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A Novel Bio-Oil–Based Binary Nanofluid with Enhanced Thermal Conductivity for Heat-Transfer Applications

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Abstract- The conversion of solar radiation into thermal energy depends significantly on the performance of heat-transfer fluids (HTFs), which are responsible for both heat transport and thermal energy storage. In recent years, bio-oil-based nanofluids have attracted considerable attention as sustainable, efficient, and environmentally friendly alternatives to conventional HTFs due to their renewable origin and enhanced thermophysical properties. However, challenges associated with thermal stability, long-term dispersion stability, and the development of binary nanocomposite formulations capable of further improving the thermal conductivity of bio-oil-based HTFs remain largely unresolved. This study presents the development of a novel palm kernel oil (PKO)-based binary nanofluid produced through transesterification of PKO followed by the two-step nanoparticle dispersion method. Binary nanoparticles consisting of Al_2O_3 and TiO_2 were dispersed in the bio-oil to enhance its heat-transfer performance. The synthesized nanoparticles and the resulting nanofluid were comprehensively characterized using Scanning Electron Microscopy (SEM), Energy-Dispersive X-ray Spectroscopy (EDX), Fourier Transform Infrared Spectroscopy (FTIR), Transmission Electron Microscopy (TEM), and Zeta Potential analysis to evaluate their morphology, composition, chemical interactions, and dispersion stability. The experimental results revealed a maximum thermal conductivity enhancement of 61.1% at a nanoparticle concentration of 0.3 wt% and a temperature of 80 °C, demonstrating a substantial improvement over the base fluid. These findings confirm that the developed PKO-based Al_2O_3–TiO_2 binary nanofluid possesses excellent thermophysical properties and stability, making it a promising heat-transfer fluid for low- and medium-temperature thermal energy systems, particularly in solar thermal applications. Furthermore, this work provides an innovative and sustainable approach to the development of renewable, high-performance, and environmentally friendly heat-transfer technologies.

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

I. INTRODUCTION

Heat transfer fluids (HTFs) serve as intermediary media between a heat source, such as a boiler or solar collector, and a system requiring heating or cooling. These fluids absorb thermal energy from the heat source, transport it through a closed-loop system, and deliver it to the desired location via heat exchangers (Malviya et al., 2021).

HTFs are widely utilized in industrial processes, chemical manufacturing, solar thermal power plants, and other energy systems where efficient heat transfer is required. For instance, in concentrated solar power (CSP) plants, HTFs absorb solar energy, transfer it to a power generation cycle, and subsequently facilitate electricity production.

The performance and durability of HTFs depend largely on their thermophysical and chemical properties, which determine their ability to withstand harsh operating conditions while maintaining long-term operational reliability.

Historically, water has been extensively used as a heat transfer medium because of its high specific heat capacity and ability to absorb and store significant thermal energy per unit mass.

These characteristics have made water a cost-effective HTF for applications such as solar water heating, industrial heating processes, ventilation, and air-conditioning (HVAC) systems (Nair et al., 2022). Despite these advantages, water exhibits several limitations in high-temperature applications.

Its boiling point of 100 °C restricts its use in elevated-temperature systems without pressurization or additional equipment (Mourad et al., 2022). In recent years, passive heat transfer enhancement techniques based on nanotechnology have attracted significant attention due to their ability to improve thermal system performance without requiring additional power input or moving components.

These techniques involve dispersing nanoparticles into conventional HTFs such as water, oils, and glycols to create nanofluids with enhanced thermophysical properties.

Nanofluids typically exhibit improved thermal conductivity, specific heat capacity, and heat transfer performance while maintaining acceptable viscosity and density characteristics. Such improvements enable more efficient energy absorption, storage, and dissipation, making nanofluids suitable for applications including electronic cooling, automotive thermal management, and renewable energy systems.

Binary nanoparticle dispersed in bio-oil-based fluids have emerged as promising HTFs because of their superior thermal performance and environmental sustainability (Malan & Kumar, 2021). The development of binary nanofluids aims to achieve higher thermal conductivity, improved mechanical strength, enhanced chemical stability, and better overall heat transfer characteristics compared with mono nanofluids (Sreekumar et al., 2022).

Several studies have reported substantial improvements in the thermophysical properties of bio-oil-based nanofluids, highlighting their potential application in solar thermal systems and other energy-related technologies (Brzóska et al., 2021; Chan et al., 2020). Table 1 summarizes recent studies on the enhancement of thermophysical properties of bio-oil-based nanofluids as advanced heat transfer fluids.

Table 1 Review of Recent Studies on Thermophysical Property Enhancement of Bio-Oil-Based Nanofluids

Ref	Nanoparticles	Base fluid	Concentration (%)	Type of nanofluid	Max. Thermal conductivity (%)	Temp. Range (ºC)	Enhancement
(Samylingam et al. 2020)	MXene	olein palm oil (OPO)	0.01- 0.2	Mono	68.5	25-70	The superior thermal conductivity of the bio-oil-based nanofluid enhances heat transfer performance, thereby improving the thermal and electrical efficiencies of (PVT) systems
(Umar et al. 2020)	TiO_2	PKO	0.2 1	Mono	16.76	-	The favorable thermophysical properties exhibited by the bio-oil-based nanofluid

							projected it a promising heat transfer fluid (HTF) for solar thermal applications.
(Sofiah et al. 2021)	CuO	RBD palm olein	0.04, 0.1, 0.36, 1.91, 1.92 & 1.93	Mono	11.7	30-80	The bio-oil-based binary nanofluid exhibited enhanced thermophysical properties and improved stability, making it a promising heat transfer fluid (HTF) for solar thermal systems.
(Wanatasanappan et al. 2022)	Al_2O_3 -TiO_2	Coconut oil, soybean oil, and palm oil	0.2, 0.4, & 0.6	Binary	27.5	25-65	The developed bio-oil-based binary nanofluid exhibited enhanced thermophysical properties and excellent stability, making it a promising heat transfer fluid (HTF) for solar thermal applications.
(Azizie et al. 2023)	ZnO	Palm oil	0.02, 0.04, 0.06, 0.08, 0.1, 0.12 & 0.14	Mono	59.1	30-60	The significant enhancement in thermal conductivity suggests that the developed HTF can improve thermal management performance in cooling and

							insulation applications.
(Hasbi et al. 2023)	Graphene and Titanium oxide	palm wax, beeswax, and coconut oil	0.5, 1.0, 1.5, & 2.0	Mono	46.1	-	The enhanced thermal conductivity of the nano-enhanced bio-oil-based phase change materials (BPCMs) demonstrates their strong potential for use as latent thermal energy storage materials in building applications.
(Kulandaivel et al. 2024)	CNC-GNP	Palm oil	02, 0.4, 0.6. 0.8 & 1	Binary	0.35	30-70	The improved thermal conductivity and enhanced stability of the developed bio-oil-based nanofluid make it a promising heat transfer fluid (HTF) for solar thermal energy systems.
(Sofiah et al. 2024)	CuO-PANI	RBDL	1, 5 & 10	Binary	31.34	30-80	The bio-oil-based fluid displayed improved thermal conductivity and enhanced stability, making it a promising heat transfer fluid (HTF) for solar thermal

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systems.

II. METHODOLOGY

Bio-oil based nanofluids are advanced heat transfer fluids developed by dispersing nanoparticles into bio-derived oils. They combine the renewable and eco-friendly nature of bio-oils with the superior thermophysical properties of nanoparticles, offering enhanced thermal conductivity, stability, and efficiency for applications in thermal energy systems.

A. Materials

This unit presents the materials used for nanofluid preparation and properties assessment and, in the same way, describes the method employed in obtaining the thermophysical properties of the nanofluid. The binary nanoparticle materials used in this research work are Al_2O_3 (with high scattering qualities) and TiO_2 (with high absorption capabilities).

The nanoparticles Al_2O_3 and TiO_2 with > 99.8% purity and particle size < 30 nm were used in this research work. Other crude PKO oil synthesis materials and their specifications used are given in Table 2

Table 2 Materials specification

Type	Al_2O_3	TiO_2	CH_3OH (Methanol)	NaOH (Sodium Hydroxide)	$C_6H_8O_7$ (Citric Acid)	$C_{18}H_{34}O_2$ (Oleic Acid)	Silica Gel ($SiO_2 \cdot nH_2O$)	C_2H_5OH (Ethanol)	HCl (Hydrogen Chloride)
Purity	99.8%	99+%	99.8%	99.9%	99.9%	99.9%	~99%	99.9%	37% (aqueous) / 99.9% (gas)
Particle size	< 30 nm (TEM)	< 30 nm (TEM)	–	–	–	–	Porous (2–25 nm pores)	–	–
Coating colour	Yellowish	Yellowish	–	–	–	–	White/Blue indicator type	–	–
Colour	White	White	White (powder)	White (pellet)	–	Colorless to pale yellow (oily liquid)	White to bluish	Colorless liquid	Colorless to slightly yellow (gas/liquid)
Density	2.3 g/cm³	–	–	–	–	~0.89 g/cm³ at 25 °C	~0.7 g/cm³	0.789 g/cm³ (20 °C)	1.19 g/cm³ (aqueous, 37%)

B. PREPARATION OF PALM KERNEL OIL-BASED HEAT TRANSFER FLUID

Palm kernel oil (PKO) used in this study is a non-edible vegetable oil that was chemically modified for application as a heat transfer fluid (HTF) in solar thermal systems. PKO has been reported to possess reliable and durable heat transfer characteristics at elevated temperatures while maintaining satisfactory thermal efficiency under low- and medium-temperature operating conditions (Abdelmalik, 2014; Oparanti et al., 2022).

Furthermore, the incorporation of nanoparticles into bio-based oils has been shown to significantly enhance their thermophysical properties, thermal stability, and environmental sustainability, thereby improving their suitability as HTFs. Prior to modification, the crude PKO underwent a purification process to remove phospholipids, gums, free fatty acids, and moisture content.

The purification procedure involved the use of 400 mL of crude PKO, sodium hydroxide (NaOH), and citric acid ($C_6H_8O_7$). The mixture was heated to 60 °C and continuously stirred for 30 minutes to facilitate neutralization and degumming reactions. Thereafter, silica gel and fuller's earth were added to the mixture and stirred for an additional 1 hour to further reduce gum content, phospholipids, and free fatty acids (Oparanti et al., 2022).

Following purification, the oil was heated under vacuum at 70 °C for 30 minutes to remove residual moisture. The refined oil was subsequently filtered twice and oven-dried to eliminate remaining impurities, resulting in purified PKO suitable for further processing. The purified oil was then subjected to a transesterification process to convert the triglycerides into methyl esters and improve the thermal properties of the oil (Oparanti et al., 2021).

In this process, sodium methoxide (CH_3ONa) was first prepared by dissolving sodium hydroxide in methanol (CH_3OH). The sodium methoxide solution was then added to the purified PKO, and the mixture was heated to 60 °C while being continuously stirred for 15 minutes to facilitate the transesterification reaction (Bashir et al., 2021; Salah et al., 2023). The resulting product was sonicated for 1 hour to enhance reaction completion and mixture homogeneity.

Thereafter, the reaction mixture was allowed to separate into two distinct phases: glycerol and methyl ester. Excess glycerol, residual sodium hydroxide, and other by-products were carefully removed. The obtained PKO methyl ester was subsequently dried in an oven at 60 °C for 12 hours to significantly reduce its moisture content and improve its thermal stability.

C. PREPARATION OF AL_2O_3–TIO_2/PKO BINARY NANOFLUID

The Al_2O_3–TiO_2/palm kernel oil (PKO) binary nanofluid was prepared using the two-step method, which involves the separate synthesis of nanoparticles followed by their dispersion into the base fluid through physical mixing techniques (Bhattad et al., 2023; Malik et al., 2024; Oparanti et al., 2020).

The required quantities of dry Al_2O_3 and TiO_2 nanoparticles were dispersed in PKO and initially mixed using a magnetic stirrer operating at 40 Hz for one hour. During the stirring process, the temperature was maintained at 25 °C using a thermostatically controlled water bath to ensure uniform dispersion and prevent overheating.

Following magnetic stirring, the suspension was subjected to ultrasonication for 3 hours to further break down nanoparticle agglomerates and enhance nanoparticle distribution within the base fluid (Wanatasanappan et al., 2022; Xian et al., 2020).

To improve the stability of the nanofluid, oleic acid was employed as a surfactant during nanoparticle functionalization. Although surfactants are widely used to enhance nanoparticle dispersion, excessive concentrations may increase thermal resistance and adversely affect the thermophysical properties of nanofluids. Previous studies have reported that surfactant concentrations within the range of 0.01–0.10 wt.% do not significantly deteriorate nanofluid performance (Khairul et al., 2016; Xian et al., 2020).

In this study, stable nanofluids were successfully obtained by functionalizing the nanoparticles with oleic acid concentrations ranging from 0.02 to 0.10 wt.%, with optimum thermal stability achieved at a concentration of 0.026 wt.%. For the functionalization process, 3 g of Al_2O_3–TiO_2 nanoparticles were dispersed in 60 mL of methanol and stirred on a hotplate magnetic stirrer for 15 minutes at 60 °C. Subsequently, 0.026 wt.% oleic acid was added to the suspension, and the mixture was continuously stirred for 2 hours to facilitate effective surface modification of the nanoparticles.

After the functionalization process, the mixture was filtered using Whatman No. 1 filter paper to separate the modified nanoparticles from the methanol and excess oleic acid.

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The recovered nanoparticles were then dried in an oven at 70 °C to remove residual methanol, followed by washing with distilled water to eliminate any remaining impurities. Nanoparticle functionalization was carried out to address one of the major challenges in nanofluid technology achieving long-term suspension stability.

Unstable nanofluids tend to exhibit behaviour similar to that of conventional fluids due to nanoparticle sedimentation and agglomeration. Therefore, enhanced suspension stability and durability are essential for maintaining improved thermal conductivity and heat transfer characteristics.

III. RESULT AND DISCUSSION

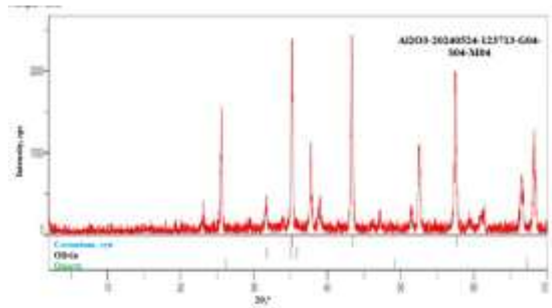
A. X-Ray Diffraction Analysis (XRD)

The XRD technique was used to identify the degree of crystalline interaction between the nanoparticles and functionalized agents. The XRD analysis of functionalized Al_2O_3 & TiO_2 nanoparticles is given in

Figure 1. The functionalized nanoparticles detailed information about the crystalline structure, phase composition, quality, and interactions of the coatings with the core nanoparticles show the XRD peaks in Figure 1 (a) obtained at 2 degrees = 25.6°, 35.1°, 43.4°, and 57.5°, which correspond to Al_2O_3, indicating a well-crystallized alumina coating.

Moreover, the XRD peaks obtained in Figure 1 (b) at 25.3° and 62.7° correspond to anatase TiO_2, suggesting the presence of this phase in the TiO_2 coating. The XRD pattern of the Al_2O_3 and TiO_2 obtained in this work was confirmed to be in good agreement with those obtained in the literature. These insights are critical for developing effective and well-stable bio-oil-based nanofluids suitable for systems application.

(a) XRD of a Functionalized Al_2O_3



(b) XRD of a Functionalized TiO_2

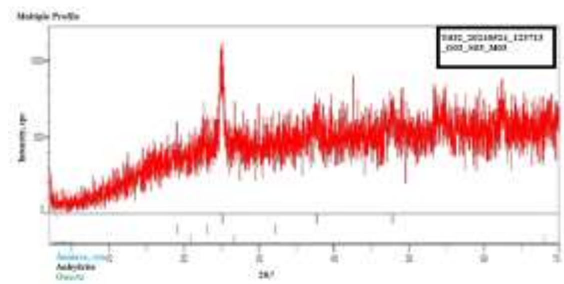


Figure 1 XRD result of the functionalized nanoparticles

B. FOURIER TRANSFORM INFRARED SPECTROSCOPY (FTIR)

Fourier Transform Infrared (FTIR) spectroscopy was employed to investigate the chemical structure of the binary Al_2O_3–TiO_2/PKO nanofluid and to identify the functional groups associated with both the palm kernel oil (PKO) base fluid and the dispersed nanoparticles.

The resulting spectrum exhibits characteristic absorption bands corresponding to the organic constituents of PKO as well as the vibrational modes of the Al_2O_3 and TiO_2 nanoparticles. The identified bands include C–H stretching of alkanes, C=O stretching of ester groups, C–H bending of methylene groups, C–O stretching of esters and alcohols, together with the characteristic vibrations of alumina and titanium dioxide.

The FTIR spectrum of the binary Al_2O_3–TiO_2/PKO nanofluid is presented in Figure 2. A strong absorption peak observed at approximately 2855 cm^{-1} is assigned to the symmetric C–H stretching vibrations of the aliphatic hydrocarbon chains present

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in PKO. Another distinct peak at 1740 cm^{-1} corresponds to the carbonyl (C=O) stretching vibration of ester functional groups, confirming the triglyceride composition of the oil.

The absorption band located near 1166 cm^{-1} is attributed to C–O stretching vibrations associated with ester and alcohol groups. In the lower wavenumber region (1000–400 cm^{-1}), the spectrum displays bands that are characteristic of Ti–O stretching and Ti–O–Ti bridging vibrations, which are widely recognized as the fingerprint region of titanium dioxide.

The absorption peak at approximately 723 cm^{-1} falls within the reported range for anatase TiO_2, thereby confirming that the titanium dioxide nanoparticles retained their anatase crystalline phase after nanofluid preparation. In addition, a weak absorption band at 1461 cm^{-1} is attributed to carboxylate species, indicating the successful interaction between oleic acid and the nanoparticle surfaces.

This observation suggests that the carboxyl (-COOH) groups of oleic acid reacted with the surface hydroxyl (-OH) groups of the TiO_2 nanoparticles through both physical adsorption and chemical bonding. Such surface modification enhances nanoparticle compatibility with the PKO matrix, thereby improving dispersion stability and reducing particle agglomeration

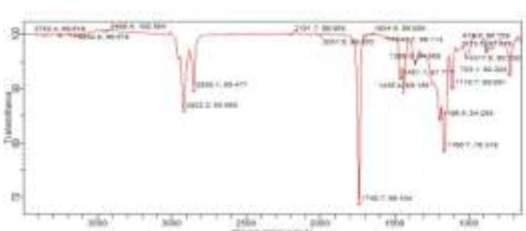

Figure 2 FTIR result of binary Al_2O_3-TiO_2/PKO Nanofluids

C. TRANSFORM ELECTRON MICROSCOPE (TEM)

Transmission Electron Microscopy (TEM) analysis was conducted to evaluate the dispersion stability, morphology, and particle size of the Al_2O_3–TiO_2/PKO binary nanofluid. TEM has been widely employed to characterize nanofluids because it provides detailed information on nanoparticle morphology, size distribution, dispersion state, and aggregation behaviour at the nanoscale.

Furthermore, its high spatial resolution enables direct observation of the internal structure of nanoparticles, making it an effective technique for assessing nanofluid stability. The TEM micrograph, presented in Figure 3, reveals that the Al_2O_3–TiO_2 nanoparticles are uniformly dispersed within the palm kernel oil (PKO) base fluid, with minimal particle agglomeration.

The nanoparticles exhibit predominantly spherical morphology and possess an average particle size of less than 30 nm. The observed homogeneous distribution and low degree of clustering indicate excellent dispersion stability, suggesting effective interaction between the nanoparticles and the base fluid.

In addition, the relatively narrow particle size distribution of the Al_2O_3–TiO_2 nanocomposite contributes to enhanced colloidal stability by minimizing differential sedimentation and reducing the tendency for particle aggregation. These findings confirm that the prepared binary nanofluid exhibits good structural stability, making it a promising heat transfer fluid for solar thermal applications.

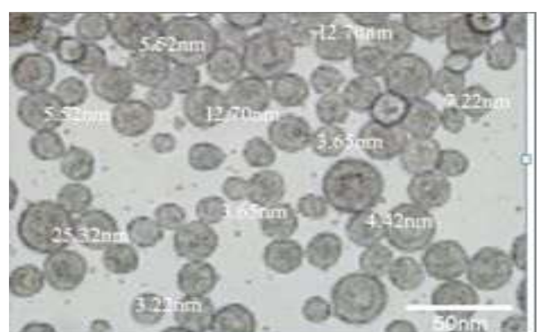

Figure 3 TEM image of binary Al_2O_3-TiO_2/PKO (magaji et al. 2025) https://www.ukm.my/jkukm/wp-content/uploads/2025/3708/01.pdf

D. ZETA POTENTIAL

The zeta potential of the Al_2O_3–TiO_2/PKO binary nanofluid was measured using a Brookhaven Zeta Potential Analyzer to evaluate its colloidal stability.

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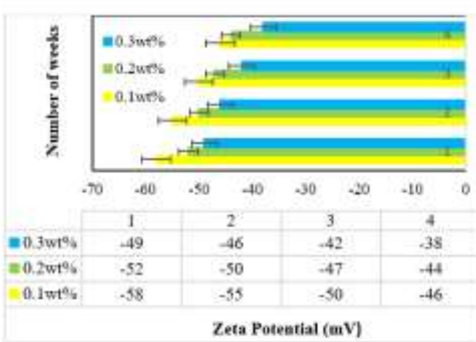
The zeta potential results, presented in Figure 4, exhibit negative surface charge values, which are attributed to the presence of oleic acid as the surfactant.

The negative charge originates from the deprotonation of the carboxylic acid functional group of oleic acid as the pH of the suspension increases, resulting in negatively charged nanoparticle surfaces (Manca et al., 2022). Consequently, stronger electrostatic repulsive forces develop between the nanoparticles, reducing their tendency to agglomerate and settle.

Previous studies have also reported that increasing the pH of oleic acid-coated nanofluids leads to more negative zeta potential values, thereby improving colloidal stability through enhanced electrostatic repulsion (Kumar et al., 2022).

The degree of deprotonation of oleic acid and the consequent negative charge contributes to the stability of the nanofluid by producing an electrical double layer that prevents particle aggregation. Over the four weeks, there has been a gradual decrease in the zeta potential values for both concentrations, but it still maintains good stability. For 0.2wt%, the zeta potential decreases from -52 mV to -44 mV, while for 0.3wt%, it decreases from -49 mV to -38 mV. The maximum zeta potential was obtained at 0.1wt% concentration which shows the maximum zeta potential of -58 mV.



	1	2	3	4
0.3wt%	-49	-46	-42	-38
0.2wt%	-52	-50	-47	-44
0.1wt%	-58	-55	-50	-46

Figure 4 Zeta potential measurement

E. THERMAL CONDUCTIVITY OF THE NANOFLUID

The KD2 Pro thermal properties analyzer was used to measure the thermal conductivity of the nanofluid over a broad temperature range of 30–80 °C, with measurements taken at intervals of 10 °C. This instrument operates using the transient line heat source technique, which involves applying a controlled heat pulse through a probe and monitoring the resulting temperature response to accurately determine thermal conductivity.

The experimental nanoparticle concentration ranges of 0.1–0.3 wt% was selected based on both practical and optimization considerations. Figure 5 presents the thermal conductivity of the nanofluid at different temperatures and nanoparticle concentrations. At 30 °C, the average thermal conductivity of the binary nanofluid was measured as 0.459 W/m·K, compared with 0.438 W/m·K for the base fluid, representing a thermal conductivity enhancement of approximately 4.8%.

The highest thermal conductivity was obtained at a nanoparticle concentration of 0.3 wt% and a temperature of 80 °C, where the thermal conductivity reached 1.126 W/m·K, compared with 0.488 W/m·K for the base fluid, corresponding to an enhancement of approximately 130.7%. The results demonstrate that the thermal conductivity of the binary nanofluid increases with both nanoparticle concentration and temperature.

The enhancement can be attributed to intensified Brownian motion of the nanoparticles at elevated temperatures, which promotes microscopic convection and facilitates heat transport within the base fluid.

Furthermore, the higher nanoparticle concentration increases the number of heat-conducting pathways, thereby improving the effective thermal conductivity of the suspension. The formation of an interfacial nanolayer between the nanoparticles and the palm kernel oil (PKO) base fluid also contributes to enhanced heat transfer by providing a region with thermal properties different from those of the surrounding fluid. Collectively, these mechanisms

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account for the significant improvement in the thermal conductivity of the binary nanofluid, highlighting its potential as an efficient heat transfer fluid for solar thermal applications.

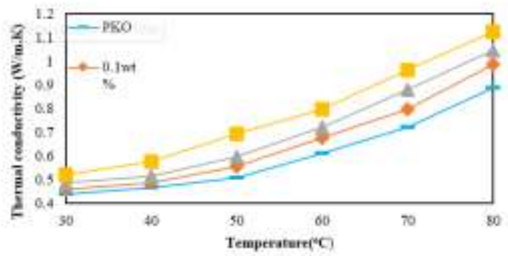

Figure 5 Thermal conductivity of Al_2O_3-TiO_2/PKO against temperature

Figure 6 reveals that temperature more substantially influences thermal conductivity enhancement than particle concentration. The analysis shows that the nanoparticle concentration increases the thermal conductivity from 0.459 W/m.K to 0.522 W/m.K at 30 ºC, which implies a significant increase compared to the pure PKO value of 0.438 W/m.K. The percentage of nanoparticle concentration increment is approximately 16.09% at 30 ºC and 23.3% at 60 ºC. For temperature increments, the percentage ranges from 55.62% at 0.1 wt% to 61.1% at 0.3 wt%.

The percentage increase for each concentration level ranges from PKO thermal conductivity to the individual particle concentration increment. Results show that the temperature increment is 31.98% more pronounced than the concentration of the nanoparticle in increasing the thermal conductivity of the binary nanofluid.

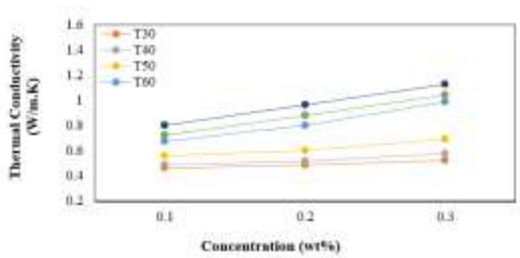

Figure 6 Temperature Enhancement of the thermal conductivity of Al_2O_3-TiO_2/PKO

IV. 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, stability characteristics, and thermal performance of the developed HTF were thoroughly investigated. Based on the findings obtained, the following conclusions were drawn:

- X-ray diffraction (XRD) analysis confirmed the successful functionalization and crystalline nature of the Al_2O_3 and TiO_2 nanoparticles. Characteristic diffraction peaks were observed at 2θ = 25.6°, 35.1°, 43.4°, and 57.5° for Al_2O_3, and at 25.3° and 62.7° for anatase TiO_2. These results provide valuable information regarding the crystalline structure of the nanoparticles and the interactions between the coating material and the nanoparticle core.
- Fourier Transform Infrared (FTIR) spectroscopy revealed prominent absorption bands at approximately 2855 cm^{-1}, 1740 cm^{-1}, 1461 cm^{-1}, 723 cm^{-1}, and within the range of 1000–400 cm^{-1}. These characteristic peaks confirmed the presence of both the organic constituents of palm kernel oil and the functionalized nanoparticles, indicating effective surface coating, strong interfacial interactions, and successful nanofluid formation.
- TEM analysis indicated that the mono nanofluid exhibited moderate stability with noticeable particle clustering and agglomeration. In contrast, the binary nanofluid demonstrated superior dispersion characteristics, featuring uniformly distributed spherical nanoparticles with minimal aggregation. The narrower particle size distribution contributed significantly to enhanced suspension stability and reduced sedimentation tendencies.
- The thermal conductivity of the nanofluid increased substantially with increasing temperature and nanoparticle concentration. The obtained maximum enhancement of 61.1% was achieved at a nanoparticle concentration of 0.3 wt.%, demonstrating the significant potential of the developed nanofluid to improve heat

transfer performance in solar thermal applications.

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