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Stability, Thermo-physical, and Tribological Properties of SiO_2 Nanoparticles in a Vegetable Oil-based Biodegradable Lubricant for Minimum Quantity Lubrication Machining

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ABSTRACT

Machining is essential in manufacturing for shaping materials by removing excess through contact between the tool and workpiece. However, dry machining generates significant heat and cutting forces, leading to tool degradation and surface imperfections. While flood cooling helps address these issues, it presents environmental and health concerns due to large volumes of fluid and harmful chemical additives. Minimum Quantity Lubrication (MQL) offers a greener alternative by applying only the minimum amount of lubricant directly to the cutting area. Still, it frequently proves insufficient in handling difficult-to-cut materials like nickel-based alloys, owing to poor heat removal and lubrication. This study investigates enhancing MQL using silicon dioxide (SiO_2) nanoparticles in vegetable oil-based formulations, creating an improved nanolubricant system (NMQL). The volume concentrations of five different percentages were tested: 0.01%, 0.03%, 0.05%, 0.07%, and 0.1 % of SiO_2 biodegradable nanolubricant. Stability was evaluated through visual sedimentation observation, UV-visible measurements, and zeta potential analysis. Some slight sedimentation occurrences through visual observations indicated nanolubricant stability even after 10 days. UV-visible stability was measured at a 0.1% volume concentration, showing a linear correlation adhering to Beer-Lambert law principles. The most stable nanolubricant resulted from 2 hours of sonication at a 349 nm wavelength, exhibiting an excellent zeta potential stability of 98.3 mV. Thermophysical testing revealed that 0.1% concentration produced the highest dynamic viscosity compared to the base oil.

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In the tribological evaluation, the 0.07% concentration exhibited the lowest coefficient of friction and wear scar diameter. Overall, biodegradable nanolubricants serve as a potential for Minimum Quantity Lubrication (MQL) machining.

Keywords: Dynamic viscosity, MQL, nanolubricant, SiO_2, tribology

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INTRODUCTION

The significance of sustainability in machining processes becomes evident due to the large-scale production involved and the associated environmental risks. Machining operations play a crucial role in every manufacturing industry. Machining involves a method that achieves the anticipated size, shape, and quality on the surface by removing excess material from the work specimen through direct contact of the machining tool with the work specimen (Roy et al., 2019). Therefore, it was crucial to use a coolant to dissipate the heat generated in the machining area and control the machining temperature throughout the operation. A substantial amount of heat in the cutting area and usage of high cutting forces were generated from the dry machining of metals, resulting in tool wear, workpiece hardening, and intensified surface roughness (Pawanr et al., 2024). To mitigate these effects, flood cooling techniques are commonly used for lubrication and cooling during machining. However, flood cooling faced challenges due to environmental issues, health risks, and long-term viability concerns related to flood cooling systems. These systems used a significant amount of coolant or lubricant, impacting the environment. Additionally, the coolant used might contain toxic additives, which might affect the storage, usage, and disposal of traditional lubricants that contribute to the hazardous environmental impact. To address these concerns, a new cooling method, minimum quantity lubrication (MQL), was developed (Kapil et al., 2024). The MQL involves spraying only a small amount of coolant directly at the cutting zone, minimising mist formation and reducing health risks associated with conventional flood cooling systems. The MQL represented a lubrication methodology designed to optimise machining operations. In MQL, only a minimal quantity of lubricant was applied directly to the cutting tool or workpiece throughout the machining handling (Said et al., 2019). The MQL technique was an implementation that reassigned the least volume of cutting oil to the cutting area, forming an oil mist through its combination with compressed air.

According to the research by Ahmad et al. (2022) on treated recycled cooking oil (TRCO) in machining alloy steel (AISI 4340) in MQL, the machining performance was improved, resulting in reduced cutting force. MQL also led to lower cutting forces compared to dry cutting without any lubrication and improved the surface finish of the machined workpiece. The chips produced during MQL were thinner and had a curlier shape, indicating reduced friction during cutting. However, Gupta et al. (2021) discovered that the effectiveness of conventional MQL in easing cutting forces, surface roughness, and tool wear is limited. Additionally, conventional lubricants in MQL may not adequately address the heat produced throughout the machining process of hard-to-cut metals such as Nickel-based alloys that have a remarkable mechanical and chemical quality, which is suitable for high-strength, high-temperature, and pressure applications. However, its high work-hardening properties and low heat conductivity make it difficult to machine at high cutting speeds, including in the MQL environment. MQL systems often face challenges in effectively dissipating heat, which can adversely affect the surface finish and dimensional accuracy of machined components. The restricted volume of lubricant in MQL systems can complicate chip removal from the cutting zone, potentially leading to damage to both the workpiece and the cutting tool (Gupta et al., 2021). Thus, nanolubricant seems to be a feasible solution for the challenge.

Nanolubricants consist of nanoparticles dispersed in a lubricating base fluid, exhibiting unique properties that enhance the lubricating capabilities. The use of nanolubricants significantly improved the overall efficiency of the machining process. The nanolubricant enhanced the standard base liquid related to the effective thermal conductivity and viscosity (Hamisa et al., 2023). This targeted application ensures that lubrication is provided sufficiently, enhancing the efficiency of the machining operation. The usage of nanolubricants in Minimum Quantity Lubrication (NMQL) systems represented a perfect approach to machining, offering superior lubrication where it was needed most. This not only enhanced operational efficiency but also aligned with environmentally conscious practices, making it a promising advancement in the field of manufacturing. By introducing nanolubricant into NMQL technology, the machining performance will be enhanced in terms of machining characteristics as compared to conventional flood and dry cutting methods. The improved execution of the NMQL cooling strategy can be attributed to two key elements. First, the inclusion of highly conductive nanoparticles increases the thermal conductivity of the base oil. This results in a higher heat removal rate during machining. Secondly, the rolling impact of nanoparticles at the tool-chip interface eases the friction (Nouzil et al., 2022). The increased nanoparticle concentration also creates a preservative layer on both the tool and the workpiece surface, thus improving the interaction between the tool and workpiece and effectively easing friction (Moretti et al., 2024).

Research by Eltaggaz et al. (2018) explored the aluminium oxide nanoparticles with a nanocrystalline structure in the air-oil mixture during the turning process of austempered ductile iron (ADI). The NMQL outperformed conventional MQL by reducing flank wear. A comparative study evaluating different cooling approaches (dry, flood, MQL, and NMQL) revealed that NMQL machining was superior to base MQL and commensurate with flood cooling (Eltaggaz et al., 2018). The authors extended their investigation to titanium machining with Alumina (Al_2O_3) nanoparticles and discovered that NMQL reduced the seizure zone as opposed to base MQL cooling (Eltaggaz et al., 2021). Moreover, they observed that higher nanoparticle concentrations positively influenced tool durability and surface finish attributes. Furthermore, the implementation of nanolubricants in MQL systems aligns with environmental sustainability goals, with the reduced volume of lubricant used, coupled with the improved lubricating properties of nanomaterials. This relationship between MQL and nanolubricants not only improved machining efficiency but also helped in eco-friendly manufacturing practices (Lim et al., 2022).

The addition of nanoparticles greatly boosts the thermal conductivity and dynamic viscosity of lubricants, leading to more effective cooling performance and better lubricity during machining processes. Studies conducted by (Lim et al., 2022; Mondragón et al., 2023), explored a range of nanomaterials for minimum quantity lubrication (MQL) methods. Their investigations covered materials such as hybrid blends of graphene and aluminium oxide (G-Al_2O_3), along with other nanoparticles like silicon dioxide (SiO_2), molybdenum disulfide (MoS_2), and pure graphene. These works revealed that nanolubricants offer enhanced heat dissipation and retain consistent viscosity even at minimal concentrations. From a tribological standpoint, they also contribute significantly to lower friction and reduced surface wear during machining. In the study by Mohd Khalil et al. (2018) The impact of different machining parameters on cutting force and tool degradation was assessed during MQL machining of nickel superalloys with nanolubricants. Dry cutting was used as a benchmark for comparison. Abrasion was found to be the leading cause of tool wear. MQL with nanolubricants proved more effective in minimising wear and reducing cutting force. According to Gutnichenko et al. (2018) Incorporating graphite nanoparticles into vegetable oil for machining alloy 718 led to notable improvements over dry and conventional MQL machining, particularly in reducing tool wear, surface roughness, cutting force, and vibration.

Among the various nanoparticles evaluated, silicon dioxide (SiO_2) stands out for its excellent heat transfer and friction-reducing characteristics (Hawwash et al., 2018). Incorporating SiO_2 into eco-friendly lubricants appears to be a promising strategy to elevate both thermal and mechanical performance. These nanoparticles offer advantages such as remarkable thermal endurance, robust mechanical integrity, high tensile strength, and rigidity. This advancement supports the objectives of sustainable manufacturing by enhancing process efficiency while minimising the environmental footprint of lubrication. SiO_2 was deliberately selected as a fundamental component in nanolubricant formulations due to its beneficial properties. As highlighted by Sia et al. (2014), SiO_2 nanoparticles are well known for their exceptional hardness and their critical function in minimising direct surface interaction in friction-intensive conditions. Additionally, their widespread availability in the market played a significant role in enabling the cost-effective commercialisation of research. Because of their affordability and seamless compatibility with oil matrices, silica nanoparticles have been recognised as valuable additives for lubricants. Dambatta et al. (2019) emphasised that incorporating SiO_2 nanoparticles enhances oil properties, attributing this effect to their unique spherical shape and the complex 3D network formed by surface molecules. The presence of unoccupied bonds in SiO_2 molecules results in high surface energy, effectively reducing friction through nanoparticle deposition on workpiece surfaces. Furthermore, studies reveal that when dispersed in base oils, SiO_2 nanoparticles exhibit remarkable diffusion and mixing capabilities. A cost-benefit analysis comparing traditional synthetic lubricants with SiO_2-based alternatives indicates potential long-term savings due to extended tool lifespan and reduced maintenance costs. In addition to this, the cost of SiO_2 is relatively competitive nowadays due to its widespread applications. The addition of a small amount of nanoparticles to the base fluids is still justified in the technoeconomic study (Czaplicka et al., 2021). Regulatory adaptation and industry adoption will be key to broader commercial use.

This research introduces a novel perspective by conducting an in-depth investigation into SiO_2 nanolubricant in biodegradable oil, as this area is still limited in the open literature. Garcia Tobar et al. (2024) provided a review of nano-additives used in lubrication studies. Their review identified Molybdenum Disulfide (MoS_2) and Zinc Oxide (ZnO) as the most frequently studied nano-additives, with 10% of the research studied. Graphene (Gr) and Aluminum Oxide/Titanium Dioxide (Al_2O_3/TiO_2) were close behind, contributing to 8% of studies. Interestingly, the review highlighted a lack of focus on SiO_2 as a nanolubricant, particularly regarding its tribological behaviour, which is a research gap that is addressed in this study.

This study encompasses a rigorous stability assessment of the prepared samples before evaluating their thermo-physical properties, including dynamic viscosity in SiO_2 biodegradable nanolubricants. Following this, tribological performance was examined through a four-ball friction test, demonstrating enhancements in friction coefficient and wear scar diameter. Additionally, the correlation between these parameters and nanoparticle concentration was analysed.

Referring to Garcia Tobar et al. (2024) who reviewed optimal concentration ranges in nanolubricants, 51.28% of researchers found that concentrations below 1% yielded superior lubrication efficiency. Accordingly, this study stands as a pioneering effort in comprehensively examining SiO_2 nanoparticles dispersed in biodegradable oil across volume concentrations of 0.01%, 0.03%, 0.05%, 0.07%, and 0.1%. All experimental findings have been meticulously validated against previous research to ensure their reliability. Ultimately, the study proposes the feasible volume concentration of SiO_2 nanoparticles in biodegradable oil, with recommendations for further applications in minimum quantity lubrication (MQL) machining.

METHODOLOGY

Nanolubricant Preparation

In this experimental investigation, SiO_2 nanoparticles were employed as the nanoparticles due to their superior performance and easily accessible. These SiO_2 nanoparticles, sourced from Xuzhou Jiechuang New Material Technology, have a typical size of 30 nm and are 99% pure SiO_2. The biodegradable oil utilised in the study was Coolube 2210 XP, developed by Unist, Inc. (2025), which is derived from pure vegetable oils and designed specifically for use with ferrous materials, as it is considered eco-friendly, which excludes any volatile organic compounds (VOCs). Table 1 shows the physical properties of nanoparticles, while Table 2 represents the physical and chemical properties of Coolube 2210 XP. The preparation of the SiO_2 biodegradable nanolubricant involved SiO_2 nanoparticles and the biodegradable oil through a two-step method Figure 1 (Nugroho et al., 2021). This approach is recommended for its ability to ensure proper mixing and particle stabilisation. In this experiment, 0.5% volume of Triton X-114 surfactant (CAS Number 9036-19-5) was incorporated into every concentration of the nanolubricant to increase the oil stabilisation (Merck, 2025). Initially, a 30-minute magnetic stirring process was performed, followed by continuous dispersion using an ultrasonic bath vibrator for an additional two hours to break down agglomerations (Nugroho et al., 2021). The two-hour sonication process was identified as the optimal duration for achieving effective mixing, which minimises the potential for sedimentation and attaining a desirable mean particle size. The sonicator plays a decisive part in breaking down agglomerations and ensuring thorough dispersion of the nanoparticles within the base solution (Sharif et al., 2017). Sharif et al. (2022) suggested the use of mono and hybrid nanolubricants at concentrations under 0.1%, due to their remarkable tribological performance. Guided by this recommendation, the current research formulated nanolubricants using low volume percentages of 0.01%, 0.03%, 0.05%, 0.07%, and 0.1% nanolubricants as part of the research.

Table 1
Properties of SiO_2

Properties	SiO_2
Chemical Abstracts Service (CAS) Number	7631-86-9
Purity (%)	99
Diameter (nm)	30
Density @ 20°C (kg/m^3)	2329
Melting Point (°C)	1440
Specific heat (J/kg.K)	745

Note. Adapted from Zawawi et al., 2019; ChemicalBook, 2025

Table 2
Properties of biodegradable oil

Chemical Name/Properties	Coolube 2210 XP
Methyl Ester -CAS No. 67784-80-9	<2%
Diisotridecyl Adipate -CAS No. 26401-35-4	<2%
Mixed Esters/Ester Blend -Proprietary	>90%
Registered Sulfurised Olefin -Proprietary	<5%
Viscosity @ 40 °C mm²/s (cSt)	10
Pour point (°C)	-12 to -20
Density @ 20 °C (kg/m³)	890
Flash Point (°C)	>200
Thermal Conductivity, k (W/mK)	0.2

Note. Adapted from Unist, 2025

The volume concentration for the experimental phase of the research was determined using the formula outlined in Equation 1 (Lim et al., 2022).

$$\phi_{NL} = \frac{\frac{m_{\mathrm{p}}}{\rho_{\mathrm{p}}}}{\left(\frac{m_{\mathrm{p}}}{\rho_{\mathrm{p}}} + Voil\right)} \times 100 \qquad [1]$$

Where ϕ_{NL} is the volume concentration of nanolubricant, m_{p} is the mass of nanoparticles in kg, $Voil$ is the volume of biodegradable oil in m³, and ρ_{p} is the density of nanoparticles in kg/m³.

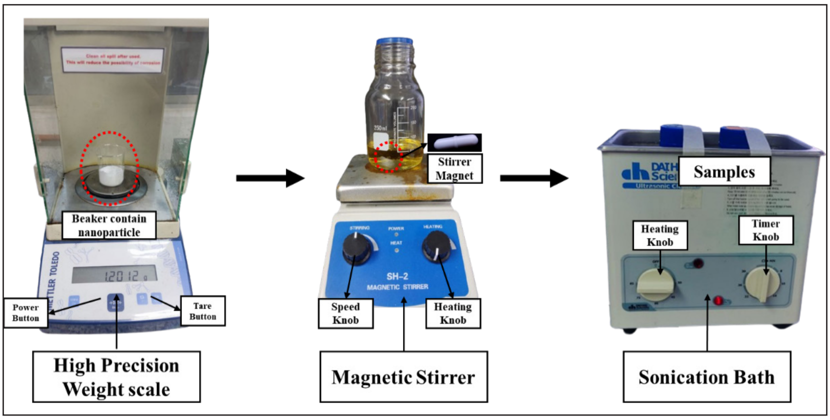


Figure 1. Two-step process in the preparation of a nanolubricant

Nanolubricant Stability

Visual Sedimentation Observation

Dispersion stability was assessed using three methods: visual sedimentation, ultraviolet-visible (UV-Vis), and zeta potential analysis. In the visual sedimentation, periodic observations were made up to a 30-day observation period to assess the nanolubricant's stability in the samples visually (Gulzar et al., 2017).

Spectra Absorption

Additionally, the dispersion stability of the SiO_2 biodegradable nanolubricant was also analysed through spectral absorbance using UV-Visible spectroscopy Jasco/V 670-EX, a highly effective technique for studying nanolubricant stability, as shown in Figure 2. The evaluation of the stability of dispersion was conducted at room temperature by quantifying the absorbance (from the 0th day to the 20th day), with variations in sonication time. The wavelength accuracy falls within 1.0 nm across the 200 to 450 nm range and was set to identify the peak absorption wavelength for a concentration of 0.1%. Given the pivotal role of UV-visible in assessing nanolubricant stability, precision becomes a significant consideration in this stability test (Hamisa et al., 2023). Absorbance indicated how much light the nanolubricant absorbed, while transmittance indicated how much light passed through it. The visible UV-visible provided the necessary light spectrum. Then, a lens allowed a beam of light to pass through a monochrome, breaking it into a spectrum of different wavelengths (Ismail et al., 2023). To enhance accuracy and reduce random error, measurements using the UV-Vis spectrophotometer were repeated three times and averaged to ensure precision.

Zeta Potential Measurement

The final stability measurements in this study were conducted using the Zeta potential test. The zeta potential refers to the developing difference between the dispersion medium and the static layer of solution bonded to the particle (Hamisa et al., 2023; Ismail et al., 2022). The Malvern Zetasiser ZEN3600 machine, as shown in Figure 3 was employed for these zeta measurements, with nanolubricants placed in the DTS1070 cell. The required parameters that were specified in the machine were the refractive index, viscosity, absorption, and dielectric constant for the base oil and nanolubricant. The zeta potential of the lowest nanolubricant, which was 0.01% volume concentration, was measured and conducted under controlled conditions. To ensure dependable and precise outcomes, the zeta potential test was conducted three times, aiming to reduce fluctuations and verify consistency across repeated measurements.

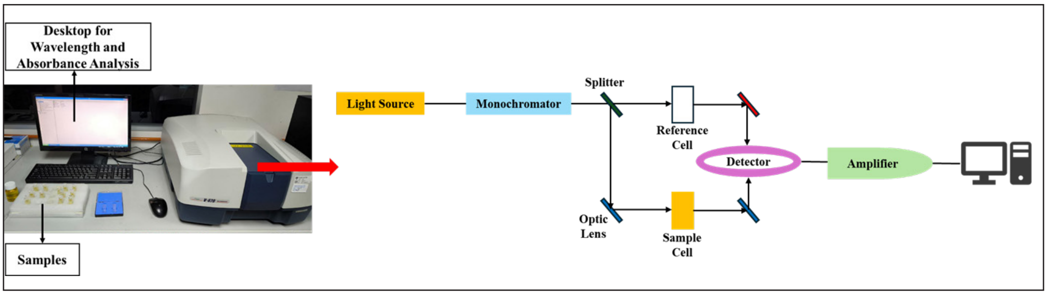


Figure 2. UV-Visible spectrometer and its schematic configuration

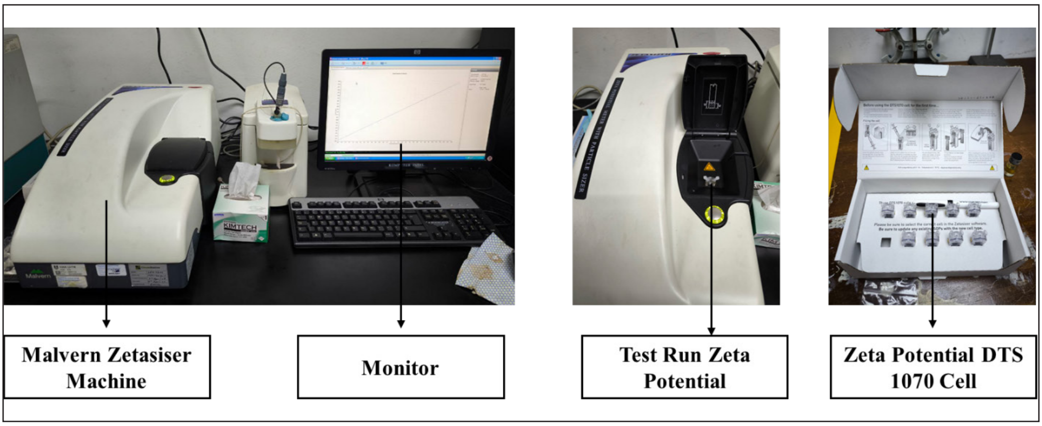


Figure 3. Zeta potential measurement

Thermo-physical Properties Measurement

Dynamic Viscosity

The dynamic viscosity is a critical property that influences lubricating efficiency, forming a stable boundary layer between the tool and the workpiece (Asadi et al., 2016). Hence, nanoparticles can modify rheological properties, improving lubricating film stability, reducing wear, and enhancing machining performance. In this study, an electronic rheometer Anton Paar Germany GmbH (2006) has been used in measuring the viscosity of the nanolubricant of five-volume concentrations for SiO_2 biodegradable nanolubricant; 0. 01%, 0. 03%, 0. 05%, 0. 07% and 0. 1% at temperatures between 27 °C and 90 °C. The spindle was immersed in the sample, with rotational speeds ranging from 0.01 to 1000 revolutions per minute (1/min). Viscosity measurements were taken once the readings stabilised. To ensure the reliability of the results, the test was conducted three times in Figure 4, and the average viscosity value was subsequently calculated.

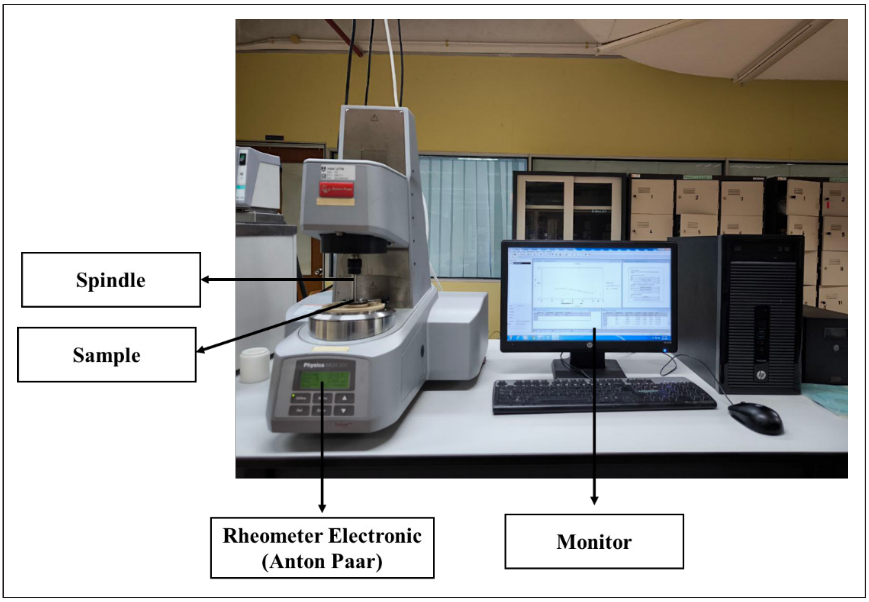


Figure 4. Dynamic viscosity rheometer electronic (Anton Paar Germany GmbH, 2006)

Tribological Properties Measurement

As per the ASTM D4172-94 standard, the tribological assessment of the biodegradable nanolubricant SiO_2 was carried out utilising a Koehler four-ball tribo tester, as depicted in Figure 5. In this inquiry, test balls with a 12.7 mm diameter, HRC 64-66 hardness range, and Grade 25 extra-polished surface finish were used. The biodegradable base oil was employed starting in the tribology assessment, and then different volume concentrations of the biodegradable nanolubricant SiO_2 (0.01%, 0.03%, 0.05%, 0.07%, and 0.1%) were applied. The ASTM D4172-94 standard was followed by the experimental circumstances, which were compliant with the requirements listed in Table 3. For a maximum of 60 minutes during the experiment, the working temperature was kept at 75°C. To control the heater and ensure that the lubricants were kept at a consistent temperature, an automatic temperature controller was employed. The lever arm was subjected to a 40.0 kg load, and 1200 rpm was selected as the rotational speed. The recorded parameters, including the friction torque and coefficient of friction for both biodegradable base oil and SiO_2 biodegradable nanolubricant, were recorded as practised by another researcher (Hamisa et al., 2023). In lubrication, lower frictional torque and coefficient of friction were preferred as they indicated decreased resistance to motion and smoother surface interaction. Each test was conducted three times to calculate the average diameter of the wear scar.

Table 3
The test conditions for the ASTM D4172-94 standard

ASTM Standard	Test Method	Test Conditions				
		Speed (rpm)	**Load (kg)**	**Duration (Minutes)**	**Temperature (^{o}C)**	**Remarks**
D4172-94	Wear preventive characteristics of lubricating fluid	1200±60	40.0±0.2	60±1	75±2	Ball pot to be torqued down between 25 and 50 ft.lb

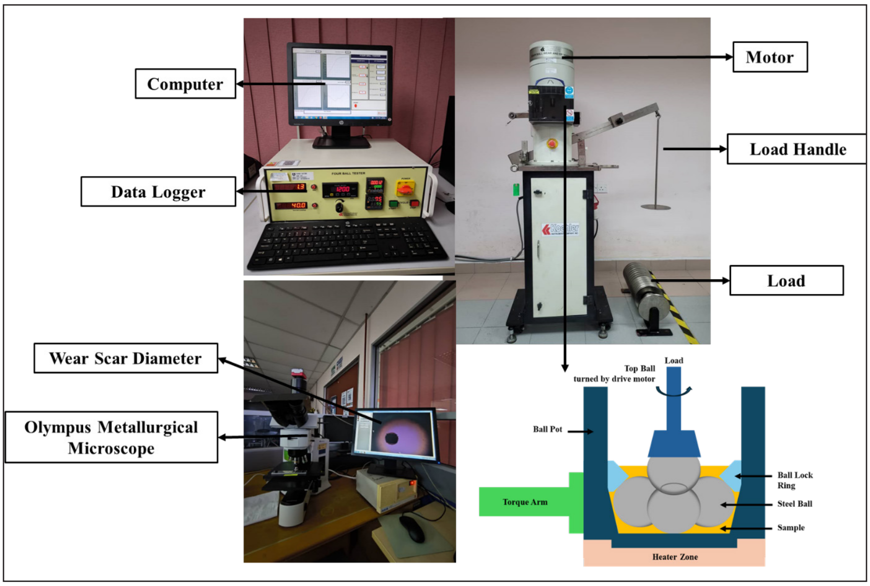


Figure 5. Four-ball tribology tester and its schematic configuration

Uncertainty Analysis

The precision of physical measurements directly impacts the accuracy of an analysed parameter and its related conclusions. The data from the zeta potential analyser, UV-vis spectrophotometer, and rotating viscometer were obtained separately. To determine the expanded uncertainties for all measured parameters in this study, the fractional uncertainty formula was applied. The level of parametric precision is determined by the accuracy of the measuring instruments and the scale of the recorded values (Zakaria et al., 2022). Table 4 outlines a summary of the uncertainties associated with the accuracy specifications of the instruments employed in zeta potential, UV-vis absorbance, viscosity, nanoparticle concentration, and other measurements.

Table 4

Uncertainties of the instrumentation for individual readings

Parameters	Range of Instruments	Least Division in Instrument	Experiment Values		Uncertainty (%)	
			Min	Max	Min	Max
Nanoparticle weight (g)	0 to 200	±0.0001	0.005	0.1	0.1	2
Lubricant volume (mL)	1 to 50	±1	100	100	1	1
Volume concentration (%)	-	-	0.01	0.1	-	-
Zeta potential (mV)	0 to 1000	±0.1	80.2	98.3	0.102	0.125
Absorbance (UV-Vis)	0 to 7	±0.001	0.015	0.095	1.05	6.67
Dynamic viscosity (Pa. s)	0.01 to 1000	±0.0001	0.003	0.023	0.435	3.33

Note. Adapted from Anton Paar Germany GmbH, 2006; Sharif et al., 2023

RESULTS AND DISCUSSION

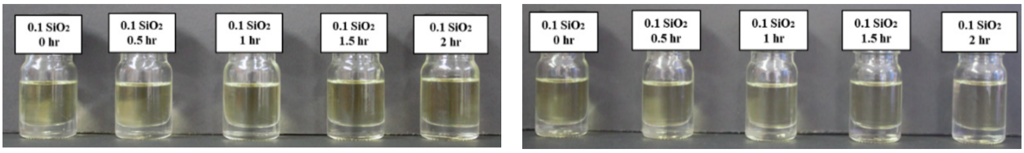
Stability Evaluation

Visual Sedimentation Observations

Figure 6 shows the sample of visual sedimentation observations of 0.1% SiO_2 biodegradable nanolubricant from day 0 (after preparation) until day 30 at room temperature. It was observed that the SiO_2 nanoparticles were shown as well-dispersed nanoparticles in the biodegradable base oil with negligible sedimentation. On the 0th and 5th days, the SiO_2 biodegradable nanolubricant showed a clear appearance without any signs of sedimentation across all sonication durations. The samples maintained consistent visual characteristics during the initial five days following their preparation. The observation was made from the 10^{th} day until the 15th day. The SiO_2 biodegradable nanolubricant still shows a stable appearance without producing any major sedimentation in the sample bottle. Observation continued for the 20th day, the 25th day, and finally on the 30th day, the sedimentation still did not occur in these samples. It showed that the nanolubricant with a 2-hour sonication time was the most stable sample through visual observation. The addition of Triton X-114 played a vital role in preventing sedimentation since surfactants work like helpers that spread out and prevent tiny particles from clumping together or settling down (Azman et al., 2019). They make sure the small particles stay evenly spread in the liquid.

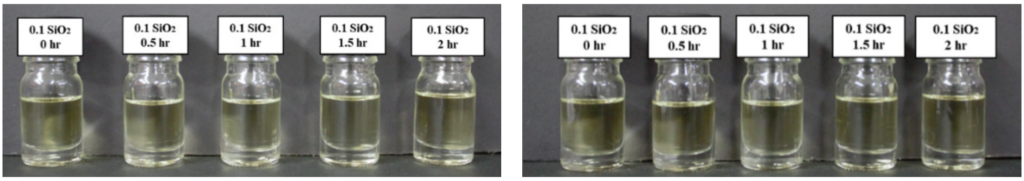
UV-Visible Analysis

The stability of the samples was then assessed quantitatively through a UV-Visible spectrometer to evaluate the peak absorbance and distinguish the acceptable wavelength from the scanning process. The absorbance value for 0.1% SiO_2 in biodegradable oil is shown in Figure 7 for wavelengths of 200 to 450 nm.



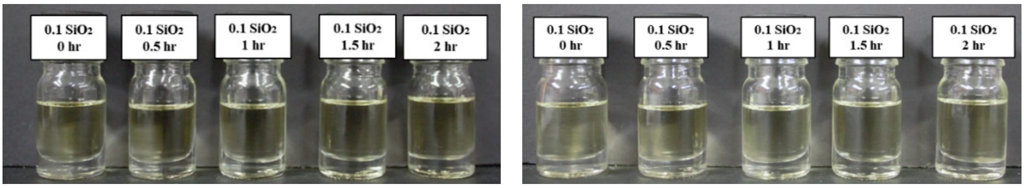
After preparation

5th day



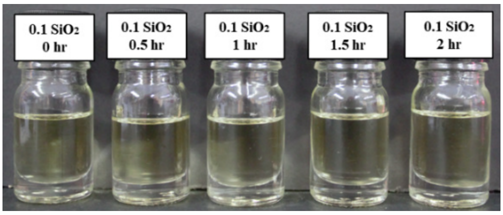
10th day

15th day



20th day

25th day



30th day

Figure 6. Sedimentation observation of SiO_2 biodegradable nanolubricant with different sonication times

The graph shows that the peak absorbance for 0.1% SiO_2 in biodegradable oil was at 349 nm wavelength.

Meanwhile, the absorbance against concentration at a constant peak wavelength of 349 nm is shown in Figure 8. The volume concentrations of 0.01%, 0.03%, 0.05%, 0.07%, and 0.1% absorbance were plotted to prove the Beer-Lambert law, which shows that absorbance is directly proportional to the concentration of substances in the mixture, translated to the ability of the substances to absorb light and the length of the light's path through the sample (Sanukrishna et al., 2019). Therefore, the concentration can be calculated from the absorbance value measured. This Beer-Lambert law principle was validated by comparing the findings with prior research conducted by Hamzan et al. (2025) on a hybrid SiO2:TiO2 biodegradable nanolubricant. The results of the current validation agree with those of the previous researchers.

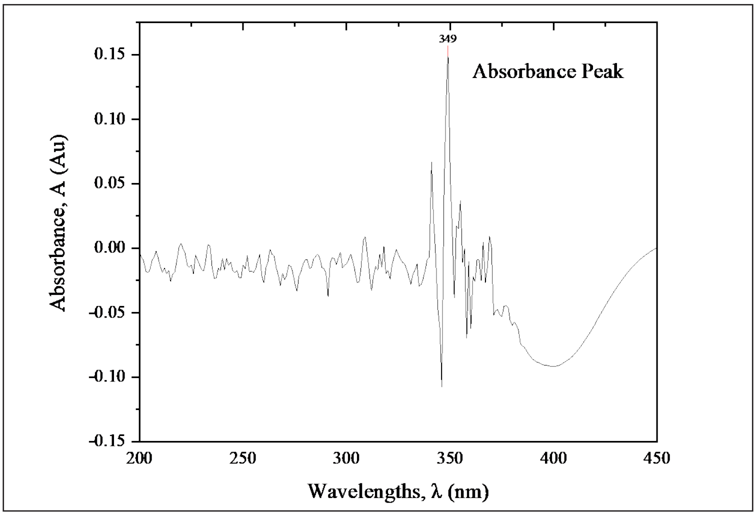


Figure 7. Absorbance of 0.1% volume concentration of nanolubricant at a different wavelength

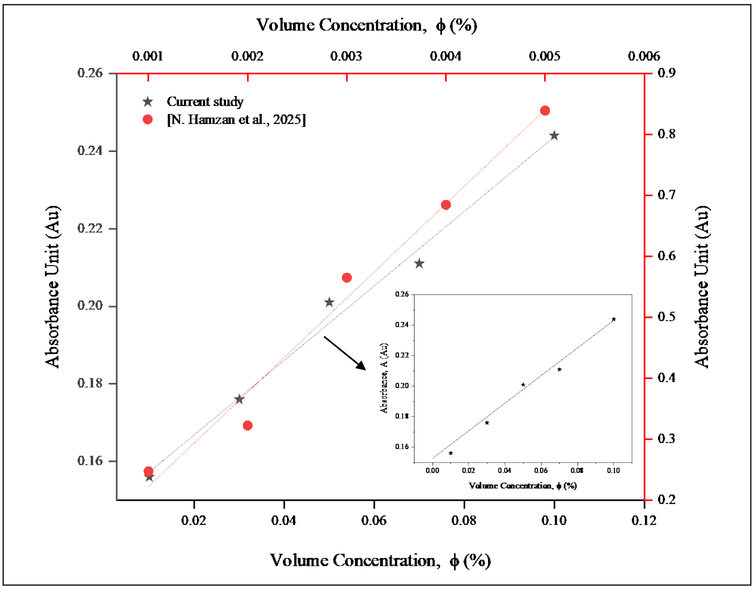


Figure 8. UV-Visible Spectrophotometer linear relative graph of the absorbance against SiO_2 biodegradable nanolubricant concentration

Figure 9 shows the relationship of the absorbance values for five different ultrasonication times, ranging from no sonication, labelled as 0, 0.5 hours, 1 hour, 1.5 hours, and 2 hours, for 0.1% volume concentrations of SiO_2 biodegradable nanolubricant. The stability was observed for 20 days. It is shown that the lowest absorbance ratio is with 0 sonication time, as expected due to its poor stability.

The 2-hour sonication process exhibited the greatest stability over the course of the evaluation, as it demonstrated excellent stability, reaching 59%. The ultrasonication time significantly influences the stability of nanolubricants, as observed in the UV-Visible spectrophotometer evaluation of the SiO_2 biodegradable nanolubricant. The longer sonication duration yielded the most favourable absorbance ratio as compared to lower sonication durations (Ramadhan et al., 2019). The general trend of the absorbance ratio is decreasing over time, which is in good agreement with other researchers' findings (Hamisa et al., 2023). Sharif et al. (2022) Investigated the stability of SiO_2/PAG nanolubricants and observed that extending ultrasonic treatment beyond 120 minutes (2 hours) did not lead to an increase in absorbance ratio. Their findings showed that ultrasonic agitation in a water bath effectively reduced particle agglomeration and minimised particle size, resulting in consistently high absorbance values. It was further noted that additional sonication beyond the initial 120 minutes (2 hours) offered no significant benefit. These observations align with the conclusions of Hamzan et al. (2025), who also identified a two-hour sonication period as the ideal duration for preparing a stable nanolubricant formulation.

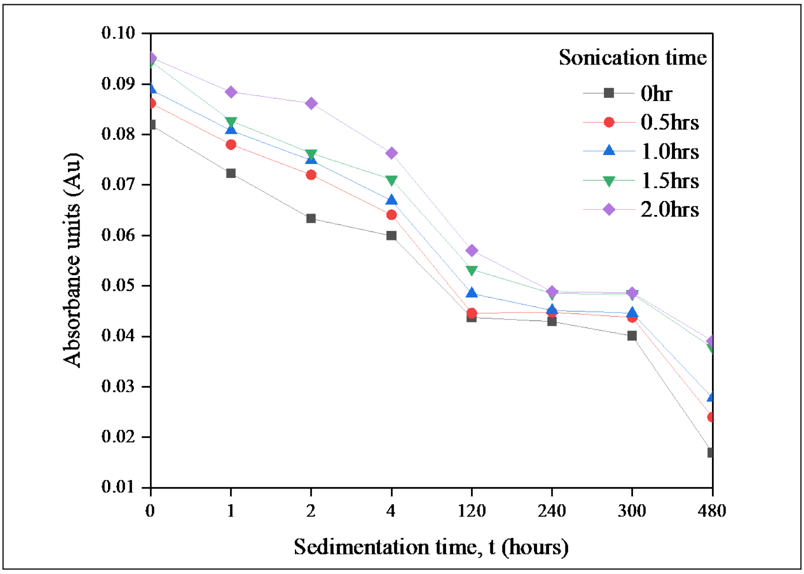


Figure 9. Absorbance units of 0.1% volume concentration of SiO_2 biodegradable nanolubricant for 20 days with different sonication times

Zeta Potential

Figure 10 shows the zeta potential measurement for SiO_2 biodegradable nanolubricant. This approach enabled the evaluation of the zeta potential of nanoparticles at a minimal concentration before potential interactions or agglomeration became significant.

Furthermore, using the lowest volume concentration aided in understanding the individual particle behaviour and characteristics, since the higher concentrations might have led to more complex interactions and the potential to influence the stability reading (Ramadhan et al., 2019). These outcomes were compared against the stability condition classification offered by Ghadimi et al. (2011) for various zeta potential ranges, which categorise absolute values exceeding 60 mV as excellent stability. The nanolubricants prepared showed an absolute zeta potential value of 98.3 mV, which exceeded the stability threshold of 60 mV. According to (Ismail et al., 2023) Stabilisation theory, a high absolute value of zeta potential signifies highly intense electrostatic repulsive interactions between nanoparticles, hence signifying a stable suspension. A similar approach was performed by Sharif et al. (2022) In the study of SiO_2/PAG nanolubricants, the stability of the nanolubricant was at 80.6 mV. Thus, proved that the SiO_2 biodegradable nanolubricant prepared was in a very good stability condition.

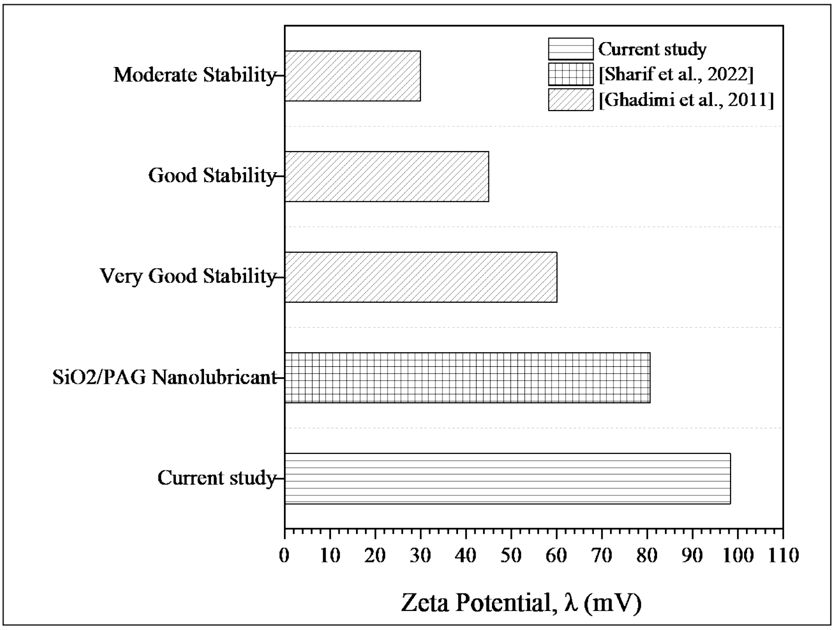


Figure 10. Zeta Potential of 0.01% SiO_2 biodegradable nanolubricant.

Thermo-physical Properties Evaluation

Dynamic Viscosity

Figure 11 shows the dynamic viscosity result of SiO_2 biodegradable nanolubricant. The graph shows a decreasing trend in the dynamic viscosity of different volume concentrations of nanolubricant with the rising temperatures from 27 °C to 90 °C.

For a comparison purpose on the effect of volume concentration towards viscosity value, at a temperature of 60 °C, the highest dynamic viscosity is shown by 0.1 vol % concentration with 17.81% increment from biodegradable base oil. This was followed by 0.07% with an increment of 16.71%, 0.05% (15.78%), 0.03% with an increment of 14.82%, and 0.01% (13.94%). This result is utterly consistent with Ismail et al. (2022) who reported that the higher the volume concentration, the higher the viscosity values will be. In terms of temperature effect, all lubricants tested exhibit lower viscosity as the temperatures are increased, which is similar to the research findings of (Asadi et al., 2016). This is favourable in MQL operation since it will involve a much higher temperature (Ismail et al., 2022).

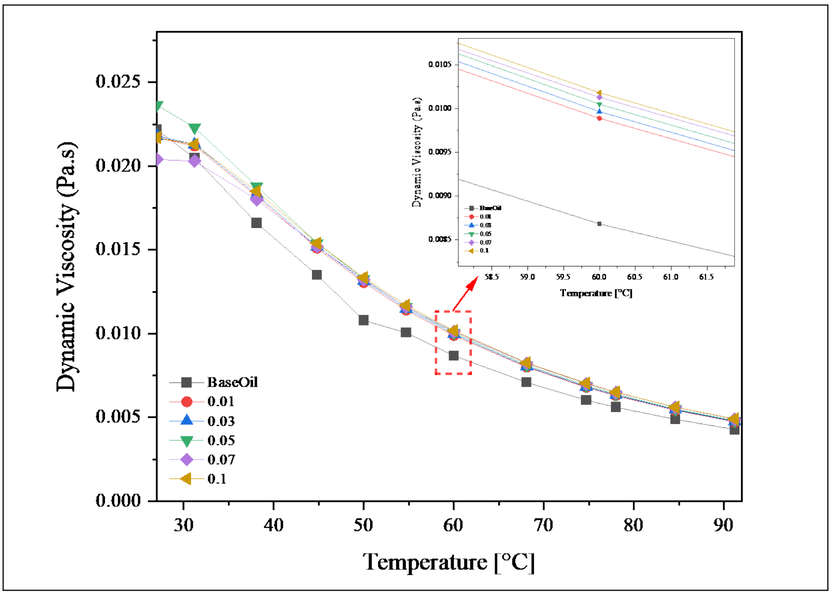


Figure 11. Dynamic viscosity of nanolubricant

Tribological Properties Evaluation

Coefficient of Friction (COF)

The coefficient of friction was a necessary constraint that significantly influenced the execution of lubricants. Figure 12 provides a visual representation of the coefficient of friction (COF) for SiO_2 biodegradable nanolubricant across different volume concentrations compared to biodegradable base oil. The experiment highlighted a significant 37.82% reduction in COF when using 0.07% SiO_2 biodegradable nanolubricant as compared to biodegradable base oil. This was closely followed by 0.05% SiO_2 biodegradable nanolubricant, which demonstrated a 20.92% reduction in COF.

The addition of 0.03% volume concentration improved the COF with a reduction of 19.03%. In general, the COF for all nanolubricants is lower than biodegradable base oil. Adding nanoparticles up to a concentration of 0.07% improves lubrication on the contact surface, leading to a reduction in COF. The maximum permitted concentration of nanoparticles is 0.07%, and going above this limit could either not improve performance at all or make it worse than the base oil. The results of a study by Kamel et al. (2021) that examined hybrid nanolubricants on engine oil, which uses many types of volume concentration of nanolubricant had supported the trend that was shown for this investigation. The decrease in COF suggests that SiO_2 nanoparticles in the biodegradable base oil enhance tribological effects, if the nanoparticle concentration remains below the threshold value (0.07%). According to Ismail et al. (2022), the main factor responsible for the decrease in friction torque and COF in the examined nanolubricant was the existence of efficient nanoparticles. Due to their reduced interfacial frictional surface activity, these nanoparticles promoted the nanoparticle mechanism, where the change from pure sliding friction to rolling friction. These findings underscore the potential of this nanolubricant to significantly improve machining processes in the future (Hamisa et al., 2020). After an initial phase, the COF progressively increased throughout the 3600-second test. This trend may stem from several factors, including thermal degradation of the lubricant at 75 °C, agglomeration or settling of nanoparticles, buildup of wear particles in the contact area, and alterations in the tribo-film characteristics. The rise in temperature also played a role by decreasing the resistance to flow between molecules and the rotating components, which led to a reduction in viscosity (Sharif et al., 2023). As the temperature increased, molecular interactions became more fluid, enhancing the lubricant's flow and affecting its frictional response.

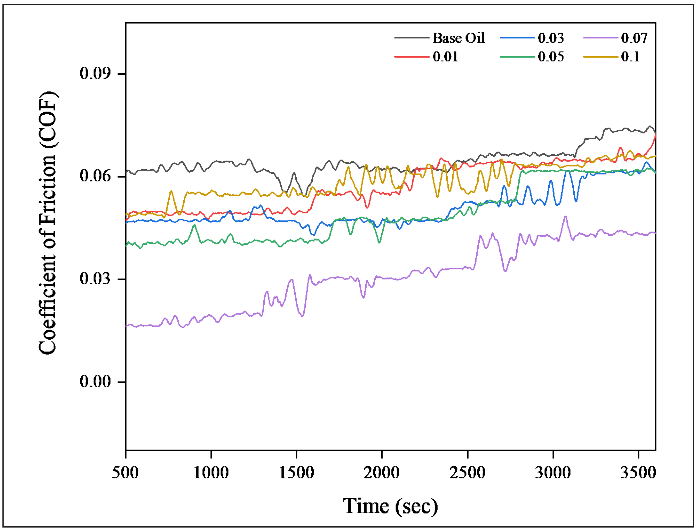


Figure 12. Coefficient of friction of SiO_2 biodegradable nanolubricant

Wear Scar Diameter (WSD)

Figure 13 shows the average wear scar diameter (WSD) of all balls used in the four-ball tribology experiment. Analysing Figure 14 revealed that the diameter for WSD of the biodegradable base oil (0.0902 mm) was the highest among the samples. This was due to the biodegradable base oil lacking specific property enhancements, leading to an increase in friction and wear between moving parts during machining (Zawawi et al., 2019). Research from Hamzan et al. (2025) On biodegradable nanolubricant also supported this finding, demonstrating that the highest WSD was associated with base oil, and the addition of nanoparticles led to a reduction in wear scar diameter and enhanced the surface finish of the ball. Among these concentrations, the most effective nanolubricant in terms of wear scar diameter reduction was 0.07% volume concentration, as it exhibited a 14.41% reduction with 0.0139 standard deviation. In comparison, the wear scar reduction for 0.05% nanolubricant was 13.53%, followed by 0.03% (13.30%), and 0.01% (12.86%). The 0.1% volume concentration of SiO_2 biodegradable nanolubricant did not give the highest wear scar reduction as expected. Similarly to the COF result, the threshold value for WSD was obtained at 0.07% volume concentration. Thus, increasing the volume concentration of nanolubricant did not give any improvement to the WSD result. Generally, the biodegradable base oil exhibited the largest WSD than the nanolubricants.

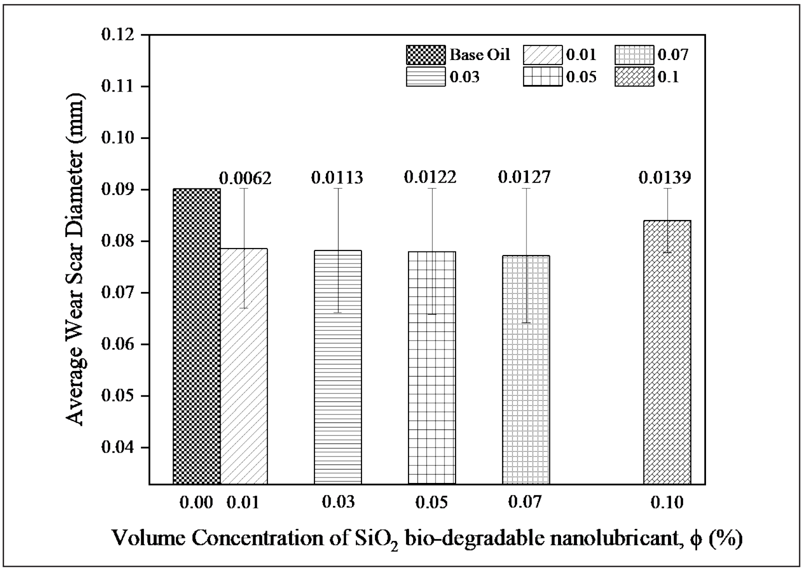
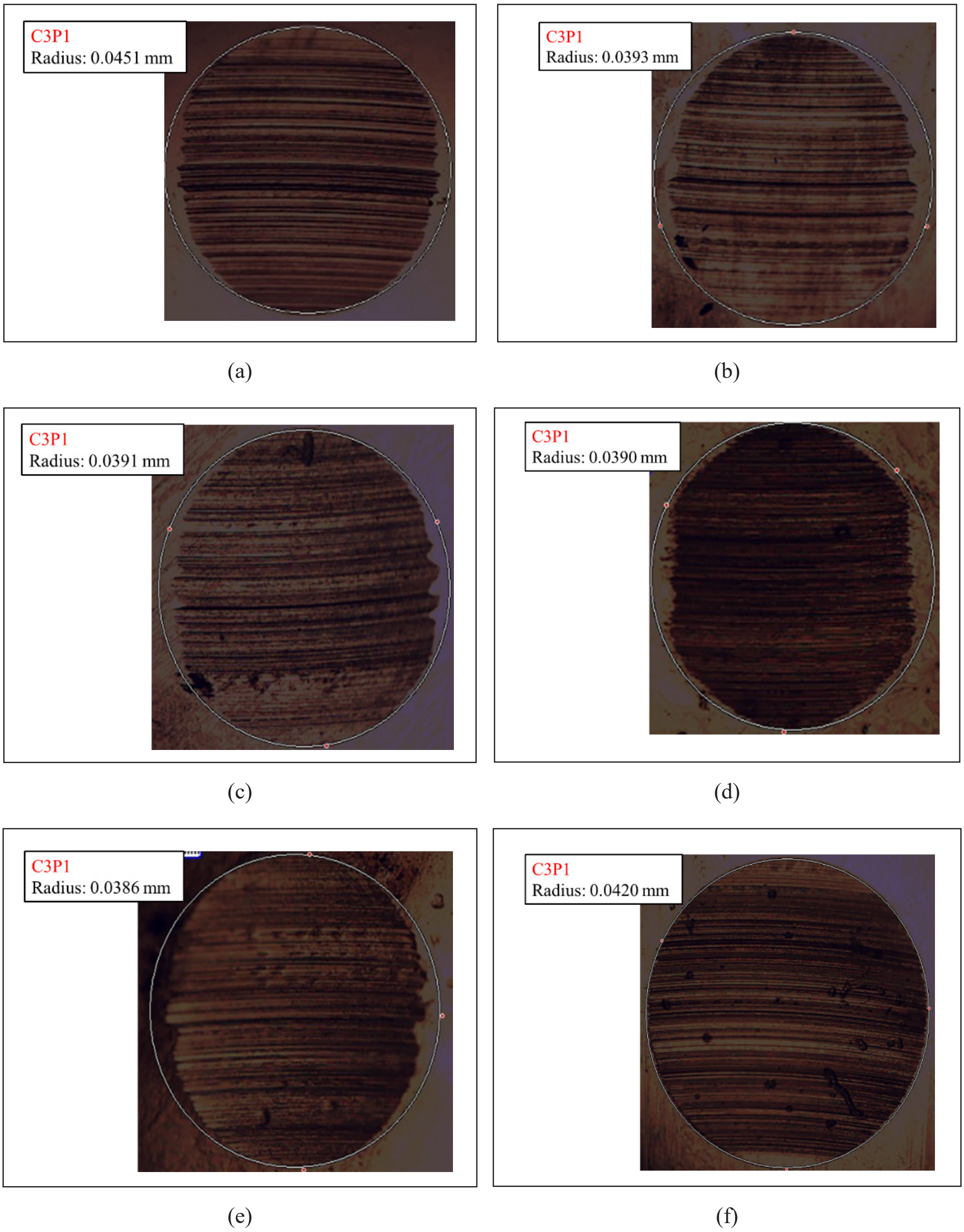


Figure 13. The average wear scar diameter of the SiO_2 biodegradable nanolubricant



(a) (b)

(c) (d)

(e) (f)

Figure 14. Optical micrograph of wear scar for (a) biodegradable base oil; (b) 0.01% SiO_2 biodegradable nanolubricant; (c) 0.03% SiO_2 biodegradable nanolubricant; (d) 0.05% SiO_2 biodegradable nanolubricant; (e) 0.07% SiO_2 biodegradable nanolubricant; and (f) 0.1% SiO_2 biodegradable nanolubricant

CONCLUSION

In conclusion, this research successfully analysed the stability, thermo-physical and tribological characteristics of SiO_2 biodegradable nanolubricant. Visual sedimentation observation held during the stability test indicated the absence of agglomeration for all volume concentrations up to day 30, affirming the compatibility of SiO_2 biodegradable nanolubricant for thorough mixing, with the two-hour sonication time yielding the cleanest and clearest observations. While occasional fluctuations were observed in the UV-Vis analysis, these values consistently fell within an acceptable range for the nanolubricant. The most stable performance during the observation period was exhibited by 0.1% SiO_2 biodegradable nanolubricant subjected to 2.0 hours of sonication. In terms of thermo-physical properties, the dynamic viscosity for 0.1% volume has the highest viscosity through the various temperature ranges of 27 °C to 90°C. Furthermore, tribological properties of COF for SiO_2 biodegradable nanolubricant consistently outperformed biodegradable base oil across all volume concentrations throughout the four-ball experiment. The 0.07% volume concentration of SiO_2 biodegradable nanolubricant demonstrated the lowest COF with the highest COF reduction. The WSD for SiO_2 biodegradable nanolubricant at all volume concentrations also showed the lowest values at 0.07% volume concentration, with a remarkable 14.41% reduction of wear scar diameter. This study also discovered the threshold value at 0.07% volume concentration of SiO_2 biodegradable nanolubricant, which was the optimum volume concentration that can improve the machining operation as compared to 0.1% volume concentration. Although SiO_2 biodegradable nanolubricants improve biodegradability and sustainability, challenges remain in waste management and nanoparticle stability. Proper disposal practices must be implemented to prevent accumulation in industrial wastewater or unintended environmental effects. Future research should focus on enhancing full biodegradation potential, ensuring that nanoparticle dispersions align with ecological safety standards. The transition to eco-friendly lubricants must also consider industrial waste treatment protocols to support responsible disposal practices. In summary, the application of SiO_2 biodegradable nanolubricant in MQL machining is feasible and demonstrates promising potential for industrial use.

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