NANOFLUIDS AND SOLAR HEAT TRANSFER

Performance Enhancement of a Novel Thermally Stable Bio-Oil–Based Al2O3–TiO2 Binary Nanofluid for Solar Heat Transfer Applications

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Abstract

The conversion of solar radiation into thermal energy is strongly influenced by the thermophysical properties and performance of heat-transfer fluids (HTFs), which play a critical role in heat absorption, transportation, and thermal energy storage. In recent years, bio-oil-based nanofluids have attracted increasing research interest as sustainable and environmentally friendly alternatives to conventional HTFs, owing to their renewable origin and potential for enhanced thermophysical properties. Nevertheless, challenges relating to thermal stability and long-term dispersion stability remain significant barriers to their practical application. In response to these challenges, this study presents the development and characterization of a novel palm kernel oil (PKO)-based binary Al_2O_3–TiO_2 nanofluid for solar thermal applications. The binary hybrid nanofluid was formulated by dispersing Al_2O_3 and TiO_2 nanoparticles into purified and processed PKO to enhance its heat-transfer characteristics. The crude PKO was subjected to purification and processing to improve its suitability as a heat-transfer fluid for solar thermal systems. The synthesized nanoparticles and formulated nanofluid were subjected to comprehensive characterization to examine their morphological, structural, chemical, and dispersion stability characteristics using relevant analytical techniques, including scanning electron microscopy (SEM) and zeta potential analysis. The experimental results demonstrated a significant enhancement in thermal conductivity, with the 0.3 wt% Al_2O_3–TiO_2/PKO nanofluid exhibiting a 30.39% increase compared with the base fluid. The viscosity decreased with increasing temperature, with the highest percentage reduction observed at a nanoparticle concentration of 0.1 wt%. Conversely, the incorporation of nanoparticles resulted in a reduction in specific heat capacity, with the maximum decrease of 8.37% recorded relative to the base PKO. Overall, these findings demonstrate the potential of the developed PKO-based Al_2O_3–TiO_2 binary nanofluid as an alternative heat-transfer fluid for low- and medium-temperature thermal energy systems.

Keywords: Bio-oil; Heat transfer fluid; Binary; Nanofluid; Thermal conductivity

1 Introduction

Nanofluids have gained considerable attention in electronic cooling, automotive thermal management, and renewable energy applications. In particular, binary hybrid nanofluids, consisting of two different nanoparticles dispersed in a base fluid, offer opportunities for improved thermophysical properties through synergistic interactions between the nanoparticles. Their application in solar thermal collectors has therefore emerged as a promising approach to enhancing heat transfer and system efficiency (Bhattad et al., 2023). However, conventional base fluids, including water, synthetic oils, and ethylene glycol, present limitations associated with thermal stability, corrosion, and environmental sustainability (Değer et al., 2021). These challenges have stimulated interest in bio-oil-based nanofluids derived from renewable biomass resources. Vegetable oils are particularly

attractive because of their biodegradability, low volatility, and availability, making them potential alternatives for sustainable heat transfer applications (Malik et al., 2024). Previous investigations have demonstrated the potential of bio-oil-based nanofluids to improve thermal conductivity and energy conversion performance. For mono nanofluids, Umar et al. (2020) reported a 16.76% increase in thermal conductivity using TiO_2 dispersed in palm kernel oil (PKO), whereas Sofiah, Samykano, Shahabuddin, et al. (2021) achieved an 11.17% improvement using CuO in refined, bleached, and deodorized palm olein. These findings demonstrate that thermal enhancement depends on the nanoparticle–base fluid combination. At the system level, Permanasari et al. (2023) reported improvements of 25.169% in thermal efficiency and 8.632% in electrical efficiency using graphene nanoplatelets in virgin coconut oil for a photovoltaic–thermal (PVT) system. Greater enhancements have also been reported for hybrid nanofluids. Sofiah et al. (2024) achieved a 31.34% improvement in thermal conductivity using CuO–PANI in RBDL oil, while Wanatasanappan et al. (2022) reported a 27.5% enhancement using Al_2O_3–TiO_2 in vegetable oils. Similarly et al. (2021) recorded a 56.59% improvement in parabolic trough collector (PTC) efficiency using MWCNT–MgO hybrid nanofluids.

Beyond solar thermal systems, Hasbi et al. (2023) reported a 46.1% increase in thermal conductivity using graphene and titanium oxide in bio-based phase change materials, while Kenfack et al. (2024) recorded a 12.08% improvement in photovoltaic system performance using TiO_2-based bio-oil systems. Collectively, these studies demonstrate the potential of bio-oil-based nanofluids and nanoparticle hybridization to enhance thermophysical properties and renewable energy system performance. Nevertheless, the reported improvements vary with nanoparticle composition, base-fluid characteristics, and dispersion stability, indicating that performance gains cannot be generalized across different formulations. More importantly, investigations specifically examining Al_2O_3–TiO_2 binary hybrid nanoparticles dispersed in palm kernel oil remain limited, despite the availability and renewable nature of PKO. Existing studies have largely concentrated on other vegetable oils, leaving a knowledge gap regarding the thermophysical properties, stability, and collector-level performance of Al_2O_3–TiO_2/PKO hybrid nanofluids. Accordingly, the present study addresses this gap by developing and experimentally evaluating a purified PKO-based Al_2O_3–TiO_2 binary hybrid nanofluid for solar thermal applications, with particular emphasis on nanoparticle concentration, dispersion stability, and thermophysical properties.

2 Methodology

2.1 Materials

The materials used in preparing the Al_2O_3–TiO_2/PKO binary hybrid nanofluid include aluminium oxide (Al_2O_3), titanium dioxide (TiO_2), methanol (CH_3OH), sodium hydroxide (NaOH), citric acid ($C_6H_8O_7$), and oleic acid ($C_{18}H_{34}O_2$). The nanoparticles had purities of 99.8% and 99+%, respectively, with particle sizes below 30 nm. Other chemicals exhibited purities ranging from 99.8% to 99.9%. The materials were characterised by their respective physical forms, colours, and densities, as specified by the manufacturers. These specifications ensured appropriate material selection for nanofluid preparation and experimental investigation.

2.2 Purification and preparation of pko-based heat transfer fluid (HTF)

Crude palm kernel oil (PKO) was initially purified using sodium hydroxide (NaOH), citric acid, silica gel, and Fuller's earth to remove gums, phospholipids, free fatty acids, and other impurities. The mixture was heated at 60 °C for 30 minutes, followed by the addition of adsorbents and continuous

stirring for one hour. Subsequently, the oil was vacuum-heated at 70 °C for 30 minutes to reduce its moisture content and filtered twice to obtain purified PKO. The purified PKO was subsequently subjected to transesterification using sodium methoxide, prepared from NaOH and methanol (CH_3OH), at 60 °C for 15 minutes (Oparanti et al., 2021; Salah et al., 2023). The resulting mixture was sonicated for one hour and allowed to separate into glycerol and ester-rich phases. The glycerol and residual impurities were removed, while the resulting PKO ester was oven-dried at 60 °C for 12 hours to minimise its moisture content (Sofiah et al., 2021). The dried PKO ester was subsequently used as the base fluid for preparing the Al_2O_3–TiO_2 binary nanofluid for solar thermal applications. Finally, the synthesized PKO-based HTF was characterized by measuring its specific gravity, pour point, flash point, fire point, lower heating value (LHV), oxidation index, free fatty acid (FFA) content, acid value, free glycerol, and methanol content. These measurements were conducted to evaluate its physico-chemical properties, thermal characteristics, chemical stability, and suitability for solar thermal applications. Figure illustrates the processes of converting crude PKO to HTFs.

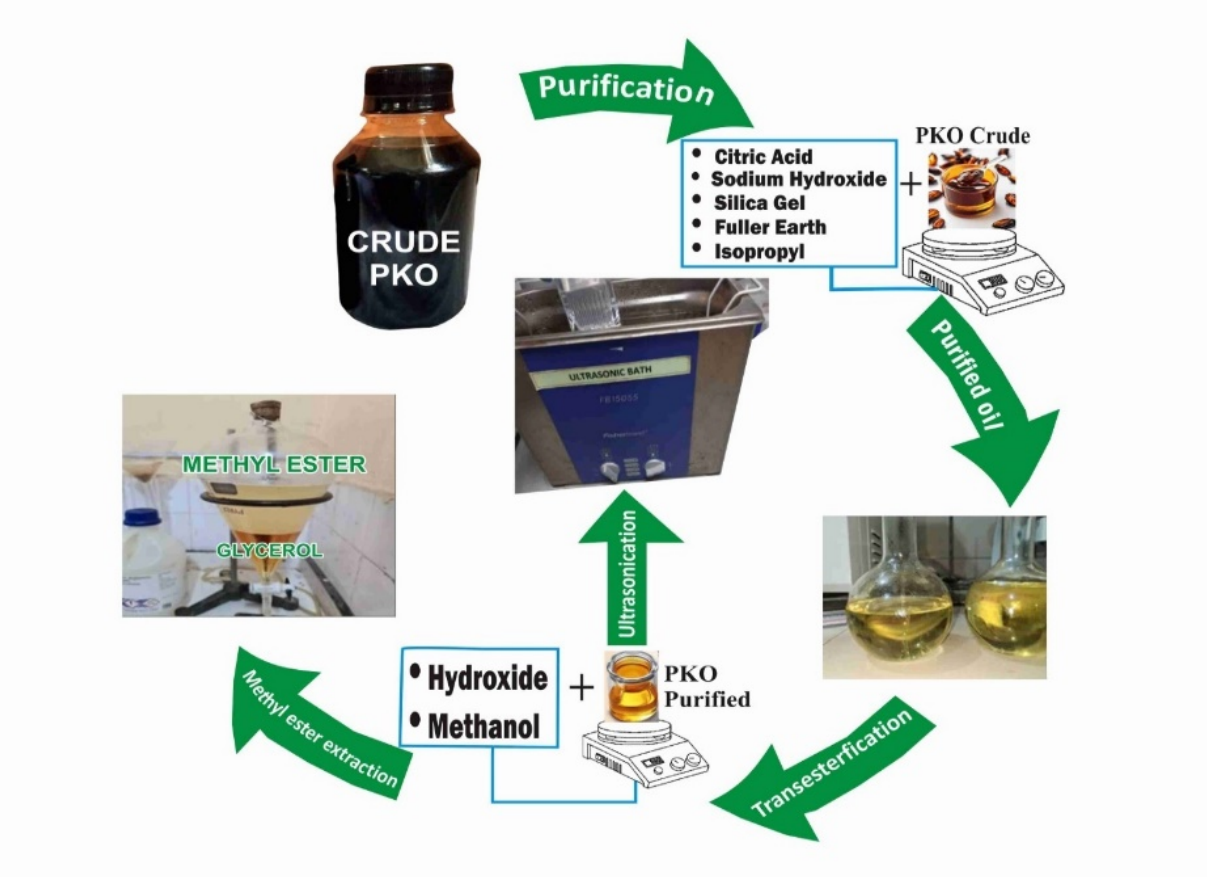


Figure 1. PKO purification flow diagram.

2.3 Binary nanofluid preparation

The Al_2O_3 and TiO_2 nanoparticles were dispersed in the PKO base fluid using a two-step physical method (Bhattad et al., 2023; Malik et al., 2024; Oparanti et al., 2020). The samples were initially stirred for one hour at 40 Hz and 25 °C using a thermostatically controlled water bath, followed by three hours of ultrasonication to enhance nanoparticle dispersion (Wanatasanappan et al., 2022; Xian et al., 2020). To improve nanofluid stability, the nanoparticles were functionalized with oleic acid as a surfactant. Although excessive surfactant concentrations may increase thermal resistance, concentrations within 0.01–0.1% have been reported to have negligible effects on thermophysical properties

(Khairul et al., 2016; Xian et al., 2020; Kumar et al., 2022). In this study, an optimum oleic acid concentration of 0.026 wt% was adopted. Specifically, 3 g of Al_2O_3 and TiO_2 nanoparticles were dispersed in 60 mL of methanol and stirred at 60 °C for 15 minutes. Oleic acid was subsequently added, and the mixture was stirred for two hours. The functionalized nanoparticles were recovered through filtration using Whatman No. 1 filter paper, oven-dried at 70 °C to remove residual methanol, and washed with water. This functionalization process was intended to improve nanoparticle dispersion and suspension stability, thereby enhancing the heat transfer potential of the resulting hybrid nanofluid.

3 Results and discussion

The physicochemical properties of the purified palm kernel oil (PKO)-based heat transfer fluid (HTF) are presented in Table 1. These properties establish the baseline characteristics of the purified PKO and provide essential reference data for evaluating its suitability as a base fluid in formulating the Al_2O_3–TiO_2/PKO binary hybrid nanofluid for solar thermal applications.

Table 1. Properties of crude PKO and the resulting HTF.

Property	Crude PKO	HTFs	Unit
Specific gravity	0.89	0.88	°C
pour point	18	-5	°C
Flash point	245	144	°C
Fire point	275	210	°C
Lower heating value	38.2	36	MJ/kg
Free fatty acid	1	0.5	%
Acid value	0.95	0.2	KOH/g
Free glycerol	3%	0.20	%
Methanol content	0	0.2	%

The zeta potential measurements indicate a gradual reduction in the magnitude of the negative surface charge of both nanofluid concentrations over the four-week storage period. Table 2 presents the zeta potential results in which the 0.1 wt% nanofluid exhibited a change from −49 mV to −40 mV, while the 0.2 wt% sample decreased from −47 mV to −37 mV. Despite this reduction, both samples maintained relatively high negative zeta potential values, suggesting reasonable electrostatic stability throughout the observation period. However, the 0.2 wt% concentration demonstrated better colloidal stability than the 0.3 wt% concentration.

Table 2. Zeta potential (mV) of Al_2O_3–TiO_2/PKO nanofluids.

Weeks	1	2	3	4
0.1 wt%	-49	-46	-43	-40
0.2 wt%	-47	-43	-40	-37

Understanding nanoparticle morphology, particularly particle size, shape, surface texture, and distribution, is essential because these characteristics influence the thermophysical properties and

stability of nanofluids. The SEM micrograph of Al_2O_3 nanoparticles at 700× magnification reveals a rough, irregular, and porous surface consisting of fine granular particles with occasional agglomeration. The particle distribution is heterogeneous, with observed particle sizes predominantly below 20 nm. Similarly, the TiO_2 micrograph at 400× magnification shows irregularly shaped particles with heterogeneous sizes and noticeable agglomeration. These features may be attributed to interparticle attractive forces associated with their high surface energy. The surface characteristics of both nanoparticles can promote fluid–particle interactions, potentially enhancing thermal conductivity and heat-transfer performance. However, excessive agglomeration may adversely affect dispersion stability and heat-transfer efficiency. Therefore, appropriate nanoparticle concentration and dispersion techniques are essential to achieving a homogeneous and stable Al_2O_3–TiO_2/PKO binary nanofluid for solar thermal applications. The SEM micrographs of the Al_2O_3 and TiO_2 nanoparticles are presented in Figure 2.

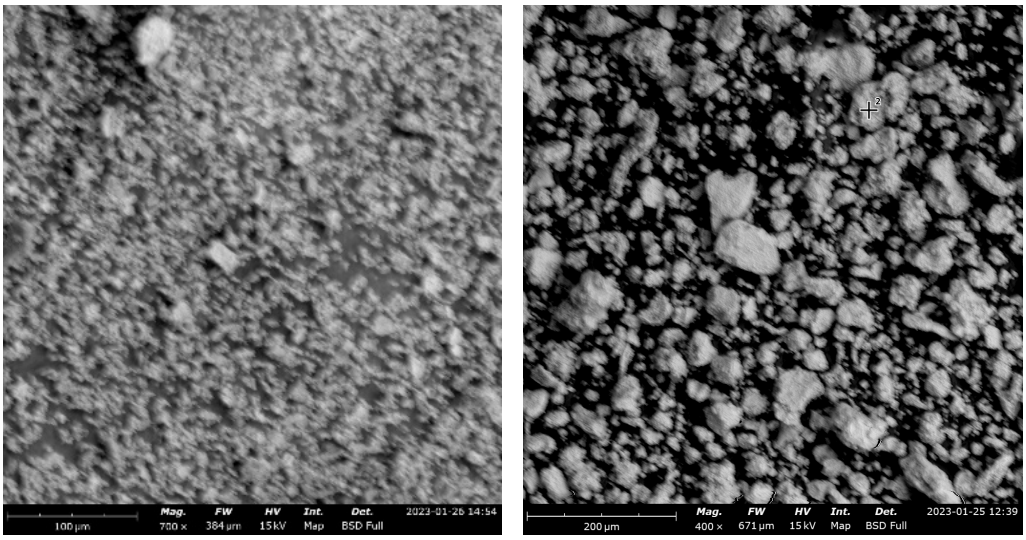


Figure 2. SEM micrographs of Al_2O_3 and TiO_2 nanoparticles.

The prepared bio-oil-based binary nanofluid underwent two months of visual and digital monitoring using the sedimentation technique. As illustrated in Figure 3, particles dispersed in the oil settled over time were observed visually and captured on camera.

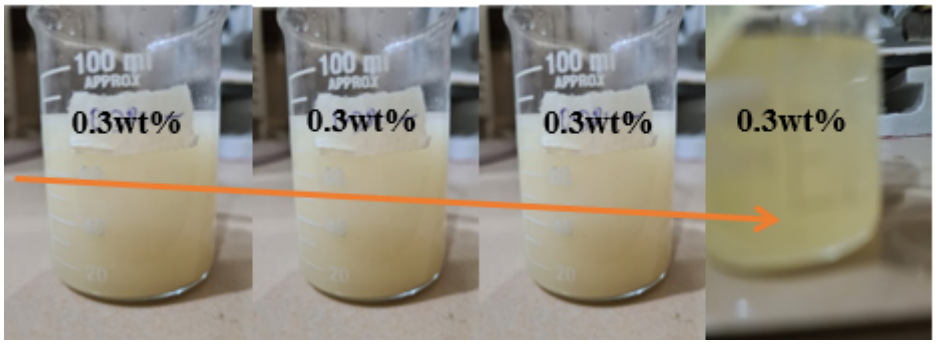


Figure 3. Sedimentation analysis of Al_2O_3–TiO_2/PKO-based nanofluid.

The thermal conductivity of the nanofluids was measured using a KD2 Pro thermal properties analyser over a temperature range of 30–60 °C at 10 °C intervals. The instrument operates based on the transient line heat source (TLS) technique, in which a controlled heat pulse is applied through a probe while the resulting temperature response is monitored to determine the thermal conductivity

of the sample. The nanoparticle concentration range of 0.1–0.3 wt% was selected based on practical considerations and optimisation requirements. Figure 4 presents a comparative evaluation of the predicted (PRED) and experimental (EXP) thermal conductivity of pure palm kernel oil (PKO) and Al_2O_3–TiO_2/PKO nanofluids at different nanoparticle concentrations (0.1, 0.2 and 0.3 wt%) and temperatures. The results demonstrate that the incorporation of Al_2O_3–TiO_2 nanoparticles enhances the thermal conductivity of PKO compared with the base fluid. Among the investigated formulations, the nanofluid containing 0.3 wt% nanoparticles exhibits the highest thermal conductivity, indicating the beneficial influence of nanoparticle concentration on the heat transfer properties of the base fluid. Furthermore, the comparison between the predicted and experimental values provides an assessment of the predictive capability of the developed model. The degree of agreement between the two sets of results indicates the model's ability to reproduce the thermal conductivity behaviour of the prepared nanofluids. The three-dimensional analysis further illustrates the combined effects of temperature and nanoparticle concentration on the thermal conductivity and enhancement ratio of the binary Al_2O_3–TiO_2/PKO nanofluids. The results indicate that temperature has a more pronounced influence on thermal conductivity and its enhancement ratio than nanoparticle concentration within the investigated ranges. This behaviour may be attributed to increased Brownian motion and thermally induced movement of nanoparticles at elevated temperatures, which can promote energy transport within the nanofluid. Consequently, the combined effects of temperature and nanoparticle concentration play important roles in determining the thermal conductivity performance of the prepared binary hybrid nanofluids.

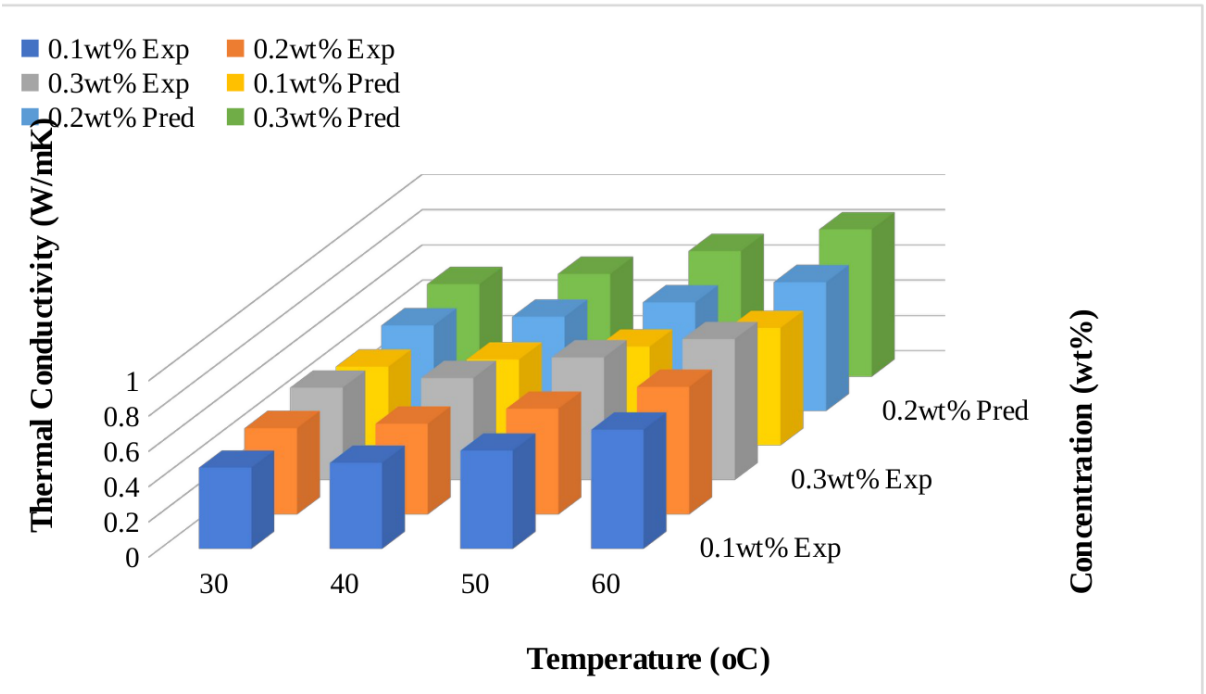


Figure 4. Comparison between the experimental and predicted results for the thermal conductivity.

The viscosity of the PKO-based Al_2O_3–TiO_2 binary hybrid nanofluid was measured using a digital RVDV-1 viscometer. The results revealed a considerable decrease in viscosity with increasing temperature from 30 °C to 60 °C across all nanoparticle weight concentrations investigated. Specifically, at a concentration of 0.3 wt%, the viscosity decreased from 4.72 mPa·s at 30 °C to 3.46 mPa·s at 60 °C. This reduction can be attributed to the increased thermal energy of the fluid molecules, which weakens intermolecular interactions and reduces resistance to flow. Such temperat-

ure-dependent viscosity behaviour is advantageous for heat transfer applications, as lower viscosity facilitates fluid circulation and reduces the pumping power requirements of the solar thermal system.

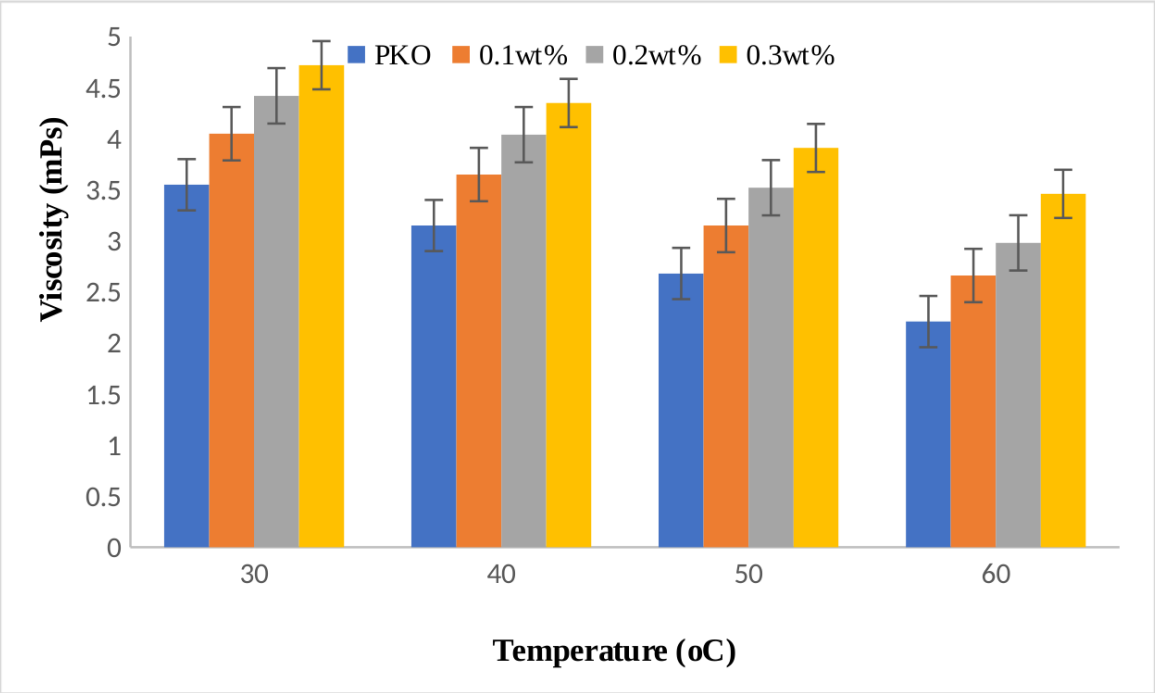


Figure 5. Viscosity of Al_2O_3–TiO_2/PKO against temperature.

The decrease in specific heat capacity given in Figure 6 indicates that increasing the concentration of Al_2O_3–TiO_2 nanoparticles reduces the overall heat storage capacity of the PKO-based hybrid nanofluid. This behaviour can be attributed to the relatively lower specific heat capacity of the solid nanoparticles compared with the PKO base fluid. Conversely, increasing temperature significantly enhances the specific heat capacity of the Al_2O_3–TiO_2/PKO binary hybrid nanofluid, demonstrating the positive influence of temperature on its thermal energy absorption and storage characteristics. These findings reveal a competing influence of nanoparticle concentration and temperature on the specific heat capacity of the hybrid nanofluid. While higher nanoparticle loading results in a reduction in specific heat capacity, elevated temperatures promote its enhancement. Therefore, the combined effects of temperature and nanoparticle concentration must be considered when evaluating the thermophysical properties and overall heat transfer performance of the hybrid nanofluid for parabolic trough solar collector applications.

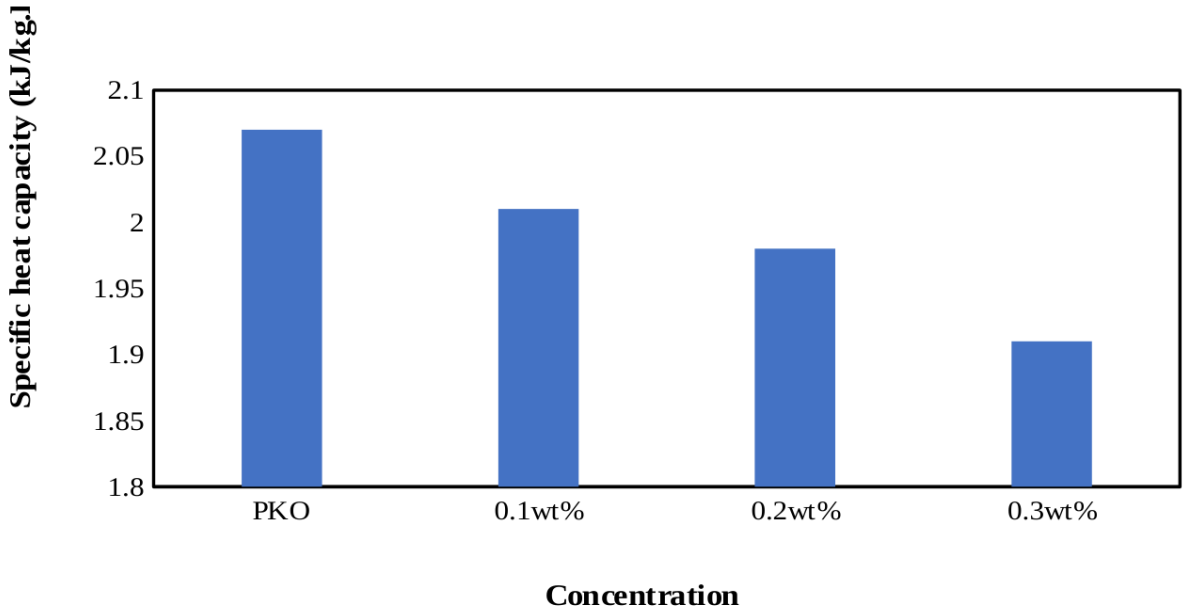


Figure 6. Reduction in specific heat capacity with weight concentration.

4 Conclusion

This study successfully developed and characterized an Al_2O_3–TiO_2/PKO binary nanofluid as a novel heat transfer fluid (HTF) for application in solar thermal systems. The thermophysical properties and stability characteristics of the developed HTF were investigated. Based on the findings obtained, the following conclusions were drawn:

The physicochemical characterization of the processed palm kernel oil (PKO) ester demonstrated its potential suitability as a renewable, bio-based HTF for solar thermal systems. Its measured properties provide a promising foundation for its application as an alternative to conventional petroleum-based heat-transfer fluids.

The incorporation of Al_2O_3–TiO_2 binary nanoparticles enhanced the thermophysical properties and dispersion characteristics of the PKO-based heat-transfer fluid, demonstrating its potential for improved thermal performance and suspension stability in solar thermal applications.

The SEM results confirm that the Al_2O_3 and TiO_2 nanoparticles possess surface characteristics suitable for nanofluid formulation, although some degree of agglomeration is evident. Their incorporation into PKO, therefore, offers potential for improving thermal transport properties, provided that appropriate dispersion techniques are employed to maintain nanofluid homogeneity and stability for solar thermal applications

The investigation of the thermophysical properties of the binary nanofluid shows that 0.3 wt% nanofluid concentration increases the thermal conductivity from 0.522 W/mK at 30 °C to 0.798 W/mK at 60 °C, which implies a significant increase of 30.39%. The viscosity decreases with increasing temperature; however, the pace varies according to nanoparticle concentration. The percentage decrease in viscosity from 30°C to 60 °C is: 0.1 wt%: ~36.8%, 0.2 wt%: 32.6%, 0.3 wt%: ~26.7%, while the pure PKO is: 0.1 wt%: ~53.33%, 0.2 wt%: 50%, 0.3 wt%: ~48.57%. The reduction in specific heat due to nanoparticle addition becomes less pronounced but still noticeable. At 60°C, the specific heat decreases from 2.39 KJ/KgK (PKO) to 2.19 KJ/Kg.K (0.3 wt%).

The overall results obtained from the research study revealed that the developed binary nanofluid could potentially be used as HTF in low and medium-temperature applications.

References

[1] Bhattad A, Kumar A, Sharma S (2023). Mono and hybrid nanofluids' preparation, characterization and stability. *Encyclopedia*. https://doi.org/10.3390/en16073189

[2] Khairul MA, Shah K, Doroodchi E, Azizian R, Moghtaderi B (2016). Effects of surfactant on stability and thermo-physical properties of nanofluids: A review. *Renewable and Sustainable Energy Reviews*, 57, 1126–1136.

[3] Malik, A., et al (2024). An extensive review of preparation, stabilization, and application of single and hybrid nanofluids. *Journal of Thermal Analysis and Calorimetry*, 149, 9523–9557. https://doi.org/10.1007/s10973-024-13449-1

[4] Oparanti SO, Khaleed AA, Abdelmalik AA (2021). Nanofluid from palm kernel oil for high-voltage insulation. *Materials Chemistry and Physics*, 259, 123961. https://doi.org/10.1016/j.matchemphys.2020.123961

[5] Oparanti, S., Khaleed, A., Abdelmalik, A. & Chalashkanov, N. *2020*. Dielectric characterization of palm kernel oil ester-based insulating nanofluid. 2020 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), pp.211-214.

[6] Permanasari, A. A., Rosli, M. a. M., Habibi, I. A., Puspitasari, P., Sukarni, S., Herawan, S. G. & Rafaizul, N. I. a. M. 2023. Efficiency of a Photovoltaic Thermal (PVT) System using Bio-nanofluid based on Virgin Coconut Oil-Graphene with Additive Surfactant: An Experimental Study. *Journal of Advanced Research in Applied Sciences and Engineering Technology* 34(2): 287-304.

[7] Tafavogh, M. & Zahedi, A. 2021. Design and production of a novel encapsulated nano phase change materials to improve thermal efficiency of a quintuple renewable geothermal/hydro/biomass/solar/wind hybrid system. Renewable Energy 169: 358-378.

[8] Xian HW, Sidik NAC, Najafi G, Japar WMAA (2020). Preparation methods and thermophysical properties of nanofluids: A review. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*.

[9] Sofiah, A., et al (2021). A comparative experimental study on the physical behavior of mono and hybrid RBD palm olein based nanofluids using CuO nanoparticles and PANI nanofibers. *International Communications in Heat and Mass Transfer*, 120, 105006.

[10] Samylingam L (2020). Thermal and energy performance improvement of hybrid PV/T system by using olein palm oil with MXene as a new class of heat transfer fluid. *Solar Energy Materials and Solar Cells*, 218, 110754.

[11] Umar, S., et al (2020). Preparation, stability and thermal characteristic of Al2O3/bio-oil based nanofluids for heat transfer applications. *Journal of Nanoscience and Nanotechnology*, 20(12), 7569–7576.

[12] Hasbi, S., et al (2023). Effects of titanium oxide and graphene as nano-fillers on the thermal conductivity of biobased phase change materials as latent thermal heat storage. *Materials Today: Proceedings*, 75, 181–187.

[13] Kulandaivel S (2024). Enhanced Heat Transfer Efficiency through Formulation and Rheo-Thermal Analysis of Palm Oil-Based CNP/SiO2 Binary Nanofluid. *Energy Technology*, 2400314.

[14] Wanatasanappan VV, Rezman M, Abdullah MZ (2022). Thermophysical properties of vegetable oil-based hybrid nanofluids containing Al2O3-TiO2 nanoparticles as insulation oil for power transformers. *Nanomaterials*, 12(20), 3621.

[15] Sofiah, A., et al (2024). Assessment on thermophysical properties of nano enhanced heat transfer fluid with hexagonal boron nitride nanoparticles for thermal management of photovoltaic thermal (PVT) system. *Process Safety and Environmental Protection*.

[16] Salah, Y., et al (2023). Influence of PST and PHF heating conditions on the swirl flow of Al+Mg+TiO2 ternary hybrid water-ethylene glycol based nanofluid with a rotating cone. *International Journal of Thermofluids*, 19, 100371.

[17] Kumar, S., et al (2022). Enhanced heat transfer using oil-based nanofluid flow through conduits: A review. *Energies*, 15(22), 8422.

[18] Değer, K., Özkaya, M. G. & Boran, F. E. 2021. Modelling and analysis of future energy scenarios on the sustainability axis. *Politeknik Dergisi* 26(2): 665-678.