SCHOLAR PUBLISHING
International Journal of Science & Advanced Technology
ISSN: 3083-9335
Journal homepage: https://e-journal.scholar-publishing.org/index.php/ijsat

Thermo-Physical Performance and Dispersion Stability of Cellulose Nanocrystal (CNC) Bio-Nano additives in SAE40 Engine Oil

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Abstract
The performance of conventional SAE 40 engine oil is limited by poor thermal conductivity and viscosity instability at elevated operating temperatures. This study investigates the feasibility of using sustainable cellulose nanocrystals (CNC) as a bio-based nano-additive to enhance the thermo-physical performance and dispersion stability of SAE 40 engine oil. CNC-based nanolubricants were prepared using a two-step dispersion method at volume concentrations ranging from 0.1% to 0.9%. Thermal conductivity, viscosity behaviour, viscosity index (VI), UV–Vis absorbance stability, and long-term sedimentation characteristics were systematically evaluated. The results indicate that thermal conductivity increased with CNC concentration, with the highest enhancement achieved at 0.9 vol%. In contrast, viscometric analysis revealed that a low CNC loading of 0.1 vol% produced the highest viscosity index of 155.32, representing an improvement of approximately 2.5% compared to base SAE 40 oil. UV–Vis and visual stability analyses confirmed that CNC dispersions remained stable for up to 60 days, with acceptable sedimentation behaviour observed at higher concentrations. Overall, the findings demonstrate a trade-off between thermal enhancement and viscosity stability, with 0.7 vol% CNC being optimal for thermal performance, while 0.1 vol% provides the most balanced overall lubricant performance. These results highlight the potential of CNC as a sustainable alternative nano-additive for environmentally responsible engine oil formulation.

Article Info	Keywords
Received: 15 December	Cellulose nanocrystals
Revised: 05 February	Nanolubricant
Accepted: 10 February	Dispersion Stability
Available online: 15 February	Sustainable additives
	Thermo-Physical

1. Introduction

Lubrication is a fundamental element in ensuring the efficiency, reliability, and durability of mechanical systems, particularly in internal combustion engines (ICEs). Although its primary role is to reduce friction and wear by forming a protective oil film, the function of a lubricant has expanded to include effective thermal management (Kumar et al., 2023). Modern engines operate at higher speeds and temperatures, increasing thermal stress on the oil and requiring a lubricant that efficiently dissipates heat without compromising viscosity stability (Tahir et al., 2024).

The ability of a lubricant to function effectively under extreme temperatures is primarily determined by its thermophysical and viscometric properties. High thermal conductivity and specific heat are essential for transferring and absorbing the heat generated by friction. At the same time, viscosity, measured at operating temperatures (40°C and 100°C), must be maintained to ensure adequate protective film thickness. An important property that unites both aspects is the Viscosity Index (VI), which measures the stability of oil viscosity against temperature changes; a higher VI is desirable because it indicates minimal viscosity change across a wide temperature range, ensuring easy engine starting in winter and stable protection at high temperatures (Vasishth et al., 2024).

Conventional engine oils, particularly SAE 40 grade, are typically formulated using mineral or semi-synthetic base oils, which naturally have low thermal conductivity. This limitation leads to inefficient heat transfer, which can cause local hot spots, accelerate oil film failure, and degrade tribological properties (Tahir et al., 2024). To overcome this weakness, the lubrication system requires high-performance additives that can improve thermal and viscometric properties without introducing toxicity issues or long-term instability.

As a result, researchers have increasingly explored the incorporation of nanoparticles to enhance the thermo-physical and tribological properties of lubricants. Nano-additives have demonstrated promising capabilities to improve heat transfer, stabilise lubricant films, and reduce mechanical losses, positioning them as an effective solution to enhance lubricant performance (Hassan & Xu, 2022; Galpaya et al., 2025). The introduction of nanoparticles has shown promise in improving oil performance, but most published work focuses on metal oxides, carbon-based materials, or hexagonal boron nitride (Alazemi et al., 2022; Sundar et al., 2023). These nanoparticles often pose challenges, including sedimentation, poor dispersibility, and environmental toxicity. Table 1 shows that while various nanoparticles demonstrate promising enhancement potential, issues related to stability, cost, and environmental impact remain unresolved. Notably, the use of cellulose nanocrystals in petroleum-based engine oils, such as SAE 40, remains limited, highlighting a clear research gap. Although these materials offer strong enhancement potential, they also present drawbacks—graphene and CNTs are costly and difficult to stabilise, while metal oxides may agglomerate or exhibit abrasive behaviour under high load (Sivaranjani et al., 2022; Alazemi et al., 2022). CNC has emerged as a sustainable alternative that mitigates many of these issues, but its behaviour in hydrophobic lubricant systems remains underexplored.

Table 1. Summary of selected studies on nanoparticle-enhanced lubricants

Nanoparticle Type	Base Oil	Key Findings	Limitation Identified	Reference
Al_2O_3	SAE40	Improved thermal conductivity and wear resistance	Agglomeration at higher loading	Rashidi et al. (2023)
TiO_2	Engine oil	Enhanced viscosity stability	Long-term stability not assessed	Alazemi et al. (2022)
CNT	Mineral oil	Significant heat-transfer enhancement	High cost and dispersion difficulty	Sivaranjani et al. (2022)
Graphene	Synthetic oil	Superior thermal performance	Environmental and toxicity concerns	Khorasani et al. (2021)
CNC	Bio-based oil	Improved thermal behaviour and eco-friendly	Limited application to engine oil	Ahmed et al. (2023b)

The increasing demand for energy-efficient and environmentally sustainable lubrication systems has prompted researchers to investigate novel additives that enhance the thermal and rheological properties of engine oils. Conventional additives, often petroleum- or synthetic-based, enhance these properties but raise environmental concerns due to toxicity and other issues, such as non-biodegradability. Among various nanoparticles explored, Cellulose Nanocrystals (CNC) have gained attention as a sustainable, biodegradable, and non-toxic alternative compared to metallic or metal-oxide nanoparticles. CNCs are derived from natural cellulose through acid hydrolysis and exhibit high crystallinity, rod-like morphology, large surface area, and excellent mechanical properties (Amini et al., 2024). These properties make CNC suitable for improving lubricant performance without introducing environmental or health risks. Their renewable origin and compatibility with green manufacturing practices make them particularly appealing as next-generation bio-nanoadditives, and their potential in lubrication has begun to be explored, especially as anti-friction and anti-wear agents (Awang, 2019).

Furthermore, Cellulose Nanocrystals (CNC) offer a compelling and sustainable alternative as a bio-nano additive due to their low toxicity and renewable nature. The potential of CNC to enhance thermal performance has been demonstrated in nanofluid studies, where they can form efficient, structured heat pathways (Li et al., 2020). However, the interaction of CNC with non-polar engine oils poses a significant challenge. CNCs are inherently hydrophilic (water-loving) and consequently incompatible with the hydrophobic oil matrix. This fundamental chemical incompatibility creates uncertainty regarding their long-term dispersion stability and functional contribution within petroleum-based engine oil formulations.

The long-term stability of the dispersion remains one of the most critical challenges in nanolubricant research. Sedimentation, aggregation, and agglomeration can rapidly diminish the benefits of the nanoparticles, particularly in hydrophobic oils where surface chemistry plays a pivotal role in preventing agglomeration (Sharma et al., 2022). CNC-based nanofluids typically show strong stability in water and glycol systems, but their oil stability is considerably less predictable. Moreover, while recent work on CNC in bio-based oils has shown moderate stability, most reported studies assess only short-term behaviour (often less than 7–14 days) and do not encompass standard internal combustion engine oil systems (Ahmed et al., 2023). This limitation is crucial because the requirements of engine lubrication heavily depend on the oil's ability to maintain stable additive dispersion, dissipate heat, and sustain its viscosity under varying temperatures throughout its service life. To provide an overview of existing research and highlight current limitations, Table 2 summarises selected studies on CNC-based nanofluids and nanolubricants, including key findings and identified research gaps.

Table 2. Summary of previous studies on cellulose nanocrystal (CNC)-based nanofluids and nanolubricants

Author (Year)	Base Fluid	Key Findings	Limitation Highlighted
Kargar et al. (2021)	Water	CNC increased thermal conductivity and stability	Not applicable to hydrophobic oils
Khalid et al. (2021)	Ethylene glycol	Enhanced heat-transfer & rheological behaviour	Short observation duration
Ahmed et al. (2023a)	Bio-based oil	Moderate thermal improvement with CNC	No long-term stability study
Li et al. (2020)	Multiple	Review of CNC potential	No engine oil application
Habibi (2020)	Water/glycol	Good mobility & dispersion	Needs surfactant in oils

Research on CNC as a lubricant additive has shown encouraging results. CNC dispersion into a polyalphaolefin (PAO) base oil has been shown to significantly reduce friction and wear by improving dispersion stability and protective film formation at contact surfaces (Wang et al., 2020). Similarly, CNC-modified lithium grease demonstrated notable reductions in frictional losses and wear depth, highlighting the material's potential versatility across different lubrication media (Zhao et al., 2022). These findings suggest that CNC can enhance surface protection under sliding conditions. Beyond tribology, CNC has also been recognised for its ability to enhance thermal conductivity, as seen in CNC-based nanofluids, where improved heat transfer performance was reported with increasing CNC concentration (Nguyen et al., 2024). Increased thermal conductivity is particularly beneficial for engine oils, as it reduces hotspots, improves thermal balance, and enhances lubrication reliability during high-temperature operation.

Nanoparticle dispersion stability remains a critical challenge in nanolubricant research. Agglomeration or sedimentation can lead to non-uniform properties, clogged channels, reduced thermal efficiency, and inconsistent tribological performance. Research shows that CNC dispersions generally exhibit good colloidal stability due to surface functional groups that prevent strong particle–particle attraction (Amini et al., 2024). However, stability performance varies across different base oils, and long-term behaviour in high-viscosity oils such as SAE40 remains insufficiently explored.

Although CNC offers a sustainable solution, the existing literature lacks reliable, systematic data on its impact on the thermophysical and viscometric properties of engine oils, particularly the widely used SAE 40 grade oils. While several studies have addressed tribological aspects (Hisham et al., 2024; Alotaibi et al., 2025), comprehensive assessments of how changes in CNC volume concentration correlate with increased thermal conductivity and, most importantly, how they affect Viscosity Index (VI)—a determinant of temperature stability—are limited. In addition, detailed studies on the long-term dispersion stability of CNC in non-polar oils without the use of aggressive chemical stabilising agents are needed (Indarti et al., 2025). Therefore, the problem this study addresses is the urgent need to formulate lubricants with superior thermal and viscometric performance that comply with sustainability standards. Existing SAE 40 oils are not sufficient for optimal heat transfer. Although CNC offers environmentally friendly additives, the optimal concentration that provides maximum thermal enhancement while ensuring long-term dispersion stability and Viscosity Index improvement has yet to be empirically determined. This study is essential for determining the optimal formulation concentration for CNC/SAE 40 nanolubricants.

Although extensive studies have reported the use of inorganic and carbon-based nanoparticles to enhance engine oil performance, systematic investigations on the thermo-physical, viscometric, and long-term dispersion stability of cellulose nanocrystals in conventional mineral-based SAE 40 engine oil remain limited. This study addresses this gap by experimentally determining the optimal CNC concentration that balances thermal conductivity enhancement, viscosity index improvement, and dispersion stability without the use of chemical surfactants.

2. Methodology

2.1 Materials

The base lubricant used in this study was commercial SAE40 engine oil, selected for its widespread use in automotive and industrial applications. Cellulose nanocrystals (CNCs) were prepared as powders before dispersion. The CNCs were initially obtained in gel form and converted to dry powder by spray drying, followed by gentle manual grinding to achieve a fine particulate form. The resulting CNC powder was characterised using transmission electron microscopy (TEM) to confirm that the particle dimensions were within the nanoscale range.

2.2 Preparation of CNC–SAE40 Nanolubricants

CNC–SAE40 nanolubricants were prepared using a two-step dispersion method to obtain a stable and homogeneous suspension. The selected CNC concentration range (0.1–0.9 vol%) was chosen to avoid excessive agglomeration while maintaining measurable thermo-physical enhancement, as reported in previous nanolubricant studies. The required nanoparticle loading was calculated using the standard volume fraction equation. The mixtures were initially subjected to magnetic stirring to promote uniform mixing, followed by ultrasonic bath sonication to enhance dispersion quality and minimise particle agglomeration. The combined stirring and sonication process effectively improved suspension stability, producing well-dispersed CNC-based nanolubricants.

2.3 Thermal Conductivity Measurement

The thermal conductivity of CNC–SAE40 engine oil was measured using a KD2 Pro thermal property analyser equipped with a KS-1 single-needle sensor, suitable for liquid measurements in the range of 0.02–2.00 W/m · K. The instrument operates by analysing the transient temperature response to an applied electrical signal and was calibrated using the supplier-provided glycerine standard before testing, yielding a measured value of 0.286 W/m·K at 25 °C, which closely matched the reference value within ±0.35% accuracy. Thermal conductivity measurements were conducted for all CNC volume concentrations over a temperature range of 30°C to 80 °C, with sample temperatures regulated using a laboratory water bath. Each sample was allowed to equilibrate to the target temperature before measurement, and average values were recorded to ensure consistent measurements.

2.4 Viscosity Characterisation

The kinematic viscosity of CNC-added SAE 40 engine oil was measured in accordance with ASTM D445 using a Cannon-Fenske Routine Viscometer and a Cole-Parmer Polystat constant-temperature bath at 40°C and 100°C. The viscometer was filled with the sample oil and placed in the temperature bath to stabilise at the desired temperature. The efflux time for the oil to flow through the viscometer was recorded, and the kinematic viscosity was calculated using the viscometer calibration constant and measured flow time. The viscosity index (VI) was then calculated based on the kinematic viscosity values at 40°C and 100°C using the ASTM D2270 standard.

2.5 UV–Vis Stability Analysis

The stability of CNC-added SAE 40 engine oil was evaluated using a UV-Vis spectrophotometer, which measures absorbance over 200-900 nm. Higher absorbance indicates better dispersion and stability of nanoparticles in the base oil. The test involved placing the nanolubricant samples in transparent quartz cuvettes and measuring their absorbance. The absorption of light through the CNC added engine oil was measured over a range of wavelengths. When directed to the sample
test, the absorbance of the light will show the presence of nanoparticles in the base oil. The Schematic diagram of the Ultraviolet-Visible Spectrophotometer is shown in Figure 1.

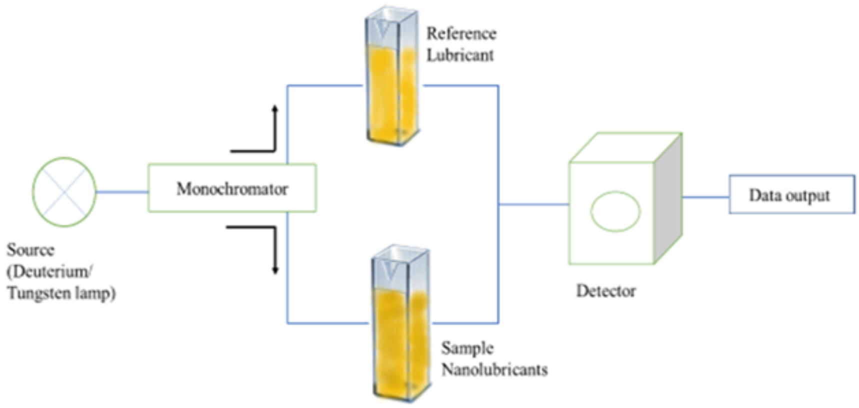

Figure 1. Schematic diagram of Ultraviolet-Visible Spectrophotometer

2.6 Visual Observation of Sedimentation

The dispersion characteristics of the CNC nanoparticles were evaluated using a visual inspection method in a test tube. Nanolubricants samples of the same volume were placed in test tubes at room temperature, without disturbance or movement (Azman et al., 2016). Then the images of sedimentation over time were captured on the first day of preparation. The image of the sedimentation behaviour, including the separation layer, was observed up to 60 days after preparation. Figure 2 illustrates the visual observation of the nanolubricants.

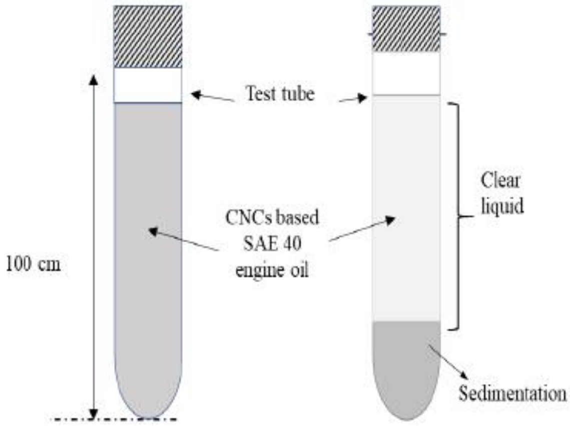

Figure 2: Illustration of visual observation of nanolubricants.

The dispersion stability of CNC–SAE40 nanolubricants was further evaluated through a scheduled observation approach, as summarised in Table 3.

Table 3. Stability Observation Schedule

Day	Analysis Performed
0	UV–Vis, visual
7	UV–Vis
14	Visual
30	UV–Vis, visual
60	Final check

The equipment used and key test parameters for all experimental measurements are summarised in Table 4.

Table 4. Equipment and Test Parameters

Test	Equipment	Parameters	Standard / Notes
Thermal Conductivity	Thermal Analyser (Transient Method)	Room temperature, 3 repetitions	Transient Hot-Wire Principle
Viscosity	Rotational Viscometer	30°C–120°C	ASTM D445
UV–Vis Absorbance	UV–Vis Spectrophotometer	2060–800 nm	Baseline corrected
Visual Stability	Glass Vials	0–60 days	Periodic observation

3. Result & Discussion

3.1 Thermal Conductivity Enhancement

The thermal conductivity of CNC added SAE 40 engine oil was studied at different volume concentrations (0.1%, 0.5%, and 0.9%) and temperatures ranging from 30°C to 90°C. The addition of cellulose nanocrystals (CNC) into SAE40 produced a noticeable improvement in thermal conductivity across all formulated samples. Although the magnitude of enhancement varied with concentration, the overall trend showed that CNC formed conductive pathways within the oil matrix, facilitating faster heat transfer than in the base oil. Results (Figure 4) showed that thermal conductivity increased with higher CNC volume concentration, with the highest value recorded at 0.147 W/m·K for 0.9% CNC at

30°C. This trend suggests that the presence of CNC enhances heat transfer efficiency by promoting effective energy transport within the base oil, particularly at intermediate concentrations. However, thermal conductivity decreased with increasing temperature due to reduced nanoparticle-nanoparticle collisions.

This indicates that CNC nanoparticles enhance the thermal conductivity of engine oil, thereby improving heat transfer. Similar findings were reported by Yang et al. (2019), who observed an increase in thermal conductivity with higher nanoparticle concentrations and lower temperatures. The thermal conductivity ratio, which compares the nanolubricant's thermal conductivity to the base oil, also increased with higher CNC concentrations. This is consistent with the findings of Sharif et al. (2016), who demonstrated that nanolubricants exhibit improved thermal conductivity due to the increased surface area of nanoparticles and their ability to form ordered molecular arrangements. This behaviour aligns with the commonly reported thermal-physical mechanisms of nanolubricants, in which phonon transport, microconvection, and particle–fluid interfacial interactions collectively enhance heat dissipation. The results therefore support the hypothesis that CNC can function as an effective thermal additive even in a hydrophobic base oil such as SAE40. However, beyond the optimal concentration, excessive CNC loading may increase particle–particle interactions, potentially affecting long-term dispersion stability.

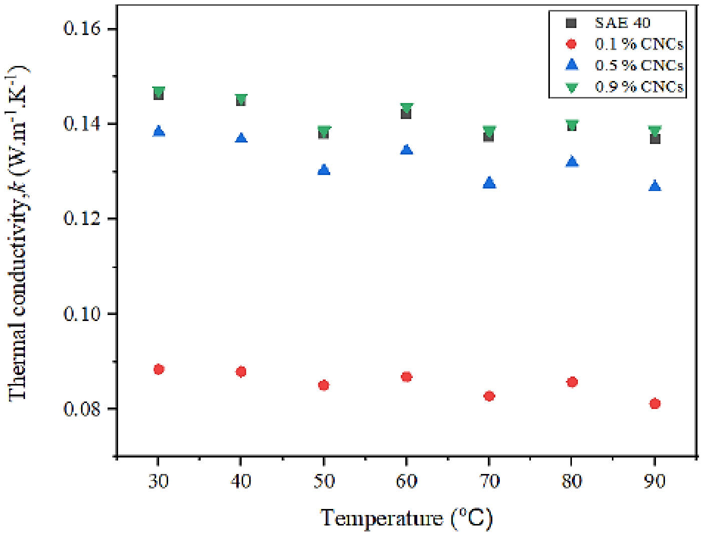

Figure 4. Thermal conductivity of CNC-added engine oil at various temperatures.

3.2 Viscosity-Temperature Behaviour

The observed decrease in viscosity with increasing temperature is associated with weakened intermolecular interactions, while the presence of CNC mitigates excessive viscosity loss by reinforcing the lubricant microstructure (Figure 5). This behaviour may be caused by a decrease in attractive intermolecular interactions, which enable suspended particles in nanofluids to move rapidly (Kotia et al., 2017). However, a notable difference emerged when comparing the base SAE40 oil and the CNC–SAE40 formulations. Samples infused with CNC exhibited better viscosity retention at elevated temperatures, suggesting that CNC contributed to structural reinforcement within the lubricant. The kinematic viscosity of CNC added SAE 40 engine oil at different concentrations was lower than that of SAE 40 engine oil. This is because when nanoparticles are added to the oil, they are placed between the oil layers, which makes it easier for the oil layers to move relative to one another. As a result, the viscosity will decrease slightly. Moreover, the rod-like morphology of CNC nanoparticles played a critical role in the rheological behaviour. The low viscosity reduction reduced viscous friction (Ali et al., 2016). As indicated in Figure 6, the viscosity index of a 0.1% concentration of CNC added SAE 40 engine oil rose by 2.6% when compared to the base oil. An increase in the viscosity index indicates a more stable kinematic viscosity with temperature changes, which improves resistance to thinning of the lubricant film and fuel economy in an automotive engine (Cabrera et al., 2019). This behaviour indicates that the incorporation of CNC does not disrupt the inherent viscosity–temperature relationship of SAE40 engine oil.

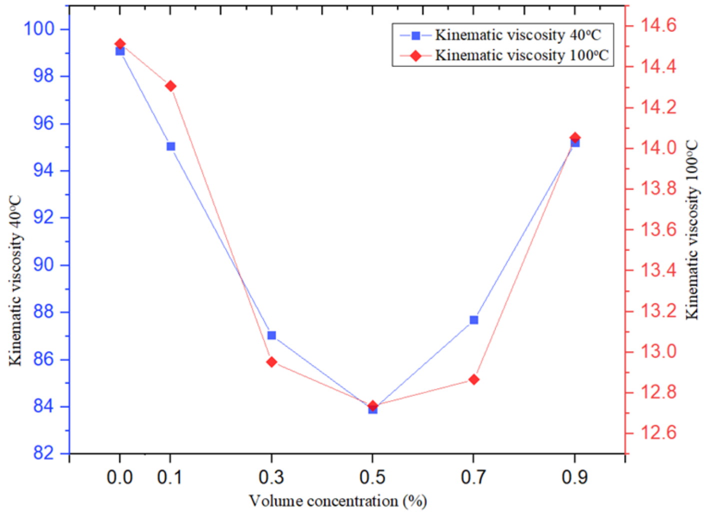

Figure 5. Kinematic viscosity (KV) of CNC added SAE 40 engine oil at 40°C and 100 °C

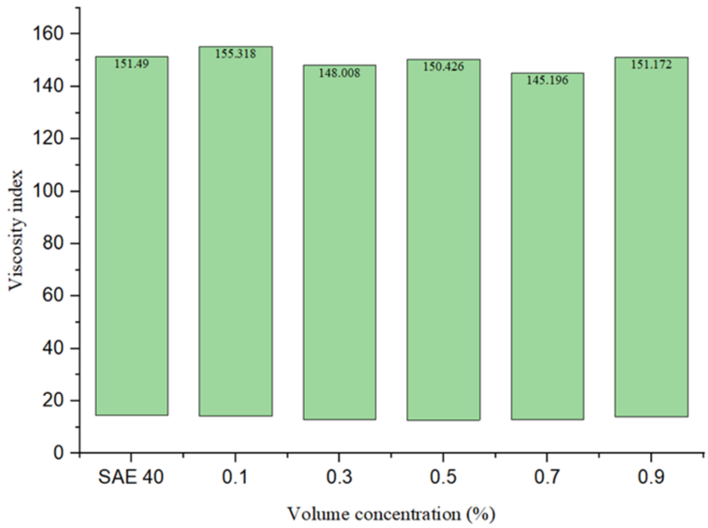

Figure 6. Viscosity index of CNC-added SAE 40 engine oil at different volume concentrations.

3.3 UV–Vis Absorbance Stability Assessment

A UV-vis spectrophotometer is one of the quantitative approaches to evaluate the stability of nanofluids. Investigating the spectral absorbance range is an effective way to assess nanofluid stability (Rajendhran et al., 2018). In this study, UV–Vis absorbance profiles provided insight into the dispersion stability of CNC in SAE40 over 60 days. Figure 7 shows the absorption spectra of the prepared sample measured directly after preparation. It was observed that the maximum absorbance peak of 0.7% CNC-added SAE 40 engine oil suspension appeared at 2.142 (403 nm). The higher absorbance observed at 0.7 vol% indicates a greater population of well-dispersed CNC particles, thereby enhancing thermal transport performance. All CNC–SAE40 samples exhibited an initial high absorbance, indicating successful dispersion and efficient light absorption by the suspended CNC particles.

Over time, gradual changes in absorbance were observed, reflecting partial sedimentation and agglomeration. Samples with lower CNC loading displayed relatively stable absorbance behaviour, whereas higher concentrations showed slightly greater variation, likely due to increased particle–particle interactions.

Although some decline in absorbance was observed across all formulations, overall stability remained within an acceptable range for extended storage, demonstrating that CNC can maintain reasonable dispersibility in hydrophobic oils despite its inherently hydrophilic nature. These findings position CNC as a viable nano-additive for applications requiring long-term lubricant stability.

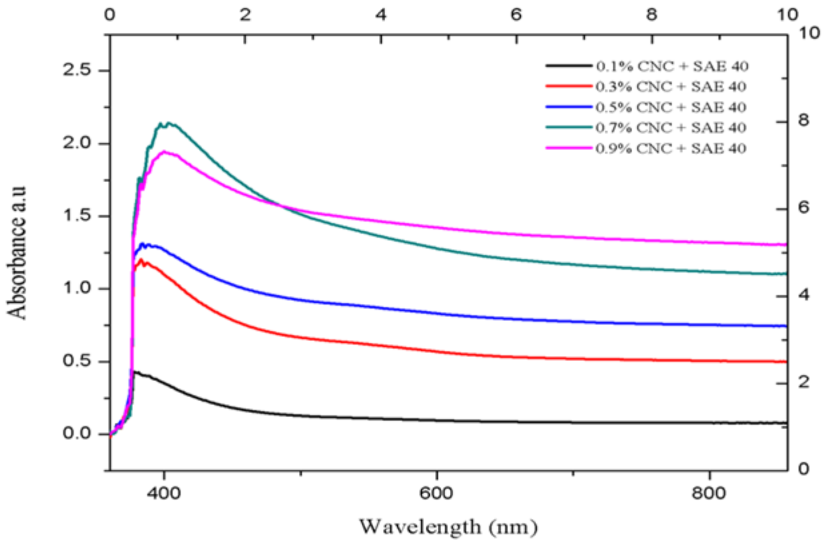

Figure 7. Peak absorbance value of CNC added SAE 40 engine oil

3.4 Visual Sedimentation Observation

The dispersion stability analysis is an essential stage before testing properties and performance. Stability measurement is an important step in reducing the possibility of nanoparticle agglomeration, which can cause damage to the sliding surfaces. The dispersion stability of CNC nanoparticles in engine oil is required for long-term stationary applications and consistent tribological results. Thus, the long-term stability of nanoparticle dispersion can be obtained by applying an appropriate method during nanofluid preparation. The photograph-capturing or sedimentation method is used to observe nanofluid samples. This technique is based on sediment formation at the bottom of the liquid column due to gravity (Ilie & Covaliu, 2016; Jiang et al., 2017; Maheswaran & Sunil, 2016). Visual inspection supported the UV–Vis findings and provided clear qualitative evidence of CNC stability behaviour. The samples were observed and recorded just after preparation, and at several hours, days, weeks, and months (Abdullah et al., 2018; Amiruddin et al., 2015; Li et al., 2016).

In the present study, visual observation was performed by capturing images within 60 days of observation to ensure that the CNC nanoparticles settled to the bottom of the test tube without disturbance. During the first several days, all samples remained uniformly dispersed with no visible settling, as shown in Figure 8(a). However, as shown in Figure 8(b), over time, minor sedimentation became apparent, particularly in samples with higher CNC concentration, where a thin layer of particles formed at the bottom of the vial. Nevertheless, the sedimentation rate remained slow, and no significant phase separation occurred throughout the 60-day observation period. The persistence of turbidity throughout storage suggests that CNC remained suspended in the oil, indicating satisfactory compatibility between CNC and the SAE40 matrix. These observations reaffirm CNC's potential as a sustainable nano-additive with adequate long-term stability for practical lubrication applications.

Across all performance indicators, including thermal conductivity, viscosity behaviour, UV–Vis absorbance, and visual stability, cellulose nanocrystals (CNC) demonstrated promising characteristics as a nano-additive for mineral-based engine oil. The findings of this study confirm the feasibility of CNC as an eco-friendly nano-additive for enhancing the thermo-physical and viscometric performance of SAE 40 engine oil. Improvements in thermal-conductivity pathways increased the thermal-transfer properties of the oil. Also, CNC contributed to maintaining viscosity at higher temperatures, which indicates better structural integrity and lubrication efficiency under thermally stressful conditions. This behaviour is consistent with the most recent studies that report CNC as a usable nano-additive that promotes heat transfer efficiency while concurrently enhancing lubrication behaviour as a result of the nano-additive's high aspect ratio and renewable surface chemistry (Ahmed et al., 2023b; Yuan et al., 2024).

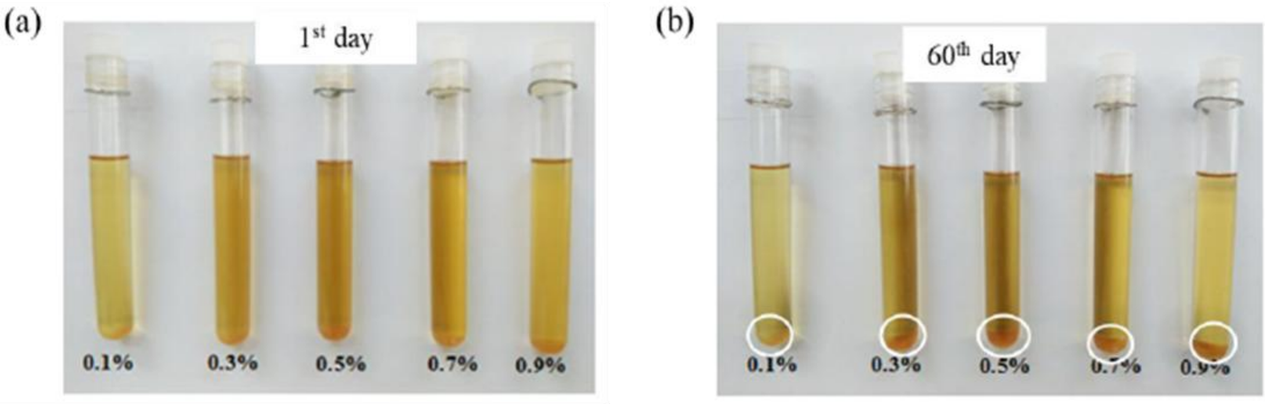

Figure 8. Samples of CNC added SAE 40 engine oil for up to 60 days after preparation

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The rod-like morphology and surface functional groups of CNC facilitate the formation of transient thermal pathways and enhance particle–fluid interactions, thereby improving heat transfer while maintaining viscosity stability (Xu et al., 2022). CNC presents unique challenges, including its intrinsic hydrophilicity, which has been reported to cause dispersion issues in non-polar lubricants. However, improved dispersion and sedimentation stability at a desired CNC concentration have been reported with a combined mechanical stirring and ultrasonic CNC dispersion strategy.

Similar findings in the studied applications of nanolubricants, where the use of ultrasonic technology mitigated agglomerate formation and enhanced stable suspension, and, more interestingly, did so without the need for surfactants. Moreover, environmental impact assessments show better results with the use of CNC-based systems than with the commonly used toxic and unsustainable metal oxides and carbon nanoparticles (Khorasani et al., 2021a; Rashidi et al., 2023). In conclusion, together with the supporting research, CNC is positioned as the optimal, renewable, and eco-friendly nano-additive for engine oils. Further enhancements in retaining the dispersed state of CNC during prolonged storage may be necessary, but, in the end, the promise CNC holds for the formulation of nanolubricants is particularly geared towards environmentally sustainable innovation.

4 Conclusion

This study confirms the feasibility of using sustainable cellulose nanocrystals (CNC) as an eco-friendly bio-nano-additive to enhance the thermo-physical and viscometric performance of mineral-based SAE

40 engine oil. The two-step preparation approach, utilising mechanical stirring and ultrasonication without chemical surfactants, proved effective in achieving acceptable dispersion stability.

The key findings are summarised as follows:

i. Thermal Conductivity: The thermal conductivity of the nanolubricants increased directly with CNC concentration. The maximum enhancement was observed at 0.9 vol% CNC, indicating that CNC facilitates efficient thermal pathways within the oil matrix.

ii. Viscosity Index (VI): The incorporation of CNC successfully improved viscosity stability under temperature changes. The highest VI improvement (2.5% over base oil) was achieved at the lowest tested concentration, 0.1 vol% CNC.

iii. Long-Term Stability: UV–Vis analysis and visual observation of sedimentation confirmed that CNC dispersions remained stable for up to 60 days, validating the non-surfactant dispersion method for use in SAE 40 oil.

The results highlight a critical trade-off between achieving maximum thermal enhancement and maximum viscosity stability. While 0.9 vol% offered the highest thermal performance, 0.1 vol% CNC was determined to provide the most balanced overall lubricant performance when considering both thermal and viscometric requirements. This study positions CNC as a promising, eco-friendly nano-additive candidate for next-generation engine oil formulations that require improved thermal management and sustainable viscometric stability.

Acknowledgement

This research is the result of a collaborative effort among all authors, with each contributing significantly to the study. The work was carried out independently without any financial support or funding from external institutions or organisations.

References

Abdullah, M., Malik, S. R., Iqbal, M. H., Sajid, M. M., Shad, N. A., Hussain, S. Z., Razzaq, W., & Javed, Y. (2018). Sedimentation and stabilization of nano-fluids with dispersant. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 554(June), 86–92. https://doi.org/10.1016/j.colsurfa.2018.06.030

Ahmed, M., Nordin, N. A., & Hussein, M. Z. (2023a). Stability and thermal behaviour of bio-based nanolubricants: A review. *Journal of Cleaner Production, 405*, 136–148.

Ahmed, S. F., Rashid, M., & Hasan, M. M. (2023b). Thermal and tribological performance of cellulose nanocrystal-based nanofluids: A sustainable approach. *Cellulose*, 30(6), 3457–3472. https://doi.org/10.1007/s10570-023-05184-9

Alazemi, A., Abdullah, M., & Almutairi, M. (2022). Advancements in nanoparticle-enhanced engine oils for thermal and tribological improvement. *Energy Reports, 8*, 1542–1555.

Ali, M. K. A., Xianjun, H., Mai, L., Bicheng, C., Turkson, R. F., & Qingping, C. (2016). Reducing frictional power losses and improving the scuffing resistance in automotive engines using hybrid nanomaterials as nano-lubricant additives. Wear,364–365, 270–281. https://doi.org/10.1016/j.wear.2016.08.005

Alotaibi, J. G., Eid Alajmi, A., Kadirgama, K., Samylingam, L., Aslfattahi, N., Kok, C. K., Ramasamy, D., Harun, W. S., Veerendra, A. S., Sivaraos, S., & Yousif, B. F. (2025). Enhancing engine oil performance with graphene-cellulose nanoparticles: Insights into thermophysical properties and tribological behavior. Frontiers in Materials, 12, 1549117. https://doi.org/10.3389/fmats.2025.1549117

Amini, M., Rahman, M. M., & Lee, W. H. (2024). Advances in cellulose nanocrystal production and applications: A review on recent progress. *Carbohydrate Polymers*, 320, 121389.

Awang, N. W., Ramasamy, D., Kadirgama, K., Najafi, G., & Sidik, N. A. C. (2019). Study on friction and wear of Cellulose Nanocrystal (CNC) nanoparticle as lubricating additive in engine oil. International Journal of Heat and Mass Transfer, 131, 1196–1204.

Azman, S. S. N., Zulkifli, N. W. M., Masjuki, H., Gulzar, M., & Zahid, R. (2016). Study of tribological roperties of lubricating oil blend added with graphene nanoplatelets. Journal of Materials Research, 31(13), 1932–1938. https://doi.org/10.1557/jmr.2016.24

Cabrera, L. I. F., Hernández, E. A. G., Pérez-González, J., Marín-Santibáñez, B. M., & Lewis, R. (2019). Effects of Jatropha lubricant thermo-oxidation on the tribological behaviour of engine cylinder liners as measured by a reciprocating friction test. Wear, 426–427(August 2018), 910–918. https://doi.org/10.1016/j.wear.2019.02.028

Galpaya GDCP, Gunasena MDKM, Induranga DKA, Priyadarshana HVV, Indupama SVAA, Wijesekara ERJMDDP, Ishra MI, Mantilaka MMMGPG, Koswattage KR. Nanoparticle-Enhanced Engine Oils for Automotive Applications: Thermal Conductivity and Heat Capacity Improvements. Molecules. 2025 Jun 22;30(13):2695.

Habibi, Y. (2020). Key advances in the chemical modification of nanocelluloses. *Chemical Society Reviews, 49*(11), 3406–3430.

Hassan, A., & Xu, H. (2022). Nanoparticle-enhanced lubricants for advanced thermal management in mechanical systems: A comprehensive review. Tribology International, 173, 107713.

Hisham, S., Kadirgama, K., Alotaibi, J. G., Alajmi, A. E., Ramasamy, D., Sazali, N., & Kok, C. K. (2024). Enhancing stability and tribological applications using hybrid nanocellulose-copper (II) oxide (CNC-CuO) nanolubricant: An approach towards environmental sustainability. Tribology International, 194, 109506.

Indarti, E., Marwan, M., & Wan Daud, W. (2020). Dispersion Stability of Nanocellulose in Nonpolar Solvent: Chloroform. Materials Science Forum, 998, 170–175. https://doi.org/10.4028/www.scientific.net/msf.998.170

Jiang, W., Du, K., Li, Y., & Yang, L. (2017). Experimental investigation on influence of high temperature on viscosity, thermal conductivity and absorbance of ammonia-water nanofluids. International Journal of Refrigeration, 82, 189–198. https://doi.org/10.1016/j.ijrefrig.2017.05.030

Kargar, F., Barani, Z., Mohammadzadeh, A., & Balandin, A. A. (2021). Emerging cellulose nanocrystal nanofluids: Thermal and physical perspectives. *Carbohydrate Polymers, 256*, 117–128.

Khalid, M., Javed, R., & Khan, M. (2021). Performance of cellulose nanocrystal-based nanofluids: A comprehensive review. *Materials Today Communications, 28*, 102708.

Khorasani, S., Darzi, R., & Amani, P. (2021). Thermal transport mechanisms in nanoparticle-enriched lubricants. *Tribology International, 161*, 107–125.

Khorasani, S., Nourbakhsh, A., & Sadeghi, M. (2021). Environmental and tribological assessment of bio-based nanolubricants: A review. *Tribology International*, 158, 106937. https://doi.org/10.1016/j.triboint.2021.106937

Kotia, A., Borkakoti, S., & Ghosh, S. K. (2017). Wear and performance analysis of a 4-stroke diesel engine employing nanolubricants. Particuology, 37, 54–63. https://doi.org/10.1016/j.partic.2017.05.016

Kumar, S., Singh, R., & Gupta, A. (2023). Lubrication and thermal management in high-performance engines: A review. Energy Conversion and Management, 278, 116670.

Li, T., Song, J., & Zhu, S. (2020). Cellulose nanomaterials: Properties, applications, and future directions. *Advanced Materials, 32*(8), 190–217.

Lv, Y., Zhang, X., & Liu, J. (2016). Preparation and stability of nanofluids by ultrasonic dispersion. Applied Thermal Engineering, 105, 70–78. https://doi.org/10.1016/j.applthermaleng.2016.05.090.

Nguyen, T. P., Salari, M., & Hosseini, S. M. (2024). Thermal conductivity enhancement of CNC-based nanofluids for heat transfer applications. Cellulose, 31(2), 985–1002.

Rajendhran, N., Palanisamy, S., Periyasamy, P., & Venkatachalam, R. (2018). Enhancing of the tribological characteristics of the lubricant oils using Nipromoted MoS 2 nanosheets as nano-additives. Tribology International, 118(October 2017), 314–328. https://doi.org/10.1016/j.triboint.2017.10.001

Rashidi, A., Amrollahi, A., & Rastegar, S. (2023a). Comparative study of nanoparticle additives in engine oil for thermal and tribological enhancement. Journal of Molecular Liquids, 371, 121065. https://doi.org/10.1016/j.molliq.2023.121065

Rashidi, A., Nasiri, P., & Azimi, M. (2023b). Thermo-rheological characteristics of advanced nanolubricants. *Renewable Energy, 205*, 1–15.

Sharma, G., Singh, R., & Kumar, P. (2022). Dispersion stability of nanofluids: Mechanisms and influencing factors. *Colloids and Surfaces A, 645*, 128–152.

Sharif, M. Z., Azmi, W. H., Redhwan, A. A. M., & Mamat, R. (2016). Investigation of thermal conductivity and viscosity of Al2O3/PAG nanolubricant for application in automotive air conditioning system. International Journal of Refrigeration, 70, 93–102.

Singh, R., Prasad, S., & Verma, P. (2023). Performance challenges of mineral-based lubricants under extreme operating conditions: A review. Energy Conversion and Management, 286, 117026.

Sivaranjani, K., Raghunathan, T., & Mohan, R. (2022). Comparative performance of nanoparticle additives in engine oil. *Engineering Tribology Journal, 15*(3), 201–213.

Soudagar, M. E. M., Mujtaba, M., & Safaei, M. R. (2020). Effect of nanoparticle dispersion techniques on the stability and performance of nanolubricants. Powder Technology, 370, 392–403. https://doi.org/10.1016/j.powtec.2020.05.031

Sundar, L., Sharma, K., & Singh, R. (2023). Review of nanoparticle-enhanced lubricants for engine applications. *Fuel, 334*, 126–139.

Tahir, Z., Al-Shehri, R., & Hussain, M. (2024). Optimizing engine oil for superior thermal conductivity and viscosity stability: A critical review. Applied Thermal Engineering, 240, 122240.

Vasishth, H., Singh, J., & Kaur, S. (2024). The effect of high temperature on the viscosity efficiency of mechanical engine oil. International Journal of Research Publication and Reviews, 5(3), 48–57.

Wang, Q., Li, J., & Chen, Y. (2020). Tribological behaviour of cellulose nanocrystals as green additives in polyalphaolefin lubricants. Wear, 456–457, 203369.

Xu, Y., Chen, W., & Li, H. (2022). Thermophysical behaviour of cellulose-based nanofluids for sustainable heat transfer applications. Renewable and Sustainable Energy Reviews, 158, 112113. https://doi.org/10.1016/j.rser.2022.112113

Yang, L., Mao, M., Huang, J. nan, & Ji, W. (2019). Enhancing the thermal conductivity of SAE 50 engine oil by adding zinc oxide nano-powder: An experimental study. Powder Technology, 356, 335–341. https://doi.org/10.1016/j.powtec.2019.08.031

Yuan, B., Wang, J., & Chen, L. (2024). Recent advances in cellulose nanocrystal-based nanolubricants: Preparation, performance and challenges. Cellulose, 31(2), 845–863. https://doi.org/10.1007/s10570-024-06181-4

Zhao, H., Hu, Y., & Kumar, P. (2022). Grease lubrication enhanced by cellulose nanocrystals: Wear suppression and friction reduction analysis. Industrial Lubrication and Tribology, 74(8), 945–956.