Type of contribution:
Editorial
▶ Research Paper
Case Study
Review Paper
Scientific Data
Report of Tech. Application

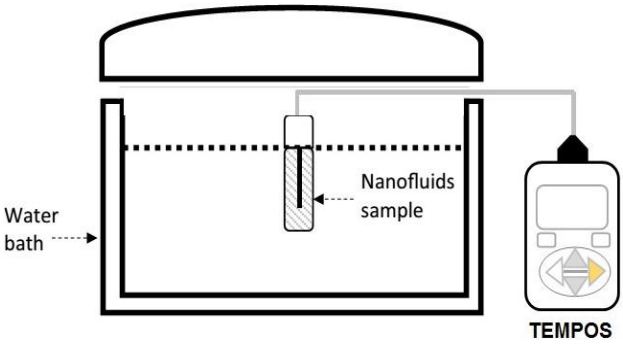
mesi
e-issn. 2798-5245

Mechanical Engineering for Society and Industry
Vol. 6, No. 1 (2026) pp 285-295
https://doi.org/10.31603/mesi.15463

An experimental approach to evaluate the stability and thermal conductivity of SiO_2/oil as green nanolubricant

Anwar Ilmar Ramadhan[1]*, Tri Yuni Hendrawati[2], Kushendarsyah Saptaji[3], Efrizon Umar[4], Kukuh Haryadi[1]

[1] Department of Mechanical Engineering, Faculty of Engineering, Universitas Muhammadiyah Jakarta, Jakarta 10510, **Indonesia**
[2] Department of Chemical Engineering, Faculty of Engineering, Universitas Muhammadiyah Jakarta, Jakarta 10510, **Indonesia**
[3] Department of Mechanical Engineering, Faculty of Engineering Technology, Sampoerna University, Jakarta 12780, **Indonesia**
[4] National Research and Innovation Agency, Jl. Tamansari No 71 Bandung, 40132, **Indonesia**
✉ anwar.ilmar@umj.ac.id



Highlights:

- SiO_2 nanolubricants were prepared using a two-step method.
- Thermal conductivity improved by up to 12% over base oil.
- Zeta potential reached 41.2 mV, indicating strong stability.
- Stable dispersion was observed over 30 days of monitoring.

Abstract

The application of nanotechnology in lubrication science has enabled the creation of nanolubricants with superior stability, improved thermal performance, and greater environmental compatibility than conventional lubricants. In this work, the stability and thermal conductivity of SiO_2 nanoparticles dispersed in base oil were experimentally examined as a green nanolubricant. SiO_2 nanoparticles were chosen owing to their chemical inertness, excellent thermal resistance, and eco-friendly nature. The nanolubricants were synthesized using a two-step method at volume concentrations of 0.1%, 0.2%, and 0.3%, with ultrasonication applied to ensure uniform particle distribution. Their stability was assessed using UV–Vis spectrophotometry, zeta potential testing, and visual sedimentation monitoring over a 30-day period. Thermal conductivity was determined via the transient hot-wire method. The results demonstrated that incorporating SiO_2 nanoparticles enhanced thermal conductivity by up to 12% compared to the base lubricant. Furthermore, stability evaluation showed zeta potential values of 41.2 mV, confirming strong electrostatic repulsion and low levels of agglomeration. Overall, these outcomes emphasize the promise of SiO_2-based green nanolubricants for thermal engineering applications, offering efficient and sustainable substitutes for traditional lubricants.

Keywords: Green nanolubricant; Lubricant; Stability; Thermal conductivity; Nanoparticles

Article info
Submitted: 2025-11-30
Revised: 2026-06-04
Accepted: 2026-06-11

This work is licensed under a Creative Commons Attribution-NonCommercial 4.0 International License

Publisher
Universitas Muhammadiyah Magelang

1. Introduction

The rapid development of modern thermal engineering systems, particularly in refrigeration and cooling technologies, has increased the demand for high-performance lubricants with enhanced thermal and tribological properties. Conventional lubricants, which are predominantly mineral-based, often face challenges such as low thermal conductivity, high frictional losses, and limited environmental sustainability. To overcome these drawbacks, nanolubricants—lubricants containing dispersed nanoparticles—have emerged as a promising alternative due to their ability to improve heat transfer performance, stability, and eco-friendliness [1], [2].

Among various nanomaterials, silica nanoparticles (SiO_2) have attracted significant attention because of their low cost, chemical inertness, non-toxicity, and abundant availability in nature [3].

SiO_2 nanoparticles exhibit good dispersion stability and can enhance the thermo-physical properties of base fluids, including viscosity, heat capacity, and thermal conductivity [4]. These characteristics make them suitable candidates for use as green nanolubricants, especially in environmentally friendly refrigerant systems where both performance and sustainability are crucial [5].

Although extensive research has established the thermophysical advantages of SiO_2 nanofluids using conventionally synthesized nanoparticles, a critical research gap remains regarding the stability, viscosity, and cost-effective scalability of fluids utilizing entirely green-synthesized SiO_2 from natural precursors (e.g., agricultural residues and oil palm bunches). While previous studies frequently relied on chemically produced nanoparticles that present environmental and economic burdens, current literature highlights an urgent need to optimize "green" SiO_2 nanofluids—specifically in controlling nanoparticle morphology and establishing long-term colloidal stability for sustainable thermal management and industrial applications [5], [6], [7].

The stability of nanolubricants plays a key role in ensuring their long-term applicability. Poor dispersion or particle agglomeration can lead to sedimentation, which decreases the performance of the nanolubricant and affects the reliability of the cooling system [6]. Therefore, stability analysis using techniques such as UV-Vis spectroscopy, zeta potential measurement, and visual observation is essential for validating the long-term performance of nanolubricants [7]. Additionally, thermal conductivity is a critical parameter in evaluating their potential to improve heat transfer efficiency in refrigeration and lubrication systems [8].

Although previous studies have reported the potential of different nanoparticles—such as Al_2O_3, CuO, and TiO_2—in enhancing the properties of nanolubricants [9], [10], limited research has been devoted to the systematic investigation of SiO_2 nanoparticles as a green nanolubricant, particularly focusing on their stability and thermal conductivity. Addressing this research gap is crucial to determine the feasibility of SiO_2-based nanolubricants for practical applications in refrigeration and energy systems.

This study aims to experimentally investigate the stability and thermal conductivity of SiO_2 nanoparticles dispersed in a base lubricant to develop a green nanolubricant. Stability was evaluated using UV-Vis spectroscopy, zeta potential, and visual sedimentation tests, while thermal conductivity was measured to assess the potential of SiO_2 nanolubricants for enhanced heat transfer performance. The outcomes of this research are expected to contribute to the development of eco-friendly and high-performance nanolubricants for use in refrigeration and lubrication systems.

2. Methodology

2.1. Preparation of Green Nanolubricant

Derived from empty palm shells (EPS), SiO_2 nanoparticles or Nano-Silicate are produced through an ultrasonication method. Sourced from Indonesia's local natural materials, these nanoparticles are subsequently dispersed in compressor oil (R600a). The mean particle size obtained is approximately 44 nm, and their detailed characteristics and Properties of Compressor Oil are listed in **Table 1** and **Table 2**.

A two-step method was employed for the preparation of the green nanolubricant, in which Nano-Silicate (SiO_2 Nanoparticles) was blended with compressor oil (R600a) and further homogenized through sonication. The preparation began by calculating the required volume for each concentration. Nanolubricants were produced at concentrations of 0.1%, 0.2%, and 0.3%, where the highest concentration (0.3%) was first prepared and subsequently diluted to lower concentrations, as outlined in **Figure 1**.

The nanoparticles were obtained in powder form with weight concentrations of 25% for SiO_2. Eq. (1) [11], [12], [13] was applied to convert weight concentration to volume concentration, while dilution from higher to lower concentrations was performed using Eq. (2) [5], [14], [15] by adding the corresponding volume of base fluid (ΔV).

Nano-Silicate or SiO_2 nanoparticles was blended with an oil-based lubricant (R600a) to produce a green nanolubricant. A total volume of 100 mL was prepared for each concentration, with the solution initially mixed using a magnetic stirrer for 15 minutes, followed by ultrasonic immersion for 15 minutes to enhance stability.

Table 1. Properties of SiO_2 nanoparticles from the synthesis process

Properties	SiO_2
Molecular mass, g mol^{-1}	60.08
Average particle diameter, nm	44
Density, kg m^{-3}	2220

Table 2. Typical properties of compressor oil for R600a refrigerant [16], [17], [18], [19]

Properties	Unit	Value
Density (at 15 °C)	kg/m³	840 – 870
Kinematic Viscosity (at 40 °C)	mm²/s (cSt)	46 – 68
Kinematic Viscosity (at 100 °C)	mm²/s (cSt)	7 – 9
Viscosity Index (VI)	-	95 – 105
Pour Point	°C	−30 to −35
Flash Point (COC)	°C	210 – 230
Thermal Conductivity	W/m·K	0.13 – 0.15
Specific Heat Capacity (Cp)	kJ/kg·K	1.8 – 2.0

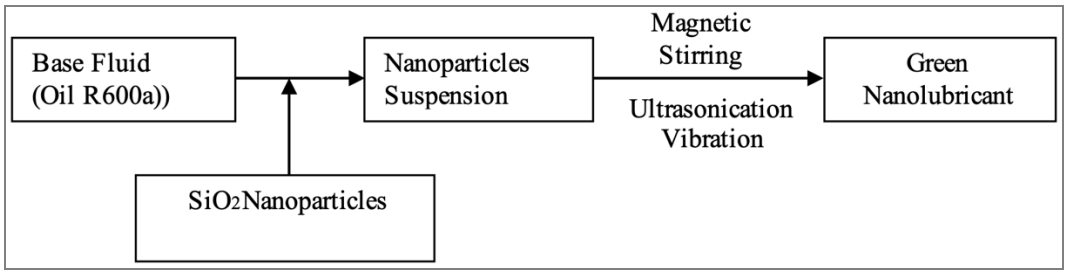


Figure 1. The preparation of green nanolubricant with SiO_2 nanoparticles or nano-silicate

$$\emptyset = \frac{\omega \rho_w}{\frac{\omega}{100}\rho_w + \left(1 - \frac{\omega}{100}\right)\rho_p} \quad (1)$$

$$\Delta V = (V_2 - V_1) = V_1\left(\frac{\emptyset_1}{\emptyset_2} - 1\right) \quad (2)$$

2.2. Characterization of Nano-Silicate (SiO_2 Nanoparticles) with SEM

The morphology of Nano-Silicate (SiO_2 Nanoparticles) was analyzed with a JSM-IT300 scanning electron microscope (SEM) at an accelerating voltage of 20.0 kV. Images were obtained at 5,000× magnification, where the samples were placed directly onto the holder without any pretreatment, even under hydrated conditions. The particle sizes were determined from the SEM images using ImageJ software (**Figure 2**), in accordance with the methodology described in earlier studies [13], [20], [21], [22].



Figure 2. (a) Scanning electron microscope (SEM) series JSM-IT300; (b) Samples of nano-silicate (SiO_2 nanoparticles)

2.3. Stability of Green Nanolubricant with Nano-Silicate (SiO_2 Nanoparticles)

The stability assessment of the nanolubricant in this research was carried out through UV-Vis spectrophotometry, zeta potential analysis, and visual inspection. Both UV-Vis measurements and visual monitoring were performed over a period of 30 days (720 hours) with varying sonication durations. The spectrophotometer was set to a constant wavelength of 850 nm, following the method described by [23], to evaluate absorbance and light scattering intensity relative to the base fluid (**Figure 3a**). Differences in sonication time resulted in varying absorbance ratios during sedimentation at the fixed wavelength of 850 nm, aligning with earlier findings [11]. Zeta potential values were determined using a Zetasizer Nano ZS (Malvern Instruments Ltd., UK) [6], [24], as depicted in **Figure 3b**. In addition, visual sedimentation tests were conducted for 30 days, where

the nanolubricant was considered stable when its concentration showed no significant changes. A comparable method for visual sedimentation analysis of nanolubricants was previously applied by [25].



Figure 3. Measurement of SiO_2/oil or green nanolubricant: (a) Stability with with UV-Vis spectrophotometer; (b) Zeta potential with with Zetasizer nano ZS

2.4. Thermal Conductivity Measurement of Green Nanofluids

The thermal conductivity was measured in accordance with ASTM D5334 and IEEE 442-1981 standards, employing the TEMPOS Thermal Property Analyzer as illustrated in **Figure 4**. The setup included the KS-1 sensor for determining thermal conductivity (k [W/m·K]), a measuring bottle to contain the test sample, and the TEMPOS controller, all of which are integral components of the system. This instrument applies a transient line heat source technique to evaluate thermal properties. Measurements were conducted over a temperature range of 30–70 °C, with a water bath used to maintain a stable sample temperature. Before testing, the thermal conductivity sensor was calibrated against a glycerine standard provided by Meter Group, yielding a reference conductivity of 0.286 W/m·K with an accuracy of ±0.35%. Each thermal conductivity measurement lasted 15 minutes, and multiple trials were conducted at different temperatures to obtain average values. This approach ensured accuracy and minimized potential errors from free convection effects caused by temperature variations along the sensor in direct contact with the fluid sample [26], [27].

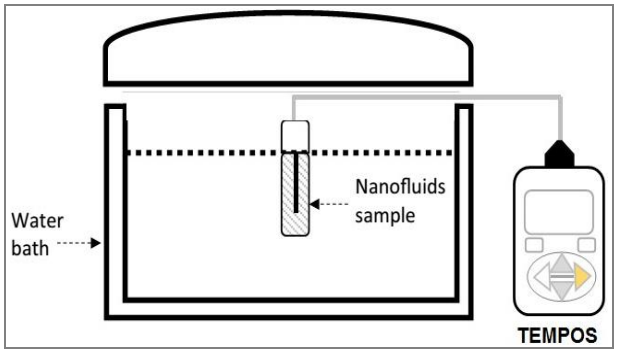


Figure 4. Values are presented as mean ± standard deviation (n = 3). TEMPOS Thermal Properties Analyzer for the measurement of thermal conductivity

3. Results and Discussion

3.1. Characterization of Nano-Silicate or SiO_2 Nanoparticles



Figure 5. Visualisation of SiO_2 nanoparticles or nano-silicate

The synthesized Nano-Silicate or SiO_2 Nanoparticles powders obtained through calcination at 50 °C are shown in **Figure 5**, exhibiting a light coloration and well-dispersed distribution. These visual findings align with earlier research on the morphology of SiO_2 nanoparticles [28], [29], [30].

Figure 6 presents the microstructural characterization of Nano-Silicate (SiO_2 nanoparticles) using scanning electron microscopy (SEM). The SEM image of SiO_2 nanoparticles prepared via ultrasonication at 50 °C reveals a fairly uniform morphology, with particle sizes ranging from 44.0 to 50.4 nm, indicating a consistent nanoscale size distribution [31].

3.2. Stability of Green Nanolubricant

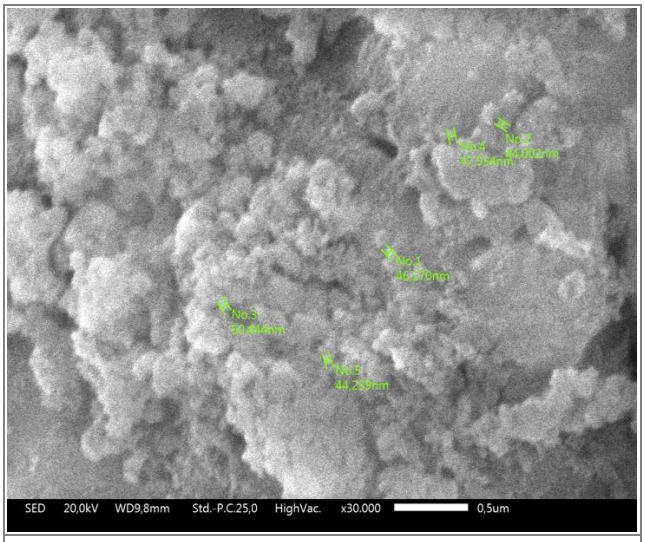


Figure 6. The SEM image for Nano-Silicate or SiO_2 nanoparticles with temperature 50 °C

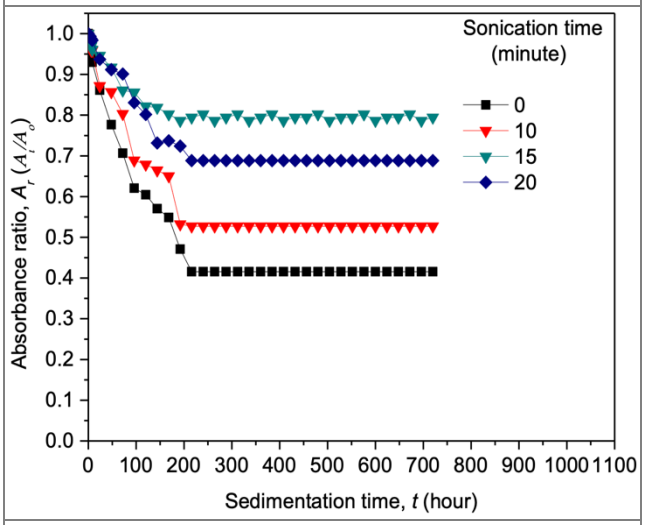


Figure 7. The absorbance ratio of green nanolubricant (SiO_2/oil) for different sonication time within 30 days

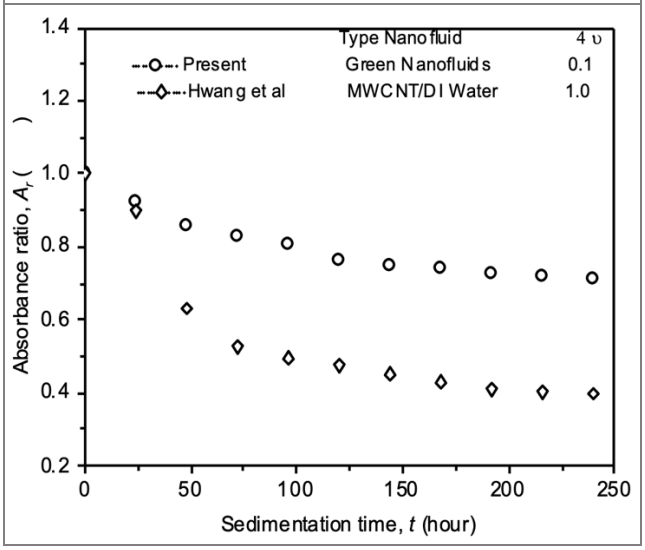


Figure 8. Comparison of absorbance ratio with sedimentation ratio from literature

Table 3. Zeta potential and classification stability [6]

Zeta potential (mV)	Stability
0	Little or no stability
15	Some stability
30	Moderate stability
45	Good stability
60	Very good stability

At a 0.1% volume concentration, the absorbance ratio of SiO_2 nanolubricant was evaluated under four different sonication conditions (**Figure 7**). An absorbance ratio of one (100%) represents optimal fluid stability. When sonicated for 20 minutes, the absorbance ratio began to decline after 50 hours, reaching 70%, and continued decreasing until stabilizing at 50% after 30 days. In contrast, a sonication time of 15 minutes maintained a favorable ratio of approximately 70–80% for up to 21 days. Sonication for 10 minutes resulted in a 60% decrease, while samples without sonication (0 minutes) showed a 40% reduction immediately after preparation. From the results, the 15-minute sonication time demonstrated the most stable absorbance ratio compared to other conditions. Therefore, this study adopted a 15-minute sonication process for preparing SiO_2 nanolubricant, achieving stability within the 70–80% range for 30 days. This method same another previous study by [11], [13], [32], [33], [34], [35], [36].

Figure 8 compares the absorbance ratio of SiO2 nanolubricants with the results obtained by [2]. In their work, multi-walled carbon nanotubes (MWCNTs) dispersed in an aqueous alkaline solution showed poor stability. Conversely, the present study employed Nano-Silicate or SiO_2 Nanoparticles in compressor oil (R600a) with a 15-minute sonication treatment, achieving a stable absorbance ratio of 70–80% that was sustained for up to 30 days.

To confirm the stability of the nanolubricant, zeta potential measurements were conducted, as this technique quantitatively evaluates particle dispersion based on electrophoretic mobility [11], [33], [34], [35], [37], [38]. According to the criteria summarized in **Table 3**, suspensions with zeta potential values greater than ±30 mV are typically regarded as stable [14], [39]. The absolute zeta potential val-

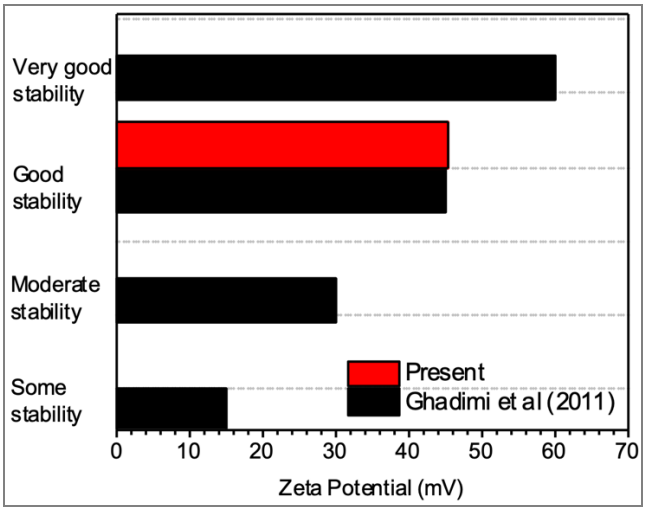


Figure 9. Zeta potential of SiO_2 nanolubricant

ue indicates the extent of nanoparticle agglomeration in the base fluid. In this work, higher absolute values of zeta potential demonstrated better dispersion of SiO_2 nanoparticles within compressor oil (R600a), thereby verifying improved stability [6].

The zeta potential of the SiO_2 nanolubricant was recorded at a maximum of 41.2 mV. This value was evaluated against the stability classification suggested by [6], [17], as shown in **Figure 9**. Because absolute zeta potential values greater than 30 mV are indicative of good dispersion and stability, the result confirms that the nanolubricant falls within the stable category. Hence, the zeta potential assessment verifies the stability of the synthesized SiO_2 nanolubricant.

Figure 10 shows the images of SiO_2 nanolubricants with volume concentrations of 0.1%, 0.2%, and 0.3%, captured both immediately after preparation and after 30 days. As illustrated in **Figure 10**, the samples exhibited neither sedimentation nor noticeable agglomeration during the 30 days, confirming that the nanolubricant maintained good dispersion and stability over time based on previous study by [13], [19], [27], [35].

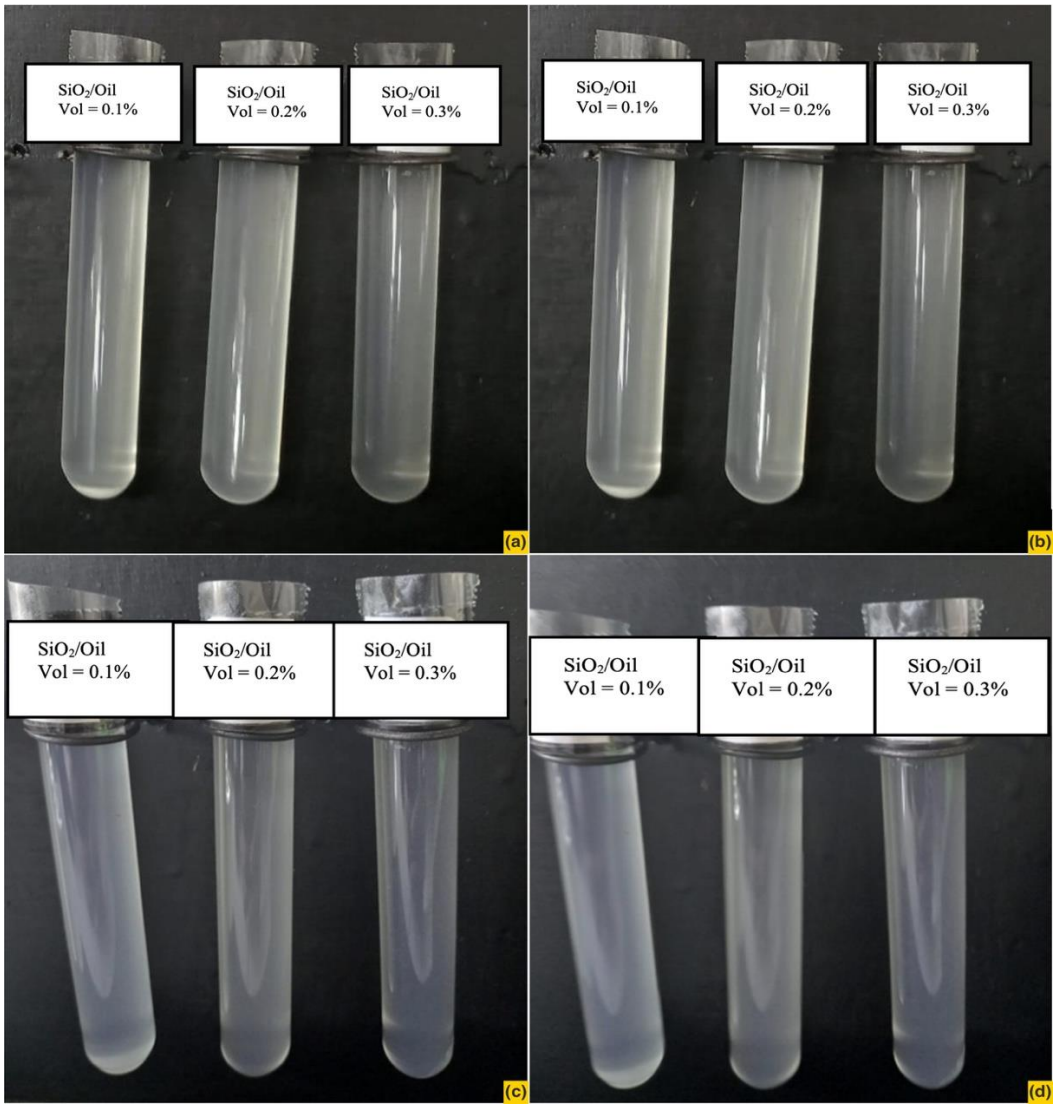


Figure 10. Sedimentation observation of SiO_2 nanolubricant or SiO_2/oil: (a) 0 day; (b) 7 days; (c) 14 days; (d) 30 days

3.3. Thermal Conductivity Enhancement

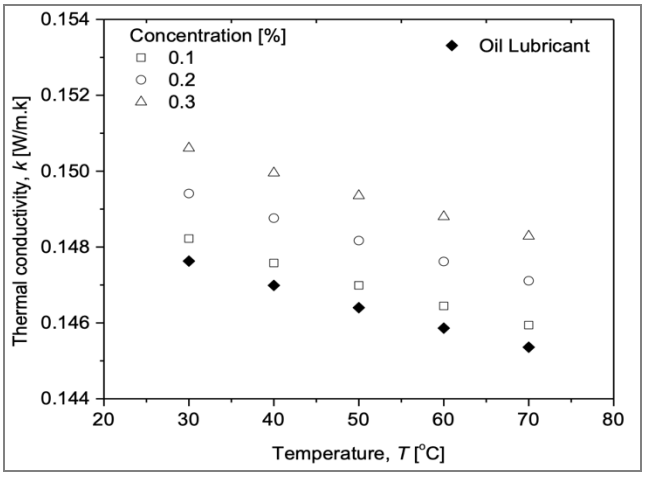


Figure 11. Thermal conductivity of SiO_2 nanolubricant at different concentrations

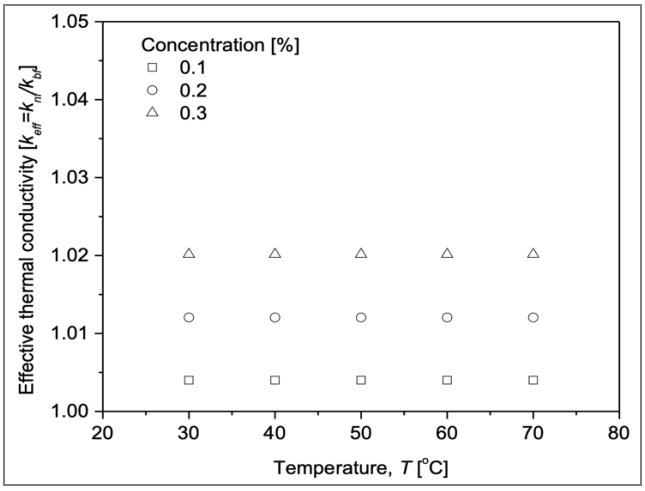


Figure 12. Relative thermal conductivity enhancement of SiO_2 nanolubricant at different concentrations

The thermal conductivity of SiO_2 nanolubricants was evaluated using the transient hot wire technique, with the results presented in **Figure 11** and **Figure 12**, showing enhanced performance compared to the base lubricant. An evident upward trend was observed as nanoparticle concentration increased. At 0.1% vol., thermal conductivity improved by about 1.004 times, while concentrations of 0.2% vol. and 0.3% vol. yielded increases of 1.012 and nearly 1.02 times, respectively. These findings are consistent with earlier studies, which reported that even small additions of nanoparticles could significantly enhance the thermal transport properties of base fluids [35], [40]. The observed improvement is attributed to the high thermal conductivity of SiO_2 nanoparticles, the development of percolation networks, and the Brownian motion of nanoparticles that promotes microconvection [12], [32], [41], [42].

3.4. Comparative Literature

Figure 13 illustrates a comparison between the current study on SiO_2/Oil nanolubricants at a 0.3% volume concentration and the work of [42] using SiO_2/PAG at 0.5%. Both studies revealed a similar trend of decreasing thermal conductivity with rising temperature. However, the thermal conductivity of the SiO_2/Oil nanolubricant (green nanolubricant) was higher than that of SiO_2/PAG at 30 and 80 °C. This indicates that green nanolubricants prepared in powder form offer superior thermal conductivity performance, consistent with findings from previous research [27]. The results confirm that SiO_2 nanoparticles can act as effective, eco-friendly lubricant additives. Compared with other nanofluids, such as carbon nanotubes [32], [43] or metal oxide-based fluids [41], [44], [45], SiO_2 offers advantages in environmental compatibility and stability. Additionally, the abundance and low cost of silica make it promising for large-scale applications. The findings further suggest that concentrations between 0.1-0.3% vol. strike an optimal balance between stability and thermal conductivity enhancement, as excessive nanoparticle loading may raise viscosity and negatively affect flow behavior and pumping power [46], [47], [48], [49].

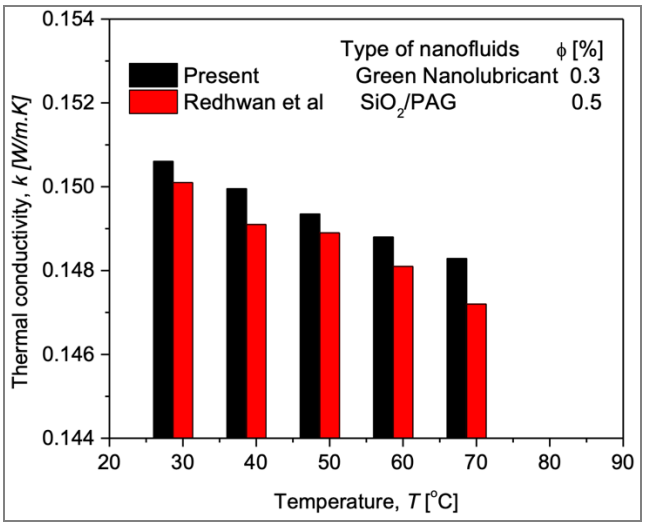


Figure 13. Comparative thermal conductivity of SiO_2 nanolubricant with literature

4. Conclusions

This research experimentally examined the stability and thermal conductivity of SiO_2 nanoparticles dispersed in R600a oil lubricant as a green nanolubricant (SiO_2/Oil). The main outcomes can be summarized as follows: UV-Vis absorbance analysis indicated that the nanolubricants maintained stability for up to 30 days with negligible sedimentation. Zeta potential analysis yielded a value of 41.2 mV, thereby confirming strong electrostatic stability. Visual inspection supported these results, revealing no significant agglomeration or sedimentation of particles over a 21-day period. Thermal conductivity was enhanced with increasing nanoparticle concentration, showing improvements of 1.004, 1.012, and 1.02 times at 0.1%, 0.2%, and 0.3% volume fractions, respectively. This improvement is linked to the inherent conductivity of SiO_2 nanoparticles, the influence of Brownian motion, and the resulting micro-convection. In summary, SiO_2 nanoparticles prove to be effective eco-friendly additives for nanolubricant development, enhancing both thermal transport characteristics and suspension stability. These findings emphasize the potential of green nanolubricants for use in thermal management and refrigeration systems, supporting energy efficiency and sustainable engineering practices.

Acknowledgements

The authors would like to thank the Department of Mechanical Engineering, Faculty of Engineering, Institute for Research and Community Services, Universitas Muhammadiyah Jakarta, LLDIKTI Region III, Ministry of Higher Education, Science and Technology of the Republic of Indonesia for funding and supported implementation grant of Fundamental Reguler on year 2025 with contract number: 124/C3/DT.05.00/PL/2025.

Authors' Declaration

Authors' contributions and responsibilities – The authors made substantial contributions to the study's conception and design. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

Funding – No funding information from the authors.

Availability of data and materials – All data is available from the authors.

Competing interests – The authors declare no competing interests.

Additional information – No additional information from the authors.

References

[1] S. U. S. Choi and J. A. Eastman, "Enhancing thermal conductivity of fluids with nanoparticles," in *ASME International Mechanical Engineering Congress & Exposition*, 1995.

[2] Y. Hwang *et al.*, "Stability and thermal conductivity characteristics of nanofluids," *Thermochimica Acta*, vol. 455, no. 1–2, pp. 70–74, Apr. 2007, doi: 10.1016/j.tca.2006.11.036.

[3] S. Akl, S. Elsoudy, A. A. Abdel-Rehim, S. Salem, and M. Ellis, "Recent Advances in Preparation and Testing Methods of Engine-Based Nanolubricants: A State-of-the-Art Review," *Lubricants*, vol. 9, no. 9, p. 85, Aug. 2021, doi: 10.3390/lubricants9090085.

[4] A. Kotia, P. Rajkhowa, G. S. Rao, and S. K. Ghosh, "Thermophysical and tribological properties of nanolubricants: A review," *Heat and Mass Transfer*, vol. 54, no. 11, pp. 3493–3508, Nov. 2018, doi: 10.1007/s00231-018-2351-1.

[5] Safril, W. H. Azmi, N. N. M. Zawawi, and A. I. Ramadhan, "Tribology Performance of TiO2-SiO2/PVE Nanolubricant at Various Binary Ratios for the Automotive Air-conditioning System," *Automotive Experiences*, vol. 6, no. 3, pp. 485–496, 2023, doi: 10.31603/ae.10255.

[6] A. Ghadimi, R. Saidur, and H. S. C. Metselaar, "A review of nanofluid stability properties and characterization in stationary conditions," *International Journal of Heat and Mass Transfer*, vol. 54, no. 17–18, pp. 4051–4068, Aug. 2011, doi: 10.1016/j.ijheatmasstransfer.2011.04.014.

[7] J. A. Eastman, S. U. S. Choi, S. Li, W. Yu, and L. J. Thompson, "Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles,"

Applied Physics Letters, vol. 78, no. 6, pp. 718–720, Feb. 2001, doi: 10.1063/1.1341218.

[8] N. A. Che Sidik, M. N. A. Witri Mohd Yazid, and R. Mamat, "Recent advancement of nanofluids in engine cooling system," *Renewable and Sustainable Energy Reviews*, vol. 75, pp. 137–144, Aug. 2017, doi: 10.1016/j.rser.2016.10.057.

[9] L. S. Sundar, M. K. Singh, V. Punnaiah, and A. C. M. Sousa, "Experimental investigation of Al2O3/water nanofluids on the effectiveness of solar flat-plate collectors with and without twisted tape inserts," *Renewable Energy*, vol. 119, pp. 820–833, Apr. 2018, doi: 10.1016/j.renene.2017.10.056.

[10] N. Hamzan *et al.*, "The SiO2:TiO2 hybrid biodegradable nanolubricant for sustainable machining: The stability, thermo-physical and tribology perspectives," *Tribology International*, vol. 207, p. 110614, Jul. 2025, doi: 10.1016/j.triboint.2025.110614.

[11] A. I. Ramadhan, W. H. Azmi, R. Mamat, K. A. Hamid, and S. Norsakinah, "Investigation on stability of tri -hybrid nanofluids in water-ethylene glycol mixture," *IOP Conference Series: Materials Science and Engineering*, vol. 469, p. 012068, Jan. 2019, doi: 10.1088/1757-899X/469/1/012068.

[12] A. I. Ramadhan, E. Diniardi, H. Basri, D. Almanda, and W. H. Azmi, "Experimental investigation of thermal conductivity of Al2O3-TiO2-SiO2 nanofluids in EG/water mixture for automotive radiator cooling system," in *3rd Borobudur International Symposium*, 2023, p. 020007. doi: 10.1063/5.0120209.

[13] Anwar Ilmar Ramadhan *et al.*, "Characterization and Stability of ZrO2-SiO2 Nanofluids from Local Minerals Indonesia as Green Nanofluids to Application Radiator Cooling System," *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, vol. 111, no. 2, pp. 126–140, Jan. 2024, doi: 10.37934/arfmts.111.2.126140.

[14] M. A. Fikri, W. M. Faizal, H. K. Adli, Z. Bo, X. X. Jiang, and A. I. Ramadhan, "Investigation on stability of TiO 2 -SiO 2 nanofluids with ratio (70:30) in W/EG mixture (60:40)," *IOP Conference Series: Materials Science and Engineering*, vol. 1062, no. 1, p. 012020, Feb. 2021, doi: 10.1088/1757-899X/1062/1/012020.

[15] A. I. Ramadhan, W. H. Azmi, R. Mamat, and K. A. Hamid, "Experimental and numerical study of heat transfer and friction factor of plain tube with hybrid nanofluids," *Case Studies in Thermal Engineering*, vol. 22, p. 100782, Dec. 2020, doi: 10.1016/j.csite.2020.100782.

[16] M. K. Navada *et al.*, "Sol–gel-assisted synthesis of ultra-fine porous SiO2 nanoparticles for investigation of lubricity and rheological properties of eco-friendly bio-lubricant oil," *Chemical Papers*, vol. 78, no. 4, pp. 2437–2450, Feb. 2024, doi: 10.1007/s11696-023-03250-z.

[17] R. S. Kumar and T. Sharma, "Stability and rheological properties of nanofluids stabilized by SiO2 nanoparticles and SiO2-TiO2 nanocomposites for oilfield applications," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 539, pp. 171–183, Feb. 2018, doi: 10.1016/j.colsurfa.2017.12.028.

[18] X. Liu *et al.*, "Hydrothermal Synthesis of Cellulose Nanocrystal-Grafted-Acrylic Acid Aerogels with Superabsorbent Properties," *Polymers*, vol. 10, no. 10, p. 1168, Oct. 2018, doi: 10.3390/polym10101168.

[19] G. Yıldız, Ü. Ağbulut, and A. E. Gürel, "A review of stability, thermophysical properties and impact of using nanofluids on the performance of refrigeration systems," *International Journal of Refrigeration*, vol. 129, pp. 342–364, Sep. 2021, doi: 10.1016/j.ijrefrig.2021.05.016.

[20] R. Agarwal, K. Verma, N. K. Agrawal, R. K. Duchaniya, and R. Singh, "Synthesis, characterization, thermal conductivity and sensitivity of CuO nanofluids," *Applied Thermal Engineering*, vol. 102, pp. 1024–1036, Jun. 2016, doi: 10.1016/j.applthermaleng.2016.04.051.

[21] S. M. T. Al-Abboodi, E. J. A. Al-Shaibani, and E. A. Alrubai, "Preparation and Characterization of Nano silica Prepared by Different Precipitation Methods," *IOP Conference Series: Materials Science and Engineering*, vol. 978, no. 1, p. 012031, Nov. 2020, doi: 10.1088/1757-899X/978/1/012031.

[22] I. Risnasari, E. Herawati, Yunasfi, S. D. Pandiangan, and P. Adelina, "Preparation and characterization of nanocrystalline cellulose using ultrasonic assisted autohydrolysis," *IOP Conference Series: Earth and Environmental Science*, vol. 374, no. 1, p. 012008, Nov. 2019, doi: 10.1088/1755-1315/374/1/012008.

[23] K. A. Hamid, W. H. Azmi, M. F. Nabil, R. Mamat, and K. V. Sharma, "Experimental investigation

of thermal conductivity and dynamic viscosity on nanoparticle mixture ratios of TiO2-SiO2 nanofluids," *International Journal of Heat and Mass Transfer*, vol. 116, pp. 1143–1152, Jan. 2018, doi: 10.1016/j.ijheatmasstransfer.2017.09.087.

[24] J. L. T. Chen, A. N. Oumer, and A. A. A., "A review on thermo-physical properties of bio, non-bio and hybrid nanofluids," *Journal of Mechanical Engineering and Sciences*, vol. 13, no. 4, pp. 5875–5904, Dec. 2019, doi: 10.15282/jmes.13.4.2019.12.0468.

[25] R. Choudhary, D. Khurana, A. Kumar, and S. Subudhi, "Stability analysis of Al 2 O 3 /water nanofluids," *Journal of Experimental Nanoscience*, vol. 12, no. 1, pp. 140–151, Jan. 2017, doi: 10.1080/17458080.2017.1285445.

[26] R. Ranjbarzadeh and R. Chaabane, "Experimental Study of Thermal Properties and Dynamic Viscosity of Graphene Oxide/Oil Nano-Lubricant," *Energies*, vol. 14, no. 10, p. 2886, May 2021, doi: 10.3390/en14102886.

[27] N. N. M. Zawawi, W. H. Azmi, M. Z. Sharif, and G. Najafi, "Experimental investigation on stability and thermo-physical properties of Al2O3–SiO2/PAG nanolubricants with different nanoparticle ratios," *Journal of Thermal Analysis and Calorimetry*, vol. 135, no. 2, pp. 1243–1255, Jan. 2019, doi: 10.1007/s10973-018-7670-4.

[28] I. A. Rahman and V. Padavettan, "Synthesis of Silica Nanoparticles by Sol-Gel: Size-Dependent Properties, Surface Modification, and Applications in Silica-Polymer Nanocomposites—A Review," *Journal of Nanomaterials*, vol. 2012, no. 1, Jan. 2012, doi: 10.1155/2012/132424.

[29] H. Adun *et al.*, "Synthesis and Application of Ternary Nanofluid for Photovoltaic-Thermal System: Comparative Analysis of Energy and Exergy Performance with Single and Hybrid Nanofluids," *Energies*, vol. 14, no. 15, p. 4434, Jul. 2021, doi: 10.3390/en14154434.

[30] M. F. Anuar, Y. W. Fen, M. H. M. Zaid, K. A. Matori, and R. E. M. Khaidir, "Synthesis and structural properties of coconut husk as potential silica source," *Results in Physics*, vol. 11, pp. 1–4, Dec. 2018, doi: 10.1016/j.rinp.2018.08.018.

[31] F. C. Dirna, I. Rahayu, A. Maddu, W. Darmawan, D. Nandika, and E. Prihatini, "Nanosilica Synthesis from Betung Bamboo Sticks and Leaves by Ultrasonication," *Nanotechnology, Science and Applications*, vol. Volume 13, pp. 131–136, Dec. 2020, doi: 10.2147/NSA.S282357.

[32] S. M. Abbasi, A. Rashidi, A. Nemati, and K. Arzani, "The effect of functionalisation method on the stability and the thermal conductivity of nanofluid hybrids of carbon nanotubes/gamma alumina," *Ceramics International*, vol. 39, no. 4, pp. 3885–3891, May 2013, doi: 10.1016/j.ceramint.2012.10.232.

[33] H. Adun, D. Kavaz, and M. Dagbasi, "Review of ternary hybrid nanofluid: Synthesis, stability, thermophysical properties, heat transfer applications, and environmental effects," *Journal of Cleaner Production*, vol. 328, p. 129525, Dec. 2021, doi: 10.1016/j.jclepro.2021.129525.

[34] A. R. I. Ali and B. Salam, "A review on nanofluid: preparation, stability, thermophysical properties, heat transfer characteristics and application," *SN Applied Sciences*, vol. 2, no. 10, p. 1636, Oct. 2020, doi: 10.1007/s42452-020-03427-1.

[35] A. I. Ramadhan, W. H. Azmi, and R. Mamat, "Stability and Thermal Conductivity of Tri-hybrid Nanofluids for High Concentration in Water-ethylene Glycol (60:40)," *Nanoscience & Nanotechnology-Asia*, vol. 11, no. 4, Aug. 2021, doi: 10.2174/2210681210999200806153039.

[36] A. Sharma, T. Mandal, and S. Goswami, "Dispersibility and Stability Studies of Cellulose Nanofibers: Implications for Nanocomposite Preparation," *Journal of Polymers and the Environment*, vol. 29, no. 5, pp. 1516–1525, May 2021, doi: 10.1007/s10924-020-01974-7.

[37] I. M. Mahbubul, R. Saidur, M. A. Amalina, E. B. Elcioglu, and T. Okutucu-Ozyurt, "Effective ultrasonication process for better colloidal dispersion of nanofluid," *Ultrasonics Sonochemistry*, vol. 26, pp. 361–369, Sep. 2015, doi: 10.1016/j.ultsonch.2015.01.005.

[38] M. F. Ismail, W. H. Azmi, R. Mamat, K. V. Sharma, and N. N. M. Zawawi, "Stability Assessment of Polyvinyl-Ether-Based TiO2, SiO2, and Their Hybrid Nanolubricants," *Lubricants*, vol. 11, no. 1, p. 23, Jan. 2023, doi: 10.3390/lubricants11010023.

[39] S. Habibzadeh, A. Kazemi-Beydokhti, A. A. Khodadadi, Y. Mortazavi, S. Omanovic, and M. Shariat-Niassar, "Stability and thermal conductivity of nanofluids of tin dioxide synthesized via microwave-induced combustion route," *Chemical Engineering Journal*, vol. 156, no. 2, pp. 471–478, Jan. 2010, doi: 10.1016/j.cej.2009.11.007.

[40] S. N. M. Zainon and W. H. Azmi, “Stability and thermo-physical properties of green bio-glycol based TiO2-SiO2 nanofluids,” *International Communications in Heat and Mass Transfer*, vol. 126, p. 105402, Jul. 2021, doi: 10.1016/j.icheatmasstransfer.2021.105402.

[41] A. Boroomandpour, D. Toghraie, and M. Hashemian, “A comprehensive experimental investigation of thermal conductivity of a ternary hybrid nanofluid containing MWCNTs-titania-zinc oxide/water-ethylene glycol (80:20) as well as binary and mono nanofluids,” *Synthetic Metals*, vol. 268, p. 116501, Oct. 2020, doi: 10.1016/j.synthmet.2020.116501.

[42] A. A. M. Redhwan, W. H. Azmi, M. Z. Sharif, and N. N. M. Zawawi, “Thermal conductivity enhancement of Al 2 O 3 and SiO 2 nanolubricants for application in automotive air conditioning (AAC) system,” *MATEC Web of Conferences*, vol. 90, p. 01051, Dec. 2017, doi: 10.1051/matecconf/20179001051.

[43] T. T. Baby and S. Ramaprabhu, “Experimental investigation of the thermal transport properties of a carbon nanohybrid dispersed nanofluid,” *Nanoscale*, vol. 3, no. 5, p. 2208, 2011, doi: 10.1039/c0nr01024c.

[44] K. . Wickramasinghe, H. Sasahara, E. A. Rahim, and G. I. P. Perera, “Green Metalworking Fluids for sustainable machining applications: A review,” *Journal of Cleaner Production*, vol. 257, p. 120552, Jun. 2020, doi: 10.1016/j.jclepro.2020.120552.

[45] S. M. Wong, M. Z. A. Zulkifli, D. Nordin, and Y. H. Teow, “Synthesis of Cellulose/Nano-hydroxyapatite Composite Hydrogel Absorbent for Removal of Heavy Metal Ions from Palm Oil Mill Effluents,” *Journal of Polymers and the Environment*, vol. 29, no. 12, pp. 4106–4119, Dec. 2021, doi: 10.1007/s10924-021-02183-6.

[46] M. Asadi and A. Asadi, “Dynamic viscosity of MWCNT/ZnO–engine oil hybrid nanofluid: An experimental investigation and new correlation in different temperatures and solid concentrations,” *International Communications in Heat and Mass Transfer*, vol. 76, pp. 41–45, Aug. 2016, doi: 10.1016/j.icheatmasstransfer.2016.05.019.

[47] I. Kazemi, M. Sefid, and M. Afrand, “A novel comparative experimental study on rheological behavior of mono & hybrid nanofluids concerned graphene and silica nano-powders: Characterization, stability and viscosity measurements,” *Powder Technology*, vol. 366, pp. 216–229, Apr. 2020, doi: 10.1016/j.powtec.2020.02.010.

[48] A. I. Ramadhan and W. H. Azmi, “The effect of nanoparticles composition ratio on dynamic viscosity of Al2O3-TiO2-SiO2 nanofluids,” *Materials Today: Proceedings*, vol. 48, pp. 1920–1923, 2022, doi: 10.1016/j.matpr.2021.09.450.

[49] R. R. Sahoo and V. Kumar, “Development of a new correlation to determine the viscosity of ternary hybrid nanofluid,” *International Communications in Heat and Mass Transfer*, vol. 111, p. 104451, Feb. 2020, doi: 10.1016/j.icheatmasstransfer.2019.104451.