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Synthesis and characterisation of palm oil-based biolubricant for application as cutting fluid

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Abstract
Growing environmental concerns over the use of mineral-based lubricants have accelerated research into eco-friendly alternatives such as biolubricants. This study aims to synthesise and characterise biolubricants formulated from palm oil methyl ester (POME) and *Aloe vera* (AVE). Several formulations with different POME : AVE volume ratios (100 : 0, 80 : 20, 70 : 30 and 60 : 40) were evaluated for their viscosity (ASTM D445), density (pycnometer), pour point (ASTM D97), flash point (ASTM D92), thermal stability (15 minutes examinations while sample is heated) and cooling efficiency during CNC lathe machining. The results show that the 60 : 40 POME : AVE ratio demonstrated the best overall performance, with the highest viscosity, lowest pour point and notable thermal stability. These improved properties are believed to result from the presence of bioactive compounds in *Aloe vera*, particularly acemannan, polysaccharides and natural antioxidants, which enhance molecular cohesion, thermal resistance and oxidative stability. Additionally, cooling tests showed that the 60 : 40 biolubricant formulation significantly reduced cutting temperatures compared to commercial and dry machining conditions. These findings suggest that biolubricants formulated from POME and AVE have strong potential as sustainable and high-performance alternatives in metalworking applications.

1. Introduction

The use of mineral-based lubricants significantly contributes to soil and water pollution through unmanaged waste disposal and greenhouse gas emissions that contribute to global warming. In contrast, biolubricants derived from renewable and biodegradable vegetable oils provide an eco-friendly alternative with lower environmental toxicity and higher biodegradability [1,2].

Palm oil is one of the most promising raw materials for biolubricant synthesis due to its high saturated fatty acid content, which offers good lubricating properties that lower friction [3], as well as its relatively high oxidative and thermal stability and cost efficiency thanks to its wide availability [1,4]. Compared to vegetable oils like castor, soybean or sunflower, whose high unsaturation leads to oxidative degradation, lower flash points and poor thermal stability, palm oil stands out as a sustainable baseline material for biolubricants [5]. *Aloe vera* contains polysaccharides (like acemannan), amino acids, vitamins and antioxidants [6] that can function as natural additives to improve viscosity, oxidative resistance, flash point and corrosion protection in biolubricant formulations. Although specific studies combining palm oil and *Aloe vera* in CNC applications are limited, existing research has demonstrated the effectiveness of plant polysaccharide additives in enhancing biolubricant performance. Therefore, combining palm oil and *Aloe vera* extract potentially produces biolubricants with enhanced physicochemical properties, such as increased viscosity, a lower pour point and improved thermal stability, making them suitable for machining or automotive contexts.

2. Materials and methods

2.1 Materials

The materials used in this study were selected based on their compatibility and potential to enhance the physicochemical properties of the formulated biolubricant. The base oil was a refined, commercially packaged palm oil, which has the following specifications: moisture and impurity content not exceeding 0.1 %, free fatty acid content not exceeding 0.1 %, colour value of 1.5 red maximum (Lovibond cell 5¼) and an iodine value (Wijs method) of at least 61. *Aloe vera* was used as a natural additive and was obtained directly from a local farm located in Medan, Indonesia. The use of fresh *Aloe vera* was essential to ensure the presence of active biocompounds, such as acemannan, polysaccharides, amino acids and antioxidants, all of which are known to contribute to improved viscosity, cooling performance and oxidative resistance.

The chemicals used in the transesterification and purification processes included methanol (96 %), ethanol (96 %), sodium hydroxide (NaOH) pellets and distilled water. These reagents were of analytical grade and were acquired from CV. Rudang Jaya, a certified chemical distributor based in Medan, Indonesia. All materials were handled and stored under proper laboratory conditions to ensure safety and consistency during the experimental procedures.

2.2 Extraction of *Aloe vera* polysaccharides

In this study, *Aloe vera* gel was processed using 96 % ethanol extraction, in line with established laboratory protocols, to isolate acemannan polysaccharide, a key bioactive compound. Ethanol-based precipitation is widely recognised as an effective method for recovering acemannan. The procedure is shown in Figure 1. First, *Aloe vera* was washed with clean water to remove any adhering dirt. After that, the skin was separated so that only the gel part was used. The gel was then cut into small pieces and blended until it formed a thick liquid. The blended product was filtered using filter paper to remove coarse fibres, leaving only pure *Aloe vera* gel. Then, the extraction was carried out by mixing gel with 96 % ethanol in a 1 : 3 volume ratio [7]. In this study, 300 ml of *Aloe vera* gel was mixed with 900 ml of 96 % ethanol. The mixture was then heated using a magnetic stirrer at 40 °C for 10 minutes at a stirring speed of 200 rpm, with a magnetic bar used to homogenise the mixture. After the heating process, the mixture was placed into centrifuge tubes and centrifuged until two layers formed. The clear liquid was at the top, while the precipitate at the bottom consisted of *Aloe vera* polysaccharides.

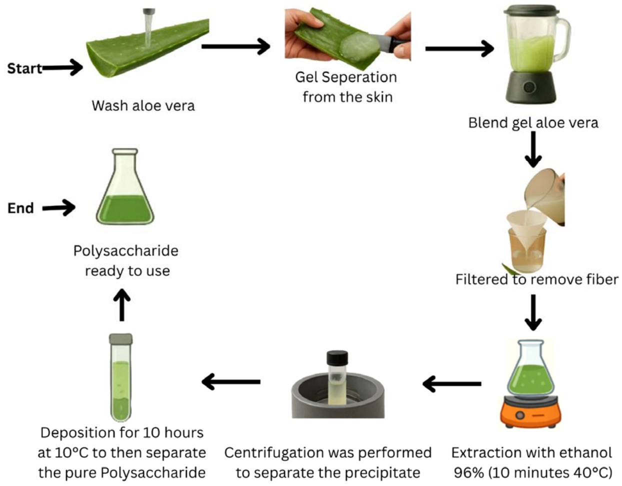

Figure 1. Extraction of polysaccharides from *Aloe vera*

To increase the purity of the polysaccharides, a redeposition process was carried out. The polysaccharide precipitate was cooled at 10 °C for 10 hours to separate residual fibres and ethanol. After that, the mixture was separated again, and the pure polysaccharide precipitate at the bottom was collected as the final extract, ready for use in the next stage of the study. A study by Redjeki et al. [8] demonstrated that extraction using 96 % ethanol at 40 °C for 14 hours yielded the highest acemannan content in *Aloe vera* flesh, recorded at approximately 515.18 milligrams per gram glucose equivalent, with an optimal sediment weight at 45 °C over 18 hours. These findings confirm that ethanol extraction is not only effective but can also be optimised for maximum yield in lab-scale procedures. Structurally, acemannan is a high molecular weight acetylated β-(1→4)-glucomannan, composed mainly of mannose (around 60 – 85 %), along with glucose and small amounts of galactose. It forms a viscous gel that contributes to *Aloe vera* rheological and thermal properties [9]. The presence of acemannan in the ethanol-precipitated fraction supports its role as a functional additive that enhances viscosity, oxidative resistance and thermal stability in biolubricant formulations.

2.3 Transesterification of palm oil

Transesterification is a chemical process widely used to convert triglycerides in vegetable oils into fatty acid methyl esters (FAME), which serve as the main component in biolubricant formulations. This reaction involves the use of an alcohol, typically methanol, and a strong base catalyst such as NaOH, producing methyl esters and glycerol as by-products. This method is well-known for its simplicity, relatively low temperature requirements and high conversion efficiency.

In this study, 200 ml of refined palm oil was used as the raw material with the procedure shown in Figure 2. The transesterification process began by dissolving NaOH (at 1 % wt./wt. of the oil) in methanol (28 % vol./vol.). At this stage, NaOH reacts with methanol to form sodium methoxide, which is the active catalyst in the transesterification reaction. Thus, sodium methoxide is not added directly. It is formed from a mixture of NaOH and methanol, and its amount is equivalent to the amount of NaOH used. The palm oil was heated to 65°C, and the sodium methoxide was slowly added while stirring continuously with a magnetic stirrer at 700 rpm for 60 minutes to ensure complete mixing and reaction.

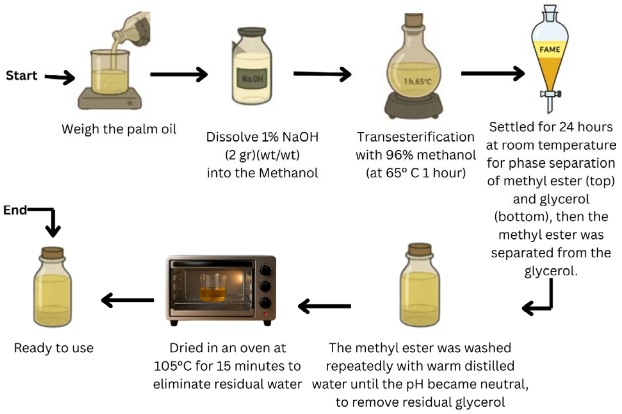

Figure 2. Process of transesterification of palm oil

Upon completion, the mixture was allowed to settle undisturbed for 24 hours at room temperature to allow phase separation between the upper methyl ester layer and the lower glycerol layer. The upper layer was collected and washed repeatedly to remove impurities, such as glycerol by-products and unreacted catalyst, using warm distilled water at 100 °C until the pH became neutral. After the washing process, the FAME is dried in an oven at 105 °C for 15 minutes to eliminate residual water. This base-catalysed transesterification protocol aligns with previous findings by Naseef and Tulaimat [10], who optimised biodiesel production from palm oil using similar ratios of methanol and NaOH under temperatures around 55 – 65 °C. The method proved effective for generating high yields of methyl esters suitable for further blending into biolubricants.

2.4 Biolubricant formulation

After obtaining purified palm oil methyl esters via transesterification and isolating *Aloe vera* extract through ethanol precipitation, biolubricant formulations were prepared by blending these two components in varying ratios to investigate the influence of *Aloe vera* concentration on physicochemical properties. *Aloe vera* extract acted as a natural additive rich in hydrophilic polysaccharides, which are hypothesised to enhance viscosity, lower pour point and improve thermal stability, while palm oil methyl esters served as the biodegradable base fluid with inherent lubricating capability.

Formulations were prepared in the following volume ratios of palm oil methyl esters (POME) to *Aloe vera* extract (AVE): 100 : 0, 80 : 20, 70 : 30 and 60 : 40. Each mixture was stirred until complete homogeneity and then stored in sealed glass bottles pending physical and thermal testing. Additionally, soy lecithin (5 ml per 100 ml mixture) was introduced as a biobased emulsifier to stabilise the blend and enhance film-forming properties. Soy lecithin, a natural phospholipid mixture, has demonstrated multifunctional emulsifying and lubrication-enhancing capabilities in oil-based systems due to its amphiphilic structure and ability to reduce interfacial tension between hydrophobic and hydrophilic phases.

2.5 Biolubricant characterisation

Characterisation of biolubricants is essential to evaluate their performance, reliability and suitability for practical applications, especially in high-friction and high-temperature environments such as CNC machining. Various physical and thermal properties were assessed to determine the quality and functional behaviour of the formulated biolubricants. These properties include viscosity, density, pour point, flash point, thermal stability and cooling performance. The reported results represent the average of three independent tests, with an average error of ± 1 %.

The dynamic viscosity of the formulated biolubricants was measured in accordance with ASTM D445, using an Ostwald capillary viscometer at controlled temperatures of 40 and 100 °C. Samples were compared to distilled water, with density corrections applied to calculate viscosity values accurately. These temperature points simulate the working conditions of industrial machinery, where high viscosity at 40 °C indicates good film-forming abilities, while adequate fluidity at 100 °C is essential under thermal stress.

Density testing was performed at temperatures of 40 and 100 °C using a 5 ml pycnometer. In this research, density values measured using the pycnometer were benchmarked against standards and empirical data. A typical acceptable range for density at 40 °C is approximately 0.88 – 0.90 g/ml, with slightly lower values (e.g. 0.86 – 0.88 g/ml) expected at 100 °C. These measurements provide insight into the fluid stability and lubricating consistency of the biolubricant formulations under different thermal conditions.

The pour point test was conducted manually according to ASTM D97 to determine the lowest temperature at which the biolubricant can still flow. The sample was cooled gradually in a water-ice-salt mixture, and at every 3 °C, the flow was checked by tilting the sample jar. The temperature at which flow did not occur for 5 seconds was recorded as the pour point. This method refers to the standard procedure used in palm oil methyl ester studies, in which the pour point was determined using ASTM D97 for biobased lubricants [11].

The flash point was determined using a Cleveland open cup (ASTM D92) apparatus, adapted manually due to the absence of a closed cup apparatus. The sample was gradually heated and intermittently exposed to a flame, and the temperature at which a brief ignition occurred was recorded as the flash point.

The thermal stability test of the lubricant was carried out to evaluate its resistance to degradation due to heating. A total of 50 ml of lubricant sample was placed in a clean and dry 100 ml beaker glass and then heated using a magnetic stirrer at low speed (150 rpm) to ensure even heat distribution. The lubricant temperature was monitored using a type K-type thermocouple connected to a digital data logger with an accuracy of ± 0.1 °C. The thermocouple sensor tip was immersed in the lubricant at a distance of about 1 cm from the bottom of the beaker to ensure that the temperature readings accurately represented the sample condition. Temperature recording was performed every minute for 15 minutes at a set point of 100 °C. In addition to temperature data, physical changes in the lubricant, such as changes in colour, the appearance of smoke and a characteristic odour, were also monitored and recorded along with the temperature and time at which the changes began to occur. With this approach, the test provides both quantitative and qualitative insights into the lubricant's resistance to thermal degradation.

The machining performance of the biolubricant formulations was evaluated using an EMCO T.U. CNC-2A lathe machine. The goal was to assess the cooling effectiveness of each lubricant by monitoring the cutting tool temperature during turning operations under real machining conditions. The used workpiece material was aluminium 6061, with specimen diameters varying between 16 and 36 mm. During measurement, the device was positioned perpendicular to the outer surface of the tool at a fixed distance of approximately 5 cm. Measurements were taken immediately after cutting stopped, within less than 3 seconds, to minimise temperature drop due to air cooling. Each measurement was repeated three times at the same position and the average value was recorded. The thermogun used had an accuracy of ± 0.5 °C, making the results sufficiently representative of the actual condition of the tool during the cooling process. The diameter variation required adjustments in spindle speed to maintain a constant surface speed. This approach is used to ensure that the cutting speed at the tool-workpiece interface remains constant, regardless of the workpiece diameter.

The test was conducted using a constant cutting speed, namely 100 m/min under medium-speed conditions and 150 m/min under high-speed conditions. It should be emphasised that cutting speed was different from feed rate, i.e. the feed rate was set at 100 mm/min for medium-speed conditions and 150 mm/min for high-speed conditions, while the cutting speed depends on the interaction between spindle rotation and specimen diameter. The tungsten carbide cutting tool insert (PLANSEE DCMT 070204EN) was used due to its resistance to wear and high temperatures. The cutting parameters were set as follows: feed rate of 100 mm/min (medium) and 150 mm/min (high), depth of cut of 5 mm and cutting length of 30 mm per cycle (cycle is defined as a single continuous cutting process along 30 mm with the predetermined machining parameters). To ensure the reliability of the results, the cooling test under the same parameters was repeated three times for each condition. This repetition was carried out to evaluate the repeatability and consistency of temperature measurements during the cooling process.

The machining performance tests were performed under five different conditions, i.e. as dry cutting (without lubricant – the initial test condition in which the cutting process is carried out without the use of lubricating fluids); with mineral-based commercial lubricant Castrol Magna BDX 68; and with biolubricants with POME to AVE ratios of 80:20, 70:30 and 60:40. As a reference, the Castrol Magna BDX 68 lubricant has the following basic properties: density of 880 kg/m^3 at 20 °C, kinematic viscosity of 68 mm^2/s at 40 °C and 8.73 mm^2/s at 100 °C, viscosity index of 100, flash point of 234 °C (closed cup) and pour point of – 12 °C. These properties were considered in the cooling performance evaluation.

3. Results and discussion

3.1 Viscosity

The viscosity test results are presented in Figure 3. Among the four formulations, the 60:40 POME to AVE blend exhibited the highest dynamic viscosity at 40 °C (2.20 mPas), indicating superior film-forming ability crucial for reducing friction and tool wear during machining. At 100 °C, viscosity decreased due to thermal thinning, but the 60:40 blend retained relatively higher viscosity compared to other formulations, signifying better thermal stability [12]. *Aloe vera* gel exhibits non-Newtonian shear-thinning behaviour, where viscosity decreases as shear rate increases, which is attributed to the hydrogel structure formed by polysaccharides such as acemannan. Usually, the flow behaviour index ranges from 0.37 to 0.71 at temperatures between 15 and 55 °C, depending on concentration. These values, which are lower than 1, indicate the pseudoplastic nature commonly noticed in *Aloe vera* gel, meaning the gel has high viscosity at low shear (which supports film formation in lubrication) but flows easily under high shear conditions.

3.2 Density

The obtained density values support efficient flow and lubrication performance in machining

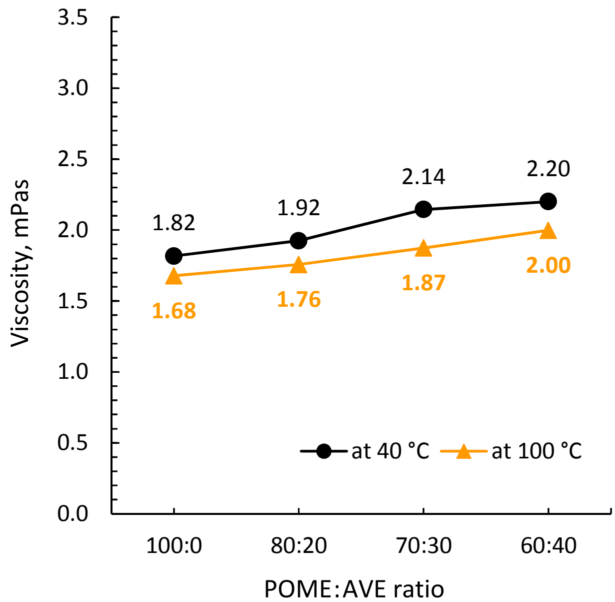

Figure 3. Viscosity at 40 and 100 °C for different POME:AVE ratios

systems. Among all formulations, the 60:40 POME to AVE blend maintained the most stable density profile across temperature changes, with minimal variation noticed between 40 and 100 °C (1.19 and 1.18 g/cm^3) as shown in Figure 4. Such stability suggests strong thermal and oxidative resistance, which is critical for maintaining consistent lubricant performance under prolonged operational conditions [13]. Furthermore, no phase separation, sedimentation or discolouration was noticed during or after the heating process, indicating excellent miscibility between AVE and palm oil esters. This chemical compatibility ensures formulation homogeneity, essential for reliable and consistent lubrication properties over time [13].

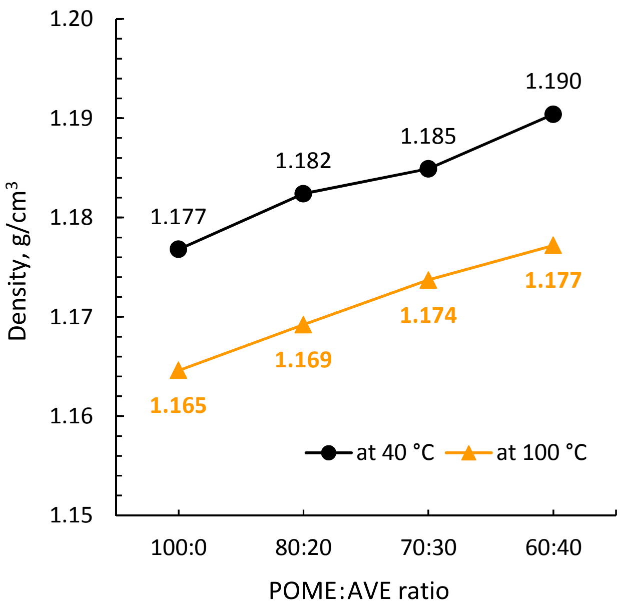

Figure 4. Density at 40 and 100 °C for different POME:AVE ratios

3.3 Pour point

The results of the pour point measurement are presented in Figure 5. Among all biolubricant formulations, the 60 : 40 POME to AVE blend exhibited the lowest pour point of 9.7 °C, indicating superior fluidity at low temperatures. A lower pour point supports better pumpability and start-up reliability in cold or variable environments [14]. This improved low-temperature performance is attributed to the presence of acemannan, a highly hydrophilic polysaccharide in *Aloe vera*. Acemannan has demonstrated strong water-retention and hydrogel-formation capacity since it can absorb and retain up to 99 % of its weight in water, enabling a supercooling effect and delaying the onset of freezing or gelation in lubricant formulations [15]. This property allows the lubricant to remain semi-liquid at lower temperatures, enhancing its function across a wider temperature range.

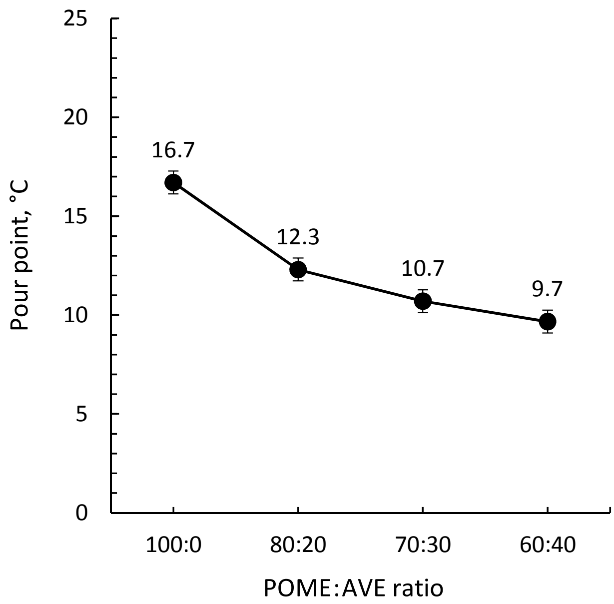

Figure 5. Pour point for different POME : AVE ratios

3.4 Flash point

The flash point results are shown in Figure 6. This parameter is essential for evaluating the safety and thermal resistance of biolubricants, especially under high-temperature operating conditions. A higher flash point indicates better thermal stability, reduced fire hazards and improved performance reliability in demanding industrial or machining environments. It also reflects the lubricant's ability to withstand extreme thermal exposure without forming volatile vapours that could ignite, making it crucial for maintaining operational safety, especially in CNC machines, heavy-duty equipment or enclosed systems.

The flash point of a lubricant is defined as the lowest temperature at which its vapour can form an ignitable mixture in air when exposed to a flame. In this study, the 60 : 40 POME to AVE blend demonstrated the highest flash point of 102.7 °C. This indicates stronger resistance to vaporisation and combustion under thermal stress compared to the other blends. The enhanced thermal resistance is attributed to the balanced chemical structure formed by the POME and AVE. *Aloe vera* contains acemannan, a polysaccharide known to create a gel-like matrix that inhibits rapid vapour release during heating [16]. In addition, *Aloe vera* is rich in antioxidant compounds such as phenolics and vitamin E, which, although not the primary determinant, help maintain chemical stability at elevated temperatures [5].

These findings are in line with prior studies. Ateeq [16] reported that biolubricant blends with more than 40 % biodiesel content tend to exhibit flash points above 100 °C, highlighting the role of ester composition and polar additives in boosting thermal resistance. Similarly, Teh et al. [5] noted that palm oil-based lubricants, particularly those processed through transesterification and mixed with natural additives, consistently reach flash points within the 100 – 150 °C range depending on formulation. The regression analysis in this study showed a strong linear correlation between *Aloe vera* concentration and flash point values, with an R^2 of 0.9917. This suggests that increasing the *Aloe vera* content significantly enhances the flash point, making the biolubricant safer and more suitable for high-temperature industrial applications.

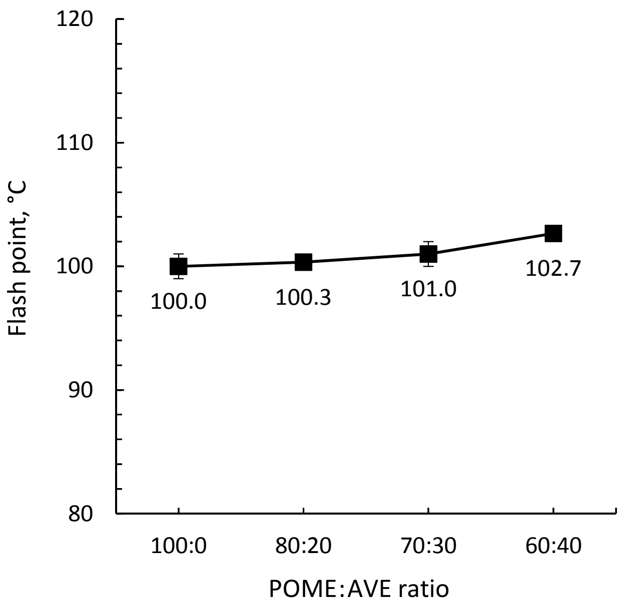

Figure 6. Flash point for different POME : AVE ratios

3.5 Thermal stability

Thermal stability refers to the lubricant's ability to resist degradation when exposed to high temperatures. This parameter is crucial for ensuring that the biolubricant remains effective during prolonged operation in heat-intensive environments such as CNC machining. High thermal stability helps maintain viscosity, prevents oxidation and reduces the formation of harmful deposits, thereby extending the service life of both the lubricant and machinery components and ensuring consistent performance under thermal stress.

The results shown in Figure 7 indicate that the 60:40 POME to AVE blend exhibited the most stable thermal behaviour. The sample temperature remained below 40 °C even under prolonged heating, demonstrating significant resistance to thermal degradation and structural breakdown. This thermal stability is attributed to the presence of acemannan polysaccharides in *Aloe vera*, which form hydrogel networks that help stabilise the lubricant matrix by retaining moisture and reducing volatility [17]. These hydrophilic networks act as thermal buffers, slowing the rate of temperature increase and preserving structural integrity. This behaviour is consistent with the pour point findings presented in Figure 5, where the 60:40 blend demonstrated a temperature response close to its pour point of 9.7 °C. The delayed phase change confirms that *Aloe vera* contributes not only to reducing pour point but also to enhancing overall thermal resilience by minimising crystallisation or gelation during cooling cycles.

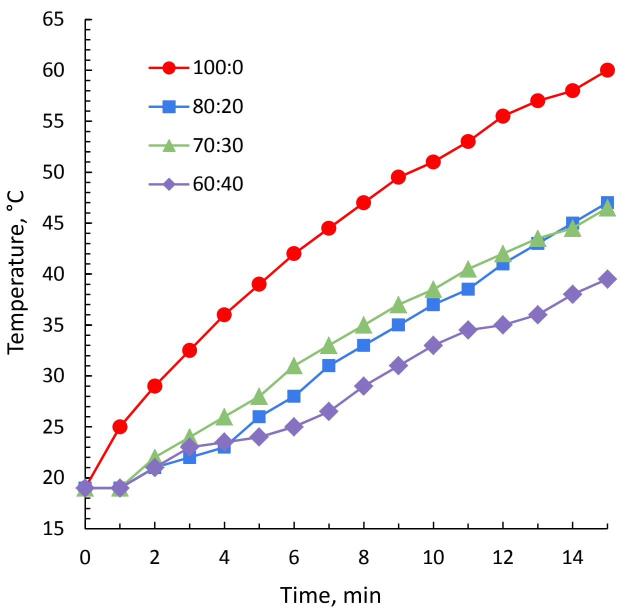

Figure 7. Thermal stability for different POME : AVE ratios

3.6 Machining performance

Cutting temperature is a critical parameter in CNC machining as it affects tool wear, surface finish and process efficiency. In this study, temperature measurements were used to evaluate the cooling performance of the formulated biolubricants during aluminium turning. Tests were carried out under medium and high spindle speed conditions using aluminium 6061 as the workpiece material. The starting temperature for all specimens was 28 °C.

Medium-speed test condition reflects typical operating parameters in CNC turning, where thermal loads are present but not extreme. The effectiveness of each lubricant formulation was assessed by comparing the temperature reduction relative to dry cutting. Figure 8 shows the results of the medium spindle speed conditions, where a biolubricant with a 60:40 POME to AVE blend exhibited the most effective temperature reduction, with an increase of only 2.6 °C, i.e. from 28 to 30.6 °C. For comparison, a mineral-based lubricant (commercial lubricant) obtained a temperature rise of 4.1 °C, while dry cutting conditions reached a temperature increase of up to 8.5 °C. These results indicate that the 60:40 biolubricant blend has better heat-dispersion capacity than either the commercial lubricant or dry cutting conditions.

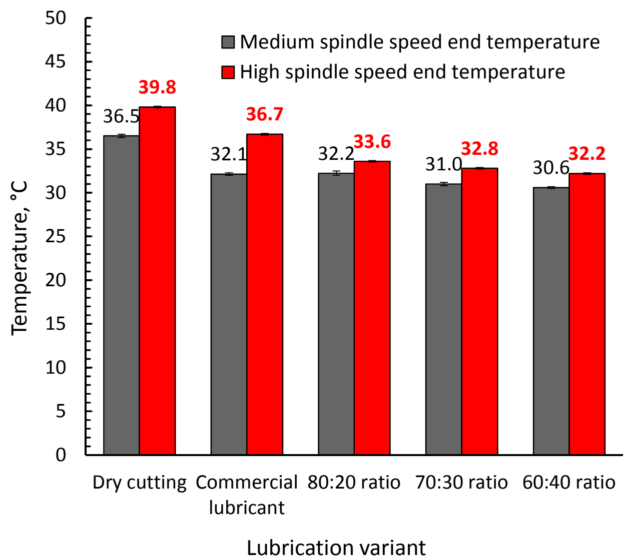

Figure 8. Results for CNC machining at medium- and high-speed conditions

Figure 8 also shows the results of the high spindle speed conditions. Thermal loads on the cutting tool increase significantly due to more intense friction in the cutting zone. Therefore, the lubricant's ability to absorb and dissipate heat becomes critical in maintaining cutting temperature stability and preventing premature tool wear. This high-speed test was conducted to evaluate the thermal performance of each biolubricant formulation under more extreme working conditions and to compare it with commercial lubricant and dry cutting.

The cooling efficiency is investigated by different studies on vegetable oil-based lubricants. Ahmad et al. [17] showed that vegetable oils deliver comparable or even better cooling performance than that of commercial lubricants when used on conventional lathes, with a significant difference in temperature reduction between dry and MQL (minimum quantity lubrication) conditions using vegetable oils [16,18]. In addition, Zhou et al. [18] confirmed that the thermophysical properties of vegetable oils, particularly viscosity and surface tension, directly correlate with lower cutting tool temperatures and longer tool life [19]. The combination of the thermal conductivity of palm oil and the heat transfer capability of *Aloe vera* through the thin film it forms explains why the 60:40 POME to AVE blend provided the best cooling performance.

Under the high spindle speed conditions, the thermal load on the cutting tool increased significantly, offering a more severe test of cooling performance. As shown in Figure 8, the 60:40 POME to AVE blend yielded the smallest temperature increase, rising only 4.2 °C (from 28 to 32.2 °C). On the other hand, commercial lubricant caused a temperature rise of 8.7 °C, while dry cutting resulted in the highest increase of approximately 13 °C. These findings highlight the superior thermal stability of the biolubricant under high-friction, high-speed operating conditions. These results align with prior research on vegetable oil-based cutting fluids. The enhanced thermal behaviour of the 60:40 POME to AVE blend is attributed to the presence of acemannan polysaccharides in *Aloe vera*, which form a gel-like protective layer on the tool–workpiece interface. This layer acts both as a lubricant and a thermal insulator, thereby reducing friction and heat transfer. Combined with the conductive properties of palm oil, the biolubricant ensures effective heat dissipation and tool protection under demanding machining conditions [20].

4. Conclusion

This study shows successfully synthesised and characterised biolubricants derived from palm oil methyl esters and *Aloe vera* extract through transesterification and ethanol-based polysaccharide extraction. Among all tested formulations, the 60:40 ratio of palm oil methyl ester to *Aloe vera* extract consistently demonstrated the best overall performance across key parameters: viscosity, pour point, flash point, density, thermal stability and machining temperature reduction.

The incorporation of *Aloe vera* significantly enhanced the oxidative and thermal resistance of the biolubricants, primarily due to the presence of acemannan and other antioxidant compounds that contribute to structural integrity under heat and friction. Additionally, the 60:40 blend demonstrated excellent cooling performance during CNC lathe operations, achieving the lowest cutting tool temperatures at both medium and high spindle speeds. These findings confirm the potential of the 60:40 blend as a biodegradable, environmentally friendly and high-performance alternative to mineral-based lubricants, particularly for metalworking and precision machining applications.

Further studies are recommended to investigate the long-term tribological behaviour, biodegradability under field conditions and scalability for industrial production, thereby paving the way for its adoption in sustainable manufacturing practices.

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