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EFFECT OF SUPER OLEIN OIL ON ENGINE MATERIALS FOR POTENTIAL USE IN HYDROGEN INTERNAL COMBUSTION ENGINES AT ROOM TEMPERATURE

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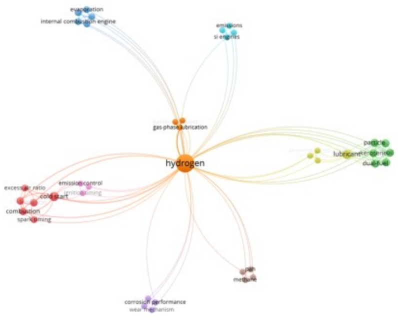
Graphical abstract



Abstract

This study investigates the tribological performance of super olein (SO), a biodegradable vegetable-based lubricant, on common internal combustion engine materials, aluminum alloy, pure copper, and SKD11 steel under conditions relevant to hydrogen-fueled engines. Using a linear reciprocating tribotester (ASTM G133-05), tests were performed at room temperature, 25 N load, and 2 Hz frequency for 10 minutes per specimen. With growing interest in sustainable lubricants for hydrogen internal combustion engines (H_2ICE), SO was compared with commercial hydrogen engine oil (CHEO). SO consistently showed lower friction (COF), with the highest value on copper (0.0438 vs. 0.0618 for CHEO). However, wear scar diameters (WSDs) were larger for SO, particularly on aluminum. SKD11 steel, with the highest hardness (219.9 HV), showed the least wear. Adhesive and abrasive wear were identified. Findings suggest SO is a promising, eco-friendly lubricant, especially with harder materials like SKD11.

Keywords: Bio-lubricant, palm oil, Alternative energy, hydrogen engine oil, material

Abstrak

Kajian ini menilai prestasi tribologi super olein (SO), pelincir berasaskan tumbuhan yang boleh terbiodegradasi, ke atas bahan-bahan yang biasa digunakan dalam enjin pembakaran dalaman—aloi aluminium, kuprum tulen, dan keluli SKD11—di bawah keadaan operasi enjin berasaskan hidrogen. Ujian dijalankan menggunakan tribotester gerakan ulang alik linear (ASTM G133-05) pada suhu bilik, beban 25 N, dan frekuensi 2 Hz selama 10 minit bagi setiap spesimen. Dengan peningkatan minat terhadap pelincir lestari untuk enjin pembakaran dalaman hidrogen (H_2ICE), prestasi SO dibandingkan dengan minyak enjin hidrogen komersial (CHEO). SO menunjukkan pekali geseran (COF) yang lebih rendah, dengan nilai tertinggi pada kuprum (0.0438 berbanding 0.0618 bagi CHEO). Namun, diameter kesan haus (WSD) lebih besar bagi SO, terutamanya pada aluminium. Keluli SKD11, dengan kekerasan tertinggi (219.9 HV), menunjukkan haus paling sedikit. Mekanisme haus lekat dan haus lelas dikenalpasti. Kajian ini mencadangkan SO sebagai pelincir mesra alam yang berpotensi, terutamanya untuk bahan yang lebih keras seperti SKD11.

Kata kunci: Bio-pelincir, Minyak sawit, Tenaga alternatif, Minyak enjin hidrogen, Bahan kejuruteraan

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1.0 INTRODUCTION

The increasing demand for sustainable and low-emission transportation has driven research into alternative powertrain technologies, with hydrogen internal combustion engines (H_2ICE) appearing as a possible transitional solution. Unlike traditional fossil fuels, hydrogen combustion produces zero carbon dioxide emissions, making it an environmentally desirable option for decreasing the carbon footprint of internal combustion systems [1]. However, the unique combustion features of hydrogen, such as greater flame speed, combustion temperature, and the potential for pre-ignition, pose significant challenges for engine component materials and their associated lubrication systems [2].

One crucial component of H_2ICE functioning is the selection of lubricants that can resist the high temperatures loads and oxidative pressure caused by hydrogen combustion, while simultaneously decreasing friction and wear across diverse engine materials [3]. Traditional mineral-based engine lubricants, however commonly used, raise difficulties related to environmental impact, biodegradability, and compatibility with the operational demands of hydrogen engines [4]. As a result, focus has turned to bio-based lubricants, such as super olein oil, because to their renewable nature, high biodegradability, and potential to minimise friction under boundary lubrication circumstances.

One promising alternative lubricant with a higher flash point and biodegradable is palm oil-based lubricant, which has demonstrated superior thermal stability compared to conventional mineral oils in previous tribological studies [5]. Research has shown that palm oil derivatives exhibit flash points typically ranging from 240°C to 320°C, significantly higher than the 160°C-220°C range of standard mineral-based lubricants, making them particularly suitable for high-temperature applications [6]. The natural ester structure of palm oil provides inherent oxidative stability and good lubricity, while its high viscosity index ensures consistent performance across a wide temperature range [7].

In order to acquire a deeper study on the current advancement of this issue, a bibliometric database that was retrieved on May 25, 2025 is being studied. The study applies bibliometric approach to uncover emerging trends in publication performance, research constituents, collaboration trends and patterns, and the intellectual structure of a field's domain [8]. The search query applied in this study covers the following string: ("Lubricant" AND "Hydrogen Engine") Scopus topic search (TS) function was used to identify relevant publications within Scopus core collection. The VOS viewer version 1.6.20 was used to visualize the science map of Lubricant and hydrogen engine literature. The total publications after limiting to only journal publications, it was finalized to 22. The number of citations received was 107. The average citations were 10.7 with an h-index of 5. The trends show the publication related to this topic will continue to increase in the coming years contributing to its relevance in various application.

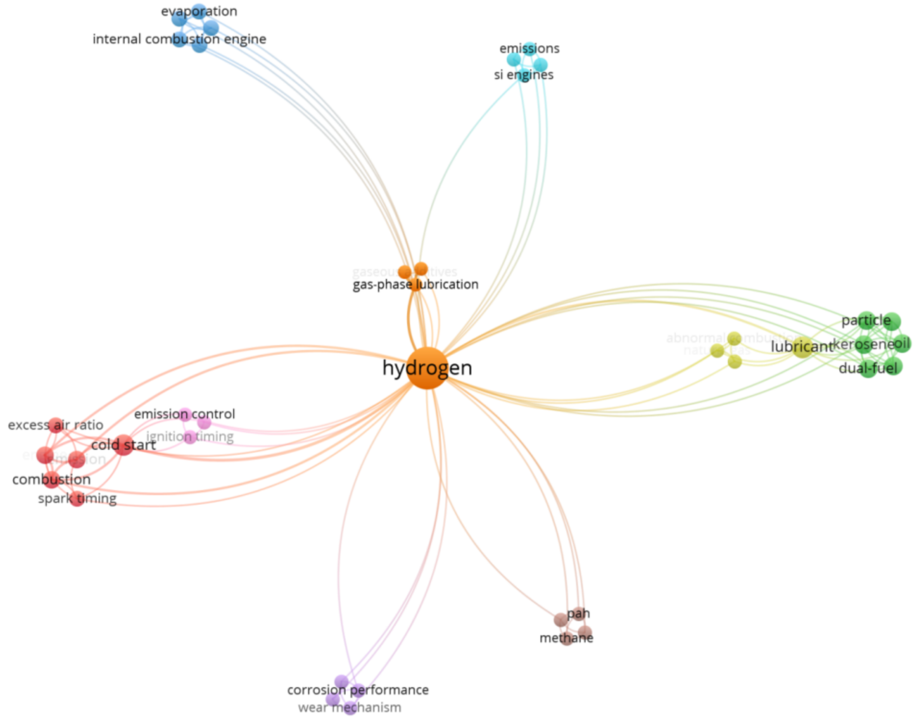


Figure 1 Co-occurrence of keyword analysis

Hydrogen internal combustion engines (H_2ICE) are gaining renewed attention as a sustainable propulsion alternative due to their ability to operate with zero carbon emissions while utilizing conventional engine architecture [9]. However, the high combustion temperatures, increased oxidative stress, and potential hydrogen embrittlement associated with hydrogen fuel demand careful selection of both engine materials and lubricants [10]. Critical engine components such as pistons, bearings, and valve seats are commonly made from materials like aluminium alloys, pure copper, and high-strength tool steels such as SKD11, which are valued for their thermal conductivity, mechanical durability, and wear resistance [11]. Ensuring the tribological compatibility of these materials with environmentally friendly lubricants is essential for reliable H_2ICE performance.

This study evaluates the tribological performance of super olein (SO) oil as a biodegradable, vegetable-based lubricant on key engine materials under room-temperature conditions relevant to hydrogen engines. The aim is to determine its potential as a sustainable alternative to conventional mineral-based lubricants on each of the material component. This finding is particularly relevant to hydrogen engine components, which often involve these materials in high-friction contact zones such as pistons (Al-alloy), bearings (Cu-based), and cylinder liners or camshafts (steel alloys). The reduced friction offered by lubricant can minimize wear, enhance component lifespan, and improve overall engine efficiency, which is critical for hydrogen engines due to their higher operating temperatures and unique combustion characteristics.

2.0 METHODOLOGY

2.1 Lubricant Sample

Super olein (PO) is used as a base lubricant in lubricating oil formulations. It consists of approximately 53.4% unsaturated fatty acids and 46.6% saturated fatty acids. Among the saturated fatty acids, palmitic acid is the most abundant, comprising 40.9% of the total fatty acid content. The high level of monounsaturated fatty acids in super olein contributes to its good oxidative stability, making it suitable for use as a lubricant. Table 1 presents the fatty acid profile of super olein, along with the characteristics of the base oil and the CHEO used in the sample.

2.2 Experiment Set-up

In this experiment, the lubricants' tribological characteristics are examined using a linear reciprocating tribometer. Due of its versatility in handling various working circumstances, such as temperature and load, a linear reciprocating tribometer was utilised for this inquiry. During setup, the following parameters must be precisely regulated: applied load, temperature, sliding speed, testing duration, and stroke length of a linear reciprocating tribometer. The experimental settings were tested and shown in Table 2, while the setup for the tests utilising the linear reciprocating tribotester is shown in Figure 1.

Table 1 Physicochemical and Fatty acid composition of sample lubricant

FAC (% by gas chromatography)	PO	CHEO
Caprylic acid (C8:0)	-	-
Capric acid (C10:0)	-	-
Lauric acid (C12:0)	0.2	-
Myristic acid (C14:0)	1.1	-
Palmitic acid (C16:0)	40.9	-
Stearic acid (C18:0)	4.2	-
Oleic acid (C18:1)	41.5	-
Linoleic acid (C18:2)	11.6	-
Linolenic acid (C18:3)	0.3	-
Arachidic acid (C20:0)	0.2	-
Eicosenoic acid (C20:1)	-	-
SFA	46.6	
MUFA	41.5	-
PUFA	11.9	-
Density (kg/m3) @ 25℃	0.890	0.865
KV (mm2/s) @ 25℃	46.74	201.32
KV (mm2/s) @ 40℃	35.00	106.00
KV (mm2/s) @ 100℃	14.4	14.27
Viscosity index, (VI)	426	137

Table 2 Experiment parameters and additive properties

Parameters	Measurement	
	Test 1	Test 2
Load (N)	25	50, 100, 150 and 200
Speed (Hz)	2	2
Temperature (˚C)	75	100
Time (min)	10	10
Stroke (mm)	10	10
Ball	10mm diameter Chrome alloy steel AISI E-5120	
Metal plate	Aluminum alloy (A100)	54.9 HV
	Copper-based	92.6 HV
	Steel Alloy	219.9 HV

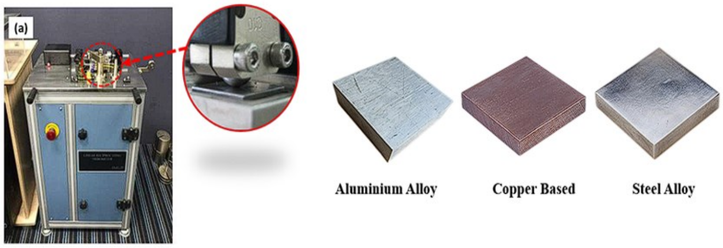


Figure 2 Experimental setup and sample material used

2.3 Wear Loss Analysis

The below equation may be employed to determine volume loss in cubic millimetres when the ball possesses an original spherical end form with parallel scratches. The rate of ball wear may be quantified using the calculation from the standard ASTM:

$$Volume\ loss, V = \left(\frac{\pi h}{6}\right)\left(\frac{3d^2}{4} + h^2\right) \qquad (1)$$

$$h = r - \left(r^2 - \frac{d^2}{4}\right)^{\frac{1}{2}} \qquad (2)$$

Where,
d = Wear scar diameter
r = Spherical ball radius

3.0 RESULTS AND DISCUSSION

3.1 Coefficient of Friction

The tribological performance of Super Olein (SO) and Commercial Hydrogen Engine Oil (CHEO) was assessed on three distinct materials, that is Aluminum Alloy, Copper-based Alloy, and Steel Alloy, utilizing a linear reciprocating tribotester. The principal parameter evaluated was the coefficient of friction (CoF), with the findings presented in Figure 3. Across all material types, SO exhibited better lubricity, evidenced by consistently lower coefficient of friction values compared to CHEO. This indicates that SO possesses advantageous friction-reducing properties that might be effective in hydrogen internal combustion engine (H_2ICE) applications.

In the case of the Aluminium Alloy, SO demonstrated the lowest coefficient of friction (about 0.01), markedly surpassing CHEO, which had a coefficient of friction of roughly 0.037. This significant difference may be attributed to the superior boundary lubrication characteristics of SO, likely owing to its intrinsic molecular structure abundant in polar molecules, which improves surface film development and adhesion [12]. In the instance of the copper-based alloy, both lubricants demonstrated elevated friction levels relative to the aluminium alloy substrate. SO showed a coefficient of friction of around 0.043, but CHEO had the highest value among all combinations, approaching 0.06. The rise in friction might result from the interplay between the lubricant's chemical additives and the propensity of copper to oxidise, resulting in less stable boundary layers [13]. Nonetheless, SO continued to exhibit a reduced CoF, confirming its superior anti-friction properties. The coefficient of friction values for the Steel Alloy with both lubricants were intermediate compared to those recorded for the Aluminium and Copper-based alloys. SO had a coefficient of friction of around 0.033, whereas CHEO recorded about 0.045. The diminished disparity between SO and CHEO in this instance may suggest that the steel surface engages more equally with both lubricants, but SO still provides a quantifiable decrease in friction.

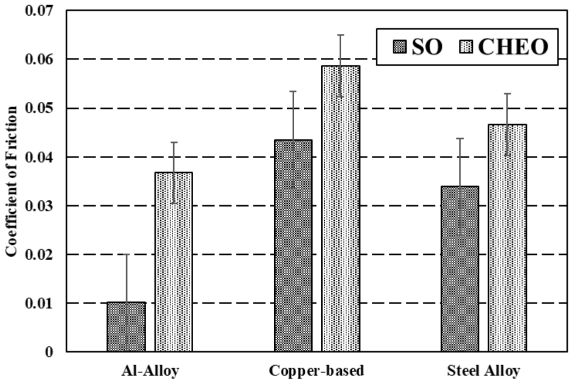


Figure 3 Coefficient of friction for Al-Alloy, cooper-based and steel alloy

3.2 Wear Scar Diameter

The wear performance of SO and CHEO was evaluated using a linear reciprocating tribotester by measuring the wear scar diameter (WSD) on both the pin and plate surfaces for three material types: Aluminum Alloy, Copper-based alloy, and Steel Alloy. The results, shown as in Figure 4, reveal clear trends that provide insight into the lubricative protective qualities of both oils under sliding contact conditions relevant to hydrogen engine components.

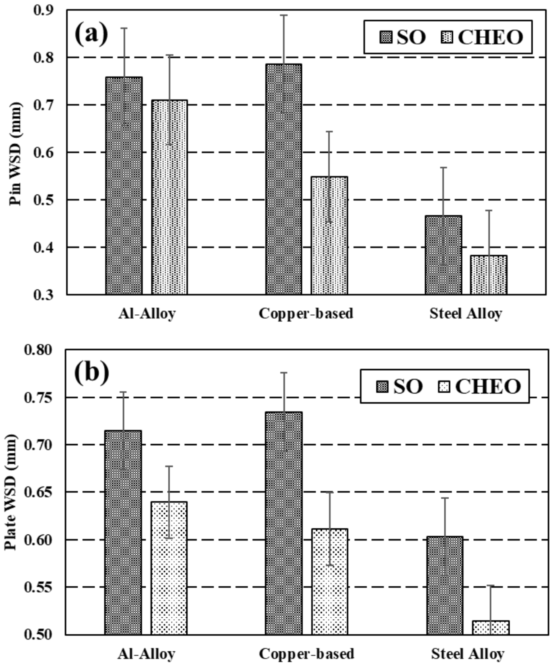


Figure 4 Wear scar diameter (a) Pin and (b) Plate

For pin wear, SO often generated greater WSDs than CHEO across all materials. The Copper-based alloy exhibited the maximum pin wear with SO lubrication (~0.79 mm), markedly exceeding the ~0.55 mm seen for CHEO. A like pattern was seen in Steel Alloy and Aluminum Alloy, but with lesser gaps. This indicates that, despite SO's lower coefficient of friction, it may not generate as resilient a tribofilm as CHEO under specific contact circumstances, particularly with materials susceptible to adhesion or softening, such as copper alloys [14].

The pattern in plate wear aligns with pin data, indicating that SO produces larger WSDs than CHEO. The Copper-based plate exhibits the most significant disparity, with SO resulting in a WSD of around 0.74 mm compared to ~0.62 mm for CHEO. Among all combinations of Steel Alloy plates, the wear scar was minimal; nevertheless, it remained greater for SO (~0.60 mm) compared to CHEO (~0.48 mm). The increased wear in SO-lubricated samples may result from oxidative degradation or insufficient extreme-pressure additive efficacy, which is generally more refined in commercial engine oils such as CHEO [15].

Previous studies have proven the potential of vegetable-based lubricants, such as palm oil derivatives, in lowering friction compared to petroleum-based oils [16], with research focusing on conventional engines but rarely addressing hydrogen-specific circumstances. Current breakthroughs, including this study, reveal that SO oil exhibits a lower coefficient of friction than CHEO on copper, matching with findings by Yahaya *et al*. [17] on biodegradable oils' anti-wear qualities. However, difficulties persist, such as SO oil's bigger wear scars on softer materials (e.g., aluminum), a trade-off previously reported in earlier investigations [18]. Current research explores nano-additives or hybrid lubricants to enhance SO oil's wear resistance under high-pressure hydrogen environments, as proposed by Zhang *et al*. [19], while investigating long-term material compatibility, particularly hydrogen embrittlement in steel components, to bridge the gap between laboratory-scale tribology and real-world hydrogen engine applications.

3.3 Volume loss

The volume loss behavior of pin and plate materials was evaluated under lubrication by Super SO and CHEO using a linear reciprocating tribotester as shown in Figure 5. The results, showing volume losses in the range of 10^{-12} mm^2, indicate that CHEO consistently outperforms SO in minimizing wear across all material types. Among the tested materials, Steel Alloy demonstrated the lowest volume loss under both lubricants, confirming its superior wear resistance. In contrast, Al-Alloy and Copper-based materials showed higher volume losses, with SO performing notably worse on copper-based alloys, indicating material-specific sensitivity to the bio-based lubricant.
Material-specific analysis reveals that for Al-Alloy, both lubricants resulted in moderate wear, but CHEO showed slightly better performance, likely due to the presence of anti-wear additives such as ZDDP that form protective tribofilms on the softer aluminium surface [12]. In the case of Copper-based alloys, SO led to significantly higher volume loss, which could be due to adverse chemical interactions accelerating oxidative and adhesive wear [14]. CHEO, on the other hand, likely benefits from corrosion inhibitors that protect copper surfaces. Steel Alloy showed minimal wear under both lubricants, although CHEO maintained a performance edge, underscoring its optimized formulation for high-contact, load-bearing applications.

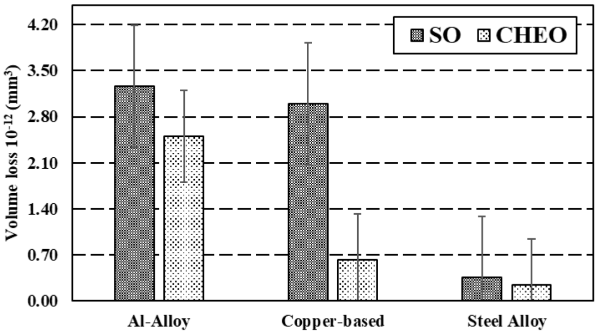


Figure 5 Volume loss of Al-Alloy, cooper-based and steel alloy

From a mechanistic perspective, SO, while environmentally friendly and rich in polar compounds, may suffer from limited thermal stability and inadequate boundary lubrication under high-load conditions, especially in the absence of synthetic anti-wear additives [12]. Its performance gaps on softer metals highlight the need for formulation improvements, such as incorporating additives to enhance tribofilm formation. CHEO's consistent performance stems from its balanced blend of synthetic base oils and additives, providing effective film formation, thermal stability, and oxidative resistance. This makes CHEO more suitable for hydrogen engine components, which often involve a combination of steel, aluminium, and copper alloys. However, the promising eco-profile of SO supports continued research into additive-enhanced bio-lubricants for future engine applications.

3.4 Wear Observation

Microscopic analysis of the wear scars on Aluminum Alloy, Copper-Based, and Steel Alloy surfaces reveals how lubricant composition and material properties collectively influence tribological performance as shown in Table 3. For the Aluminum Alloy, Super Olein (SO) lubrication results in visible adhesive wear, evidenced by a 100 µm scar, likely due to its limited anti-wear additive content. In contrast, CHEO demonstrates smaller scar widths, suggesting effective protection via additive-driven tribofilm formation, particularly through compounds like ZDDP [20]. This highlights the Aluminum Alloy's vulnerability to wear, which is significantly mitigated by the presence of robust additive systems in CHEO.

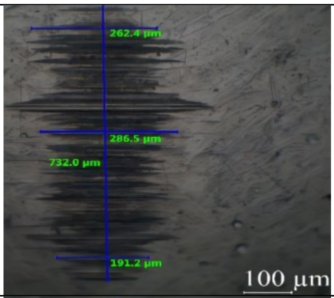
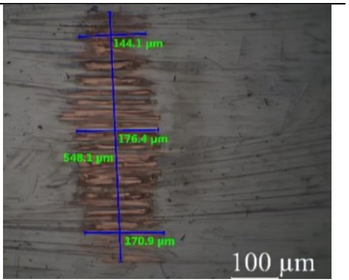
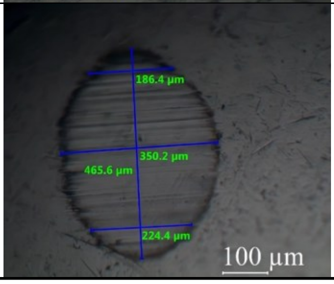
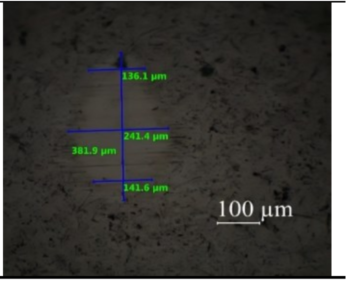
In the case of Copper-Based alloys, both lubricants produce similar scar sizes (~100 µm), but the underlying wear mechanisms likely differ. SO may induce more oxidative or abrasive wear due to chemical interactions between its organic content and the copper surface, which is known to be chemically reactive [13]. CHEO, on the other hand, likely benefits from corrosion inhibitors that prevent aggressive surface degradation. This reinforces that copper's ductility and oxidation susceptibility require well-balanced lubricant formulations, and SO, while bio-based, may need antioxidant reinforcement to achieve comparable protective performance.

Steel Alloy samples show minimal wear variation between the two lubricants, reflecting the material's inherent hardness and resistance to surface degradation. While both SO and CHEO produce similar wear scar sizes (~100 µm), CHEO's additive advantages may still play a role in reducing long-term micro-pitting and fatigue wear under more demanding conditions. Overall, the wear images confirm that lubricant performance is more critical for softer, reactive metals like aluminum and copper, whereas steel's durability lessens this dependency. These findings underscore the need to tailor bio-based lubricants like SO with targeted additive packages to broaden their viability across a range of engineering materials, especially in hydrogen engine environments where diverse material contacts are common.

The presented wear scar measurements offer important insights into the tribological behavior of three commonly used engineering materials, Aluminum Alloy, Copper-Based Alloy, and Steel Alloy, when lubricated with SO and CHEO as shown in Table 3. The data reveal that wear performance varies significantly depending on both the lubricant used and the intrinsic properties of the material. This analysis underscores how material hardness and chemical reactivity interact with lubricant chemistry to affect wear outcomes, particularly in metal-on-metal contacts.

For Aluminum Alloy, which has a relatively low hardness (54.9 HV), CHEO outperforms SO in wear reduction. While both lubricants achieve a minimum wear scar diameter of 30 µm, CHEO maintains this consistently, with only one instance of increased wear at 50 µm. In contrast, SO shows two occurrences of 50 µm scars, suggesting more variability and reduced stability in its protective behavior. This difference is likely attributable to CHEO's formulation, which includes advanced anti-wear additives such as ZDDP, promoting the formation of boundary films that protect soft, adhesive-prone surfaces like aluminum [20]. SO, being a natural oil, may lack these additives, leading to intermittent failure under stress.

Table 3 Wear observation on the pin

	SO	CHEO
Al-Alloy		
Copper-Based		
Steel Alloy		

In the case of Copper-Based Alloy, both lubricants demonstrate similar minimum wear (30 µm), but SO again shows a higher frequency of severe wear (two cases at 50 µm versus one for CHEO). Copper's intermediate hardness (92.6 HV) and higher chemical reactivity compared to aluminum may contribute to its variable wear response. While both lubricants seem capable under mild conditions, CHEO's additive chemistry provides more robust protection under load. Steel Alloy, by contrast, exhibits the least wear variation between lubricants, with all wear scar measurements remaining within the 30–50 µm range. Its higher hardness (219.9 HV) likely plays a dominant role in reducing wear, minimizing the influence of lubricant chemistry. Both SO and CHEO show comparable performance here, suggesting that for hard materials, lubricant formulation becomes less critical.

3.5 Effect of Super Olein on the Material Type

The tribological performance of Super Olein (SO) across aluminum, copper-based, and SKD11 steel alloys revealed a strong interplay between lubricant chemistry and material properties, highlighting material-specific sensitivities to bio-lubrication under hydrogen engine-relevant conditions. The findings suggest that the effectiveness of SO as a lubricant is not only governed by its intrinsic chemical composition but is critically modulated by the hardness, chemical reactivity, and surface energy of the contact materials.

For the aluminum alloy (54.9 HV), SO significantly reduced the coefficient of friction (CoF) to ~0.01, a result superior to the commercial hydrogen engine oil (CHEO) (~0.037), affirming its strong boundary lubrication potential. This is attributed to SO's high polar molecule content and natural ester structure, which enhances adsorption and film formation on relatively soft and adhesive-prone surfaces [12]. However, wear scar and volume loss data reveal larger scars under SO than CHEO, suggesting a weaker tribofilm resilience under higher localized stress, likely due to the absence of robust anti-wear additives such as ZDDP commonly found in commercial oils [20]. These findings indicate that while SO provides excellent friction reduction on aluminum, it lacks sufficient wear protection in the absence of reinforcing additives.

In the case of the copper-based alloy (92.6 HV), SO continued to demonstrate friction reduction benefits with a CoF of ~0.043, outperforming CHEO (~0.0618). Yet, copper's high thermal conductivity and oxidative reactivity presented challenges. SO, lubrication resulted in increased wear, as evidenced by higher wear scar diameters and volume loss values. This is likely due to oxidative degradation and poor chemical compatibility between copper and the unsaturated fatty acids in SO, which can accelerate corrosive and adhesive wear processes [13][14]. The limited performance of SO on copper alloys underscores the need for antioxidant or corrosion-inhibiting additives to mitigate surface degradation, particularly for materials with high chemical reactivity [21].

Conversely, SKD11 steel alloy (219.9 HV) demonstrated minimal CoF differences between SO (~0.033) and CHEO (~0.045), with both lubricants producing comparably small wear scars. The steel's high hardness and wear resistance overshadowed the limitations of the lubricant, suggesting that the mechanical robustness of the material plays a dominant role in determining wear performance. These results reinforce findings by Gonzalez and Hernandez [11] and Hirani *et al*. [15], which indicate that harder alloys like SKD11 are less dependent on the chemical intricacies of the lubricant due to their inherent resistance to deformation and surface fatigue.

Collectively, these findings highlight that the tribological effectiveness of Super Olein is inherently material-dependent. On softer metals like aluminum, SO offers superior friction performance but may require additive enhancement for adequate wear protection. For chemically reactive metals like copper, lubrication stability is challenged by possible oxidative and corrosive interactions, necessitating formulation improvements. On high-hardness materials like steel, SO's performance is more favorable and less sensitive to its compositional limitations, making it a viable sustainable option for such applications.

In alignment with recent literature [18][19][22], these results suggest that future development of SO-based lubricants should focus on tailoring additive packages, including anti-wear, antioxidant, and corrosion inhibitors that specifically to the tribological characteristics of target materials within hydrogen engine architectures. This will help bridge the gap between sustainable lubrication and the rigorous demands of high-temperature, chemically aggressive H2ICE environments.

4.0 CONCLUSION

The analysis highlights three key trends: (1) wear performance becomes more dependent on lubricant formulation as material hardness decreases, (2) CHEO consistently results in fewer instances of severe wear, and (3) the performance gap between lubricants narrows as material hardness increases. These findings suggest that lubricant selection should be strategically aligned with both the base material and expected operating conditions. For softer metals like aluminum, CHEO's formulated additive content offers superior wear protection, whereas for harder metals like steel, bio-based lubricants such as SO may be a more sustainable alternative without compromising performance. Future work should explore hybrid formulations that combine the environmental benefits of SO with targeted additive packages, particularly for materials of intermediate hardness like copper-based alloys, where neither lubricant demonstrated clear superiority.

Overall, the findings suggest that while CHEO remains the more effective lubricant for protecting hydrogen engine components, especially those involving aluminum or copper alloys, SO presents promising potential for use in less demanding or steel-dominant systems. To enhance its viability in broader applications, SO would benefit from additive optimization. Future work should focus on developing hybrid bio-lubricants that maintain SO's environmental benefits while closing the performance gap through the incorporation of tailored anti-wear and antioxidant additives.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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