 2%, 3%, and 4% EVA copolymer, across a temperature range of 40 °C to 100 °C. As expected, all samples exhibit a decrease in viscosity with increasing temperature, a common behavior due to reduced intermolecular interactions at elevated thermal conditions.

Among the samples, H_2EO demonstrates the highest viscosity values across the temperature range, indicative of its strong viscosity-temperature stability typical of mineral-based oils. In contrast, neat PKME shows the lowest viscosity, which may limit its application under high-temperature operating conditions such as those found in internal combustion engines. However, the incorporation of EVA copolymer significantly improves the viscosity-

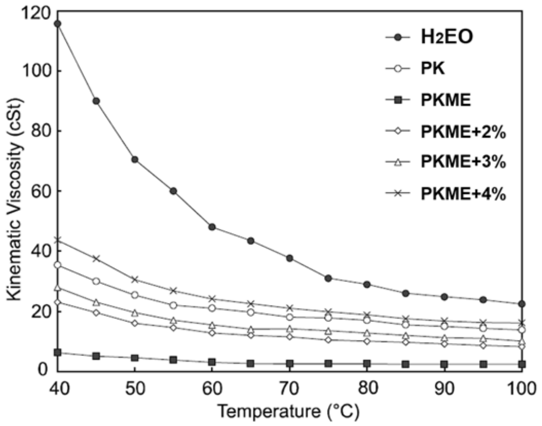


Figure 3: Graph of kinematic viscosity against temperature

index of PKME, with PKME + 4% EVA showing the most substantial enhancement. This blend offers a more stable viscosity profile at elevated temperatures, approaching that of PK and surpassing the base PKME formulation.

The bio-lubricant samples demonstrated a higher viscosity index (VI) compared to commercial hydrogen engine oil, which has a VI of approximately 230 (Azman et al., 2018). Notably, the addition of 4 wt% EVA copolymer into PKME significantly improved the VI from 238 to 383 which increase of approximately 61%. This improvement reflects the thermal resistance of the triglyceride-based structure in palm kernel oil, which maintains strong intermolecular interactions even as the temperature rises, thereby contributing to a more stable viscosity profile [9].

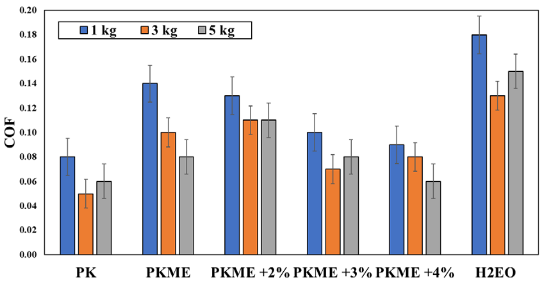


Figure 4: Coefficient of friction against load

The VI improvements observed in PKME formulations with 2%, 3%, and 4% EVA copolymer align with the polymer thickening mechanism described by Jiang et al. [10]. As temperature increases, EVA copolymer chains expand, increasing their hydrodynamic volume and resistance to flow. This thermal expansion offsets the natural viscosity drop in the base oil, narrowing the viscosity difference between low and high temperatures and resulting in a higher VI. Chen et al., [11] further supports this phenomenon, noting that improved solubility at elevated temperatures allows the polymer coils to reach their maximum extension, thus contributing significantly to the viscosity retention.

This enhancement is particularly advantageous for lubricants in hydrogen internal combustion engines (H_2ICEs), which are known to operate at higher combustion temperatures. Maintaining viscosity stability under such conditions is critical for effective lubrication, especially in components like the piston ring-cylinder liner interface.

Analysis on Tribological Test

To evaluate the tribological performance of the tested lubricant formulations, friction tests were conducted under three different loading conditions. The results in Figure 4 reveal a general trend: increasing the applied load led to a decrease in COF across all samples. This reduction is attributed to the presence of wear debris at higher loads, which can act as micro-rolling elements that facilitate sliding motion and reduce friction [12].

Interestingly, PKME with 3% and 4% EVA copolymer consistently demonstrated COF values below 0.1, indicating operation within the mixed lubrication regime. These formulations outperformed the commercial SAE 40 lubricant, which remained in the boundary lubrication regime across all loading conditions. This finding supports prior studies that have highlighted the superior friction-reducing performance of vegetable oils compared to mineral oils [8][13]. The enhanced performance is primarily due to the strong adsorption of polar fatty acid chains in vegetable oils, which form durable monolayer films on metal surfaces, thereby reducing metal-to-metal contact [14].

Among all samples, raw palm kernel oil (PK) exhibited the lowest COF under 3 kg and 5 kg loads, likely due to its fully fluid state at the test temperature (28 °C), which enabled effective hydrodynamic film formation. In contrast, PKME displayed higher COF values, but the incorporation of EVA copolymer markedly improved its performance. Particularly, PKME blended with 4% EVA copolymer achieved COF values as low as 0.054–0.074, suggesting enhanced film formation and lubrication efficiency. While viscosity plays a limited role in boundary lubrication, the presence of polymeric additives with polar functional groups supports the formation of adsorbed layers on metal surfaces, effectively acting as friction modifiers [15]. Additionally, viscosity index improvers (VIIs) such as EVA may contribute to boundary lubrication by reducing electrical contact between asperities, even under slow-speed conditions [16].

These findings are especially relevant for hydrogen internal combustion engines (H_2ICEs), where higher combustion temperatures and unique thermal environments demand robust lubricant performance. The ability of PKME–EVA blends to maintain low friction under increased load enhances their potential for use in next-generation H_2ICE systems.

Analysis on Weight Loss

The influence of lubricant formulation on piston ring wear under varying applied loads is presented in Figure 5. It was observed that the weight loss of the piston ring correlated strongly with the material's relatively low hardness compared to the rotating disc, resulting in more pronounced wear on the ring. A clear trend emerged, where weight loss increased with increasing applied load. This finding aligns with the work of Mannan et al., [17], who reported that higher applied loads lead to elevated temperatures at the contact interface, which in turn destabilize the lubricant film. Once the film becomes excessively thin, it loses its capacity to separate the contacting surfaces, leading to increased metal-to-metal interaction and wear.

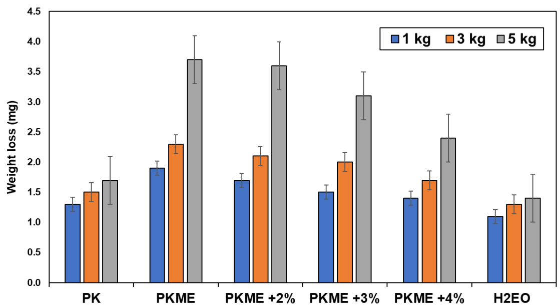


Figure 5: Weight loss against load

Among all lubricant samples, H_2EO exhibited the lowest weight loss, demonstrating superior anti-wear performance across all load conditions. Notably, under the highest load of 5 kg, H_2EO still maintained lower material loss compared to the 3 kg condition. This anomaly suggests that H_2EO retains its load-bearing and protective properties effectively even under severe conditions, likely due to its formulation with robust anti-wear additives that enhance film strength and stability.

Palm kernel oil (PK) showed marginally higher wear compared to H_2EO, particularly at higher load conditions. The abrupt increase in wear between the 3 kg and 5 kg loads highlights the limitations of PK under extreme loading. As suggested by Li et al. [18], the superior performance of mineral oils in such conditions is attributed to the presence of both physiosorbed and chemisorbed additive-derived films, which persist even under high stress. The chemisorbed layer, in particular, provides a durable barrier against surface degradation when the physiosorbed film is compromised.

In contrast, palm kernel methyl ester (PKME) exhibited the highest wear among all lubricant samples, with a recorded maximum weight loss of 3.58 mg at 5 kg. This significant wear suggests that under high load, the lubricant film was insufficiently maintained, likely resulting in lubricant squeeze-out and subsequent metal-to-metal contact. The absence of effective boundary additives in PKME could explain its poor anti-wear performance.

However, the incorporation of ethylene vinyl acetate (EVA) copolymer into PKME led to noticeable improvements. Among the polymer-enhanced formulations, PKME with 4% EVA demonstrated the most favorable anti-wear characteristics, outperforming the 2% and 3% variants. This improvement can be attributed to the viscoelastic nature of the EVA copolymer, which enhances the lubricant's film-forming ability under dynamic contact conditions. According to Wang et al., [19], such polymeric additives can significantly influence the tribological behavior by reducing friction and wear through the formation of durable and adaptive films on the contact surfaces.

Analysis on Worn Surface Analysis

A microscopic examination of the piston ring wear surfaces revealed distinct wear characteristics influenced by lubricant type and applied load. Abrasive wear, evidenced by parallel grooves, was predominant across all samples due to the lower hardness of the piston ring compared to the curved disc (see Figure 6). The H_2EO-lubricated sample demonstrated the smoothest wear track with minimal grooves and scratches, corresponding to the lowest weight loss. This performance is attributed to the presence of anti-wear and antioxidant additives, which help form protective boundary films and reduce direct surface contact.

In contrast, the PK and PKME samples exhibited more severe wear. PK-lubricated surfaces showed increased scratches and signs of oxidation, likely contributing to higher material loss. PKME, especially under higher loads, experienced significant wear with deep grooves and pit formations, suggesting inadequate film strength and lubricant breakdown under stress. This aggressive wear is believed to result from lubricant being squeezed out at the contact point, leading to direct metal-to-metal interaction.

The addition of EVA copolymer to PKME significantly enhanced anti-wear performance. A progressive reduction in scratches and dark oxide-regions was observed in PKME+2%, +3%, and +4% samples. The 4% EVA blend showed the most notable improvement, with smooth worn surfaces and the absence of severe pits under a 5 kg load. These results align with previous findings that polymeric viscosity improvers can adsorb onto surfaces, form protective layers, and maintain separation under boundary conditions, thereby minimizing wear and enhancing lubricant performance [20].

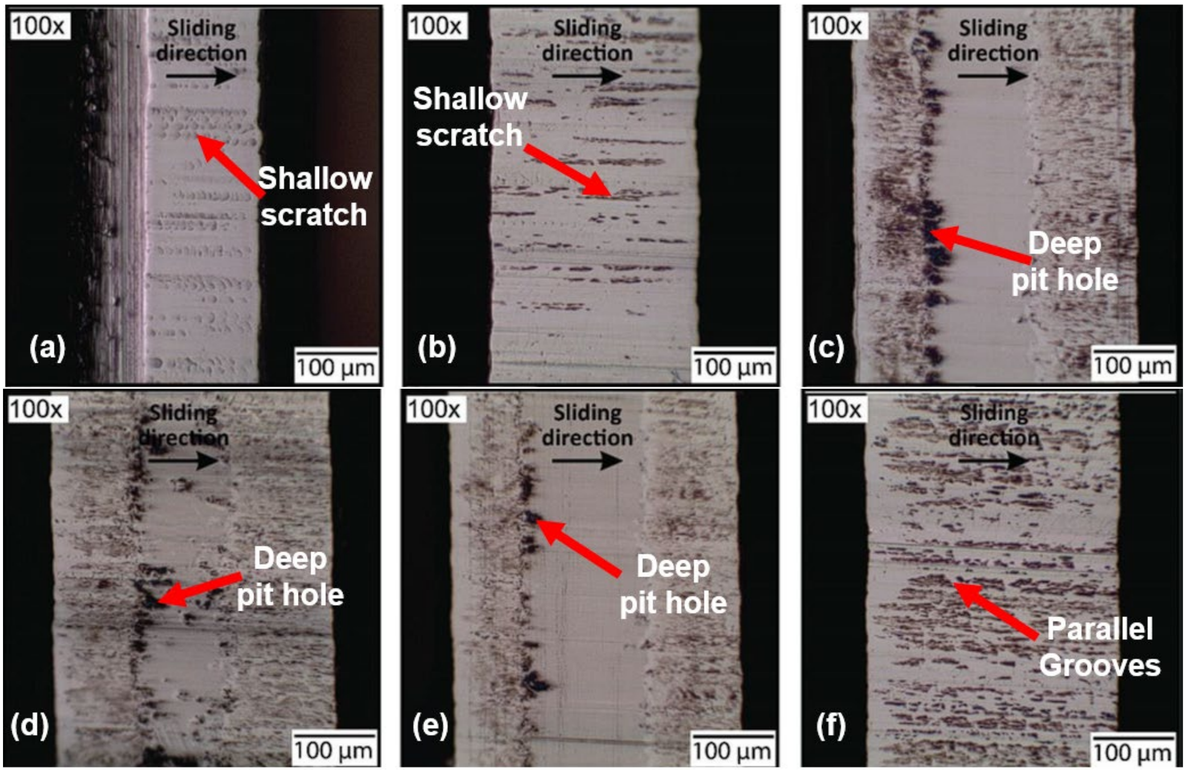


Figure 6: Worn surfaces image at 5 kg load for (a) H_2EO, (b) PKO, (c) PKME, (d) PKME+2%, (e) PKME+3% and (f) PKME+4%

Conclusion

This study demonstrates the potential of palm kernel methyl ester (PKME) modified with ethylene vinyl acetate (EVA) copolymer as a high-performance bio-lubricant for hydrogen internal combustion engines (H_2ICEs). The incorporation of EVA copolymer significantly enhanced the viscosity index (VI), with the PKME + 4% EVA blend achieving a VI of 383, surpassing both neat PKME and commercial hydrogen engine oil.

Tribological evaluation revealed that the PKME–EVA blends, particularly at 4 wt%, delivered superior friction reduction and wear resistance, maintaining a low coefficient of friction (<0.1) and minimizing piston ring material loss under elevated loads. Microscopic wear surface analysis confirmed the formation of smoother, less damaged wear tracks, supporting the role of EVA in promoting film stability and boundary layer protection. Collectively, these findings highlight the viability of PKME–EVA blends as thermally stable, environmentally friendly lubricants capable of withstanding the high-temperature, high-load demands of H_2ICEs, offering a sustainable alternative to conventional mineral-based lubricants.

These findings are significant for developing hydrogen internal combustion engines (H_2-ICE), as combustion byproducts like water vapour might impact lubricant stability and performance. PKME-EVA blends' strong thermal-oxidative resistance, biodegradability, and boundary lubrication make them compatible with hydrogen-fueled engines, which need clean-burning, low-emission, high-stability lubricants. To evaluate PKME-based formulations for sustainable and climate-friendly engine technologies, long-term hydrogen ICE testing and thermal ageing effects should be studied.

Acknowledgements

The authors would like to express their gratitude to the Ministry of Higher Education (MOHE) Malaysia for its support through the Higher Institution Centre of Excellence (HiCOE) program under the HiCOE Research Grant (R.J130000.7824.4J743) and to the Universiti Teknologi Malaysia (UTM) for the UTMFR Grant (22H46) and JVR Grant (00P63).

Conflict Of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Singh, S., Bathla, V. K., Mathai, R., & Subramanian, K. A. (2021). Performance evaluation of hydrogen-fuelled internal combustion engine. In *Advances in IC Engines and Combustion Technology: Select Proceedings of NCICEC 2019* (pp. 177–192). Springer Singapore.

[2] Huynh, D. N. L., Nguyen, T. H., Nguyen, D. C., Vo, A. V., Nguyen, D. T., Nguyen, V. Q., & Le, H. C. (2024). Using hydrogen as potential fuel for internal combustion engines: A comprehensive assessment. *International Journal of Renewable Energy Development, 14*(1), 83–103.

[3] Shadidi, B., Najafi, G., & Yusaf, T. (2021). A review of hydrogen as a fuel in internal combustion engines. *Energies, 14*(19), 6209.

[4] Afifah, A. N., Syahrullail, S., Azlee, N. I. W., & Rohah, A. M. (2021). Synthesis and tribological studies of epoxidized palm stearin methyl ester as a green lubricant. *Journal of Cleaner Production, 280*, 124320.

[5] Yahaya, W. M. A. W., Dandan, M. A., Samion, S., & Musa, M. N. (2018). A comprehensive review on palm oil and the challenges using vegetable oil as lubricant base-stock. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 52*(2), 182–197.

[6] Opia, A. C., Hamid, M. K. A., Syahrullail, S., Ali, A. I., Johnson, C. N., Veza, I., *et al.* (2022). Tribological behavior of organic anti-wear and friction reducing additive of ZDDP under sliding condition: Synergism and antagonism effect.

[7] Azman, N. F., Samion, S., Moen, M. A. A., Abdul Hamid, M. K., & Musa, M. N. (2019). The anti-wear and extreme pressure performance of CuO and graphite nanoparticles as an additive in palm oil. *International Journal of Structural Integrity, 10*(5), 714–725.

[8] Dandan, M. A., Samion, S., Yahaya, W. M. A. W., & Hadi, F. (2019). Tribological analysis of modified RBD palm kernel containing anti-oxidant additive using four-ball tribotester. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 56*(2), 157–164.

[9] Ma, M., Song, J., Dong, Y., Fang, W., & Gao, L. (2023). Structural and thermodynamic properties of bulk triglycerides and triglyceride/water mixtures reproduced using a polarizable coarse-grained model. *Physical Chemistry Chemical Physics, 25*(33), 22232–22243.

[10] Jiang, F., Wang, H., Ye, Z., Pang, S., Pu, W., & Xu, B. (2022). Thickening mechanism of water-soluble polymer in the presence of Ca^{2+} and Na^{+}. *Polymer Bulletin*, 1–13.

[11] Chen, M., Zheng, M., Zhang, L., Xu, Y., Zhang, X., & Chen, W. (2023). Correlation between structural evolution and rheological properties for polycarbonate in the molten state. *Journal of Applied Polymer Science, 140*(5), e53418.

[12] Yahaya, A., Samion, S., & Abdul Hamid, M. K. (2023). Surface modification effect of aluminium block on the tribological performance for super olein. *Industrial Lubrication and Tribology, 75*(9), 993–1001.

[13] Aiman, Y., & Syahrullail, S. (2022). Frictional and material deformation of aluminium alloy in cold forging test under different derivatives of palm oil lubrication condition. *Journal of the Brazilian Society of Mechanical Sciences and Engineering, 44*(9), 396.

[14] Marušić, K., Pezić, E., Matijaković Mlinarić, N., Dubček, P., Sancho-Parramon, J., Kralj, D., & Mihaljević, B. (2023). Green nanocoatings prepared by crosslinking self-assembled fatty acids on metals. *Small, 19*(30), 2301104.

[15] Song, Y., Fukuzawa, K., Hirayama, T., Yamashita, N., Yamada, N. L., Itoh, S., *et al.* (2023). Effects of polarity of polymers on conformation and lubricating film formation of adsorbed films. *Macromolecules, 56*(5), 1954–1964.

[16] Uniyal, P., Gaur, P., Yadav, J., Khan, T., & Ahmed, O. S. (2024). A review on the effect of metal oxide nanoparticles on tribological properties of biolubricants. *ACS Omega, 9*(11), 12436–12456.

[17] Mannan, A., Pozzebon, M. L., Daniel, W. J., & Meehan, P. A. (2023). Temperature effect on load distribution, friction, and wear of a grease-lubricated spherical roller bearing (SRB). *Tribology Transactions, 66*(1), 144–161.

[18] Li, W., Guo, F., Liu, C., & Ma, Z. (2023). Experimental study on the influence of stearic acid additive on the elastohydrodynamic lubrication of mineral oil 2137. *Lubricants, 11*(10), 446.

[19] Wang, X., Chen, G., Huang, Y., Ma, Z., Yin, X., & Chai, C. (2024). Tribological behavior and mechanism of $Mo_2Ti_2C_3$/polyimide composite films under dry friction condition. *Polymer Composites, 45*(9), 7979–7990.

[20] Yahaya, A., Samion, S., & Abdul Hamid, M. K. (2023). Surface modification effect of aluminium block on the tribological performance for super olein. *Industrial Lubrication and Tribology, 75*(9), 993–1001.