

Effect of Titanium Dioxide (TiO₂) Nanoparticle Concentration on the Thermal Conductivity and Stability of Water-Ethylene Glycol Nanofluids

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ABSTRACT

Nanofluids have attracted considerable attention for their potential use as advanced heat transfer media in various cooling applications. This study investigates the effect of titanium dioxide (TiO₂) nanoparticle concentration on the thermal conductivity and stability of nanofluids. Five concentrations of TiO₂ nanofluids were prepared using water-ethylene glycol (60:40) as a base fluid and polyvinylpyrrolidone (PVP) as the surfactant. The TiO₂ nanoparticles were characterized by ATR-FTIR, FESEM and EDX. Thermal conductivity measurements were carried out at room temperature (28 °C) and elevated temperature (e.g. 40 °C and 60 °C). The stability of the nanofluids was evaluated through visual inspection, UV-Vis spectroscopy and dynamic light scattering analysis. The TiO₂ nanoparticles displayed spherical shape and tend to form clusters with an average particle diameter of approximately 30 nm. The 0.5 wt.% nanofluid achieved the greatest thermal conductivity value of 0.748 W/m·K resulting in 49.89% thermal conductivity enhancement at 60 °C. Freshly prepared nanofluids exhibited good dispersion stability and reduced when left undisturbed for extended period. Further improvements in long term stability are required for industrial applications.

Keywords: Titanium dioxide; nanofluid; thermal stability; thermal conductivity; water-based

INTRODUCTION

Nanotechnology is the study and application of materials by controlling their structure at nanoscale, where particle size ranges from 1 to 100 nm [1]. At this scale materials show unique physical and thermal properties which are different to when the material is in bulk [1]. Nanofluid was first proposed by Choi in 1995 following the successful preparation of a stable suspension of nanoparticles within a liquid medium [2,3]. Nanofluids are the advanced heat transfer fluids formed by incorporating nanoparticles into conventional base fluids [4]. As solid nanoparticles typically exhibit significantly higher thermal conductivity compared to conventional base fluids, their addition can significantly improve the thermal conductivity of the base fluid [2].

One important application of heat transfer is in automotive cooling systems. Automotive cooling system rely on coolant to remove excess heat generated by internal combustion engines and maintain an optimal operating temperature [2,5]. This will improve the engine's performance and prevent the deformation of the components [6]. Conventional radiator coolants typically consist of water-glycol solutions. The coolants play an important role in regulating engine temperature while also providing lubrication and protection against antifreeze. However, the coolant's low thermal conductivity often restricts their heat transfer efficiency. As a result, large radiator surface areas are required to achieve efficient cooling leading to bulkier cooling systems [2].

Titanium dioxide (TiO_2) is one of those nanoparticles which has gained considerable attention due to its favorable physicochemical properties. TiO_2 has also shown promising thermal properties when dispersed in liquid mediums. The high surface area of nanosized TiO_2 particles contributes to heat transfer and enhance thermal conductivity in nanofluids [7,8]. These advantages have encouraged extensive research on TiO_2 -based nanofluids as potential alternatives to conventional coolants.

Thermal conductivity directly influences the heat transfer efficiency of a fluid and is regarded as a key thermophysical property to determine the performance of a nanofluid. Increase in TiO_2 concentration has shown to increase thermal conductivity which is consistent with the Choi nanofluid model [7]. Several works on TiO_2 , Al_2O_3 and SiO_2 trihybrid nanofluid have been reported to increase in heat transfer coefficient with increase in both concentration of nanoparticles and operating temperature [9,10,11,12]. The 0.3% concentration resulted in the greatest enhancement at 39.7%. Pusat et al. [5] investigated TiO_2 nanofluids as engine coolant and reported 40.8% of enhancement in heat transfer at a concentration of 0.6 wt.%. The results demonstrated the potential of TiO_2 to significantly improve cooling performance. Hilmin et al. [13] investigated the efficiency of the engine by adding a nanofluid with TiO_2 nanoparticles to the coolant. The study showed improvements in thermal conversion as well as overall power generation when compared with water-cooled systems. Erkan et al. [6] investigated the performance of TiO_2 , Al_2O_3 and SiO_2 nanofluids and found that TiO_2 nanofluids achieved the highest exergetic efficiency (35.67% at 0.4 wt.%). The study further demonstrated that increasing the concentration of TiO_2 nanoparticles resulted in improvement in efficiency. Senejani et al. [14] reported decrease in engine surface temperatures when TiO_2 and Al_2O_3 was added, indicating that nanoparticle addition enhanced the coolant's heat transfer capabilities. Nieh et al. [15] evaluated the heat transfer capabilities of TiO_2 and Al_2O_3 based nano coolants. They reported the TiO_2 nano coolant has better heat transfer

performance than the Al_2O_3 coolant. The greatest increase in heat dissipation was 27.2%. Due to this, the evaluation of nanofluid stability is essential for determining its suitability for heat transfer application [13]

Several methods are commonly employed to improve stability, such as ultrasonication and surface modification using surfactants. Polyvinylpyrrolidone (PVP) is a commonly used surfactant that improves the stability by reducing particle agglomeration. Saidi et al. [16] reported that nanofluids containing PVP exhibits improved stability and reduced sedimentation compared with nanofluids without surfactants. Moreover, Wu et al. [17] observed that increased ultrasonication time improved the nanoparticle dispersion and contributed to long term stability in TiO_2 - SiO_2 hybrid nanofluids.

While the individual components of titanium dioxide, water-ethylene glycol and polyvinylpyrrolidone (PVP) are well-established in thermal engineering, this study focuses on their optimized integration rather than introducing entirely novel compounds, utilizing a systematic two-step preparation method where PVP and high-frequency ultrasonication are deployed to overcome the critical challenge of nanoparticle agglomeration and sedimentation. This specific combination is deliberately chosen because water-ethylene glycol provides essential automotive antifreeze and baseline fluid properties, while suspended titanium dioxide nanoparticles introduce a high surface-area-to-volume ratio and superior thermal conductivity that conventional coolants lack. These special thermophysical properties are harnessed to drastically improve heat dissipation and exergetic efficiency in compact automotive cooling systems and by detailing the rigorous application of surfactant-assisted stabilization, ultrasonication and quantitative evaluation via UV-Vis spectrometry and visual observation, the methodology provides a clear, scientifically justified framework that highlights the precise mechanisms governing nanofluid stability and thermal performance.

This study aims to explore the effect of TiO_2 nanoparticle concentration on the stability and thermal conductivity of TiO_2 nanofluids in water-ethylene glycol base fluid. The stability of the nanofluids will be assessed via visual observation and UV-Vis spectrometry to observe for sedimentation behavior overtime. The finding of this will provide valuable insights of how nanoparticle concentration effects the thermal conductivity and stability of TiO_2 nanofluids.

MATERIALS AND METHODS

This section outlines the experimental procedures used to formulate, characterize and evaluate TiO_2 nanofluids in a 60:40 water-ethylene glycol base fluid. The synthesis of TiO_2 powder was carried out in accordance with established procedures [18]. Details are provided regarding the two-step synthesis method, surfactant stabilization using PVP and the analytical techniques employed for structural and morphological characterization. Furthermore, the experimental setups for thermal conductivity measurements across varying temperatures and the multi-technique protocols for evaluating dispersion stability

over time are described. The ethylene glycol and PVP powder were purchased from Sigma Aldrich.

Preparation of Nanofluids

Five concentrations of TiO₂ nanofluids were prepared using water-ethylene glycol mixture (60:40) as the base fluid and polyvinylpyrrolidone (PVP) as surfactant. PVP was added as a stabilizing agent to promote uniform nanoparticle distribution within the suspension. The formulation details of the prepared nanofluids are listed in Table 1.

The required masses of TiO₂ nanoparticles, PVP and base fluids were calculated to obtain a total nanofluid mass of 40 g for each concentration. The TiO₂ nanoparticles, base fluid and surfactant were weighed and stirred together for 5 min to obtain a preliminary suspension. Following this, the suspension was sonicated for 60 min at room temperature to promote uniform nanoparticle dispersion and minimize sedimentation. The preparation procedure was applied consistently to all the nanofluid samples with different nanoparticle concentrations as shown in Figure 1.

Table 1. Preparation parameters and mass composition of TiO₂ nanofluids

Weight percentage of TiO ₂ (wt.%)	Mass of TiO ₂ (g)	Mass of 10%PVP (g)	Mass of base fluid (g)	Stirring (min)	Sonication (min)
0.1	0.04	0.004	39.956	5	60
0.2	0.08	0.008	39.912	5	60
0.3	0.12	0.012	39.868	5	60
0.4	0.16	0.016	39.824	5	60
0.5	0.20	0.020	39.780	5	60

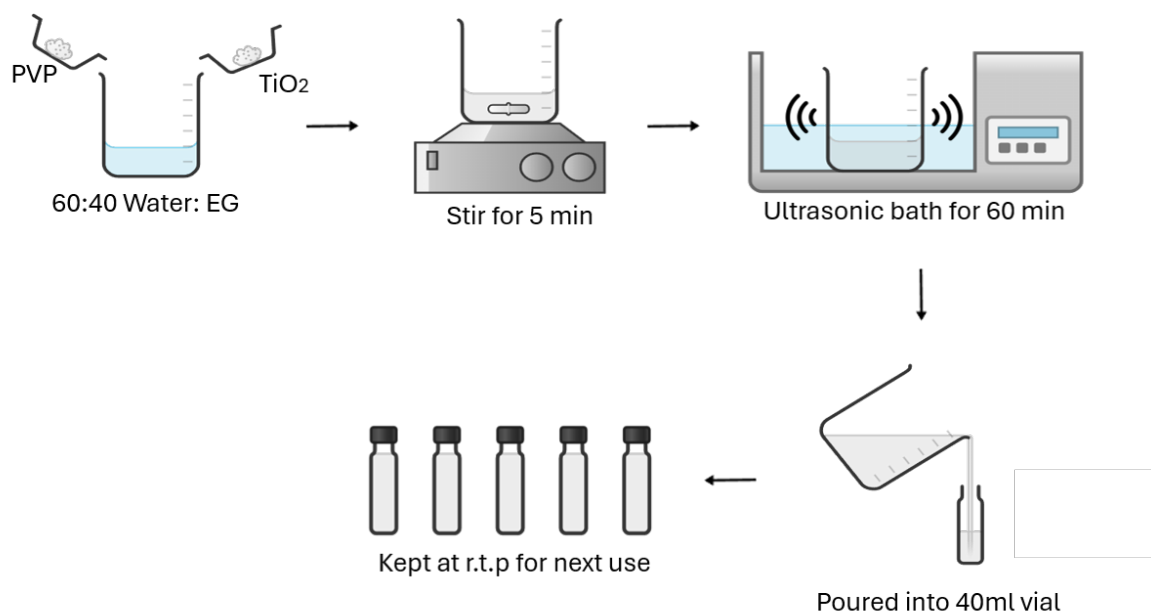


Figure 1. Preparation procedure of the TiO₂ nanofluids

The preparation conditions were carefully selected to produce homogenous nanoparticle dispersion within the base fluid. This approach will ensure accurate assessment of how nanoparticle concentration influences nanofluid stability and thermal conductivity.

Characterization Techniques and Thermal Conductivity

TiO₂ nanoparticles were characterized using multiple analytical instruments. Attenuated Total Reflectance - Fourier Transform Infrared (ATR- FTIR) spectroscopy was employed to determine the functional groups present. Morphology and elemental composition of the TiO₂ nanoparticles were analyzed using Field Emission Scanning Electron Microscope (FE-SEM) coupled with Energy Dispersive X-ray Spectroscopy (EDX). The FE-SEM images were obtained at magnifications of 10,000 $\times$ and 30,000 $\times$. ImageJ software was used to measure particle size diameter from the FE-SEM images. The EDX Spectrum was used to identify the elements present and the quantitative elemental composition obtained from EDX analysis is reported as weight percentage (wt.%) together with the apparent concentration and measurement uncertainty (wt.% sigma).

Thermal Conductivity Analysis

KD2 Pro Thermal Properties Analyzer was used to measure the thermal conductivity of the nanofluids at room temperature, 40 °C and 60 °C as depicted in Figure 2(a). These temperatures were selected to represent the conditions commonly encountered in automotive cooling systems and was achieved using a water bath as shown in Figure 2(b).

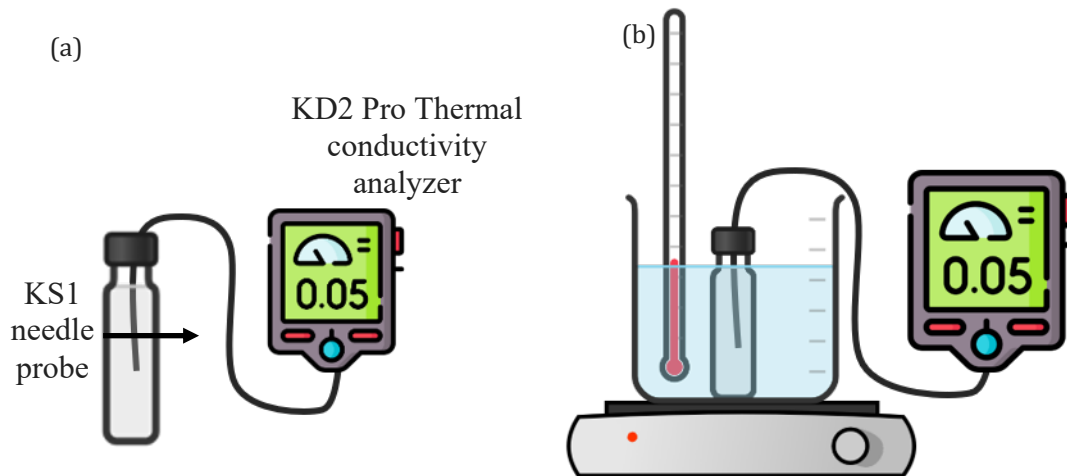


Figure 2. Measurement of thermal conductivity: (a) room temperature (b) using water bath for 40 °C and 60 °C

Thermal conductivity was also measured approximately 66 h after preparation to evaluate nanofluid stability. The thermal conductivity of the base fluid was measured and used as a reference for the comparison. Each measurement was carried out three times to ensure reproducibility and accuracy. Thermal conductivity analyzer was calibrated with glycerin before use. The percentage enhancement in thermal conductivity was determined using Eq. (1) as follows:

$$\% \text{ TC Enhancement} = \frac{k_{nf} - k_{bf}}{k_{bf}} \times 100\% \quad (1)$$

Stability Analysis

TiO₂ nanofluids were visually observed to evaluate the stability of the nanofluid by monitoring for sedimentation behavior overtime. The samples were photographed and examined immediately after preparation, after 7 days and after 14 days. Changes in appearance, sediment formation and phase separation were noted and used as an indicator of nanoparticle agglomeration and sedimentation.

The stability of TiO₂ nanofluids was also analyzed using a Shimadzu UV-3600i Plus UV-Vis-NIR Spectrophotometer over a wavelength range of 200-800nm. Analyses were conducted immediately after preparation, after 7 days and after 14 days. The particle size of the TiO₂ nanofluids was determined using dynamic light scattering (DLS) with an Anton Paar Litesizer 500 Particle Size Analyzer.

RESULTS AND DISCUSSION

FTIR Spectrum of TiO₂ Nanoparticles

The Fourier-Transformed Infrared (FTIR) spectroscopy of the TiO₂ nanoparticles as shown in Figure 3 shows the vibrational bands associated with its major constituents. A strong band between 500 cm⁻¹ and 800 cm⁻¹ is attributed to the stretching and bending vibrations of Ti-O-Ti bonds. O-Ti-O bonds commonly occur in a highly crystalline phase and shows a peak at 698 cm⁻¹ [16]. The bands located around 1600 cm⁻¹, 3000 cm⁻¹ and 3600 cm⁻¹ are characteristics of H-O-H bending and O-H stretching vibrations stretching from hydroxyl group present on TiO₂ surface and absorbed moisture. The peak at 1371 cm⁻¹ corresponds to vibrations associated with residual functional groups such as methylene and carboxylate groups, while the peak at 1738 cm⁻¹ and 1212 cm⁻¹ corresponds to C=O and C-O stretching respectively. These peaks are commonly present in carboxylic acids, esters or other oxygen containing compounds. These organic related peaks indicate the possible presence of carbon containing species on the TiO₂ nanoparticle surface. These observations are consistent with FTIR spectrum of TiO₂ nanoparticles [16,19]. The weak absorption peak appears between 2200 and 1950 cm⁻¹ represent an instrumental artifact arising from lattice absorption of diamond ATR crystal plate [20].

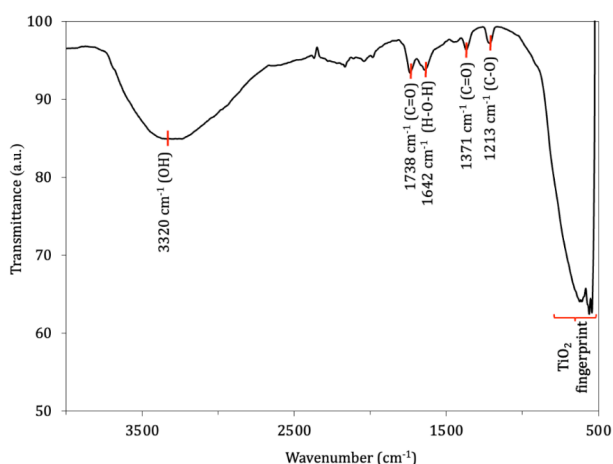


Figure 3. FTIR spectrum of TiO₂ nanoparticles

FESEM Morphology of TiO₂ Nanoparticles

Figure 4 shows the morphology of the TiO₂ nanoparticles was examined using Field Emission Scanning Electron Microscope (FESEM). Morphology of TiO₂ nanoparticles appeared to be spherical and clustered. The agglomeration of the nanoparticles occurred to the interactions between particles such as Van der Waals attraction and the high surface energy of the nanoparticles [18,19]. The spherical morphology offers several advantages for nanofluid applications. It minimizes viscosity and lowers pumping power compared to elongated or irregular shaped particles. Their uniform geometry also promotes more homogenous dispersion within the base fluid, which results in uniform dispersion and enhanced heat transfer [21].

ImageJ analysis of the FESEM images show that the nanoparticles had diameters ranging from 26-33 nm. Nanoparticles of this size possess a high relative surface area which improves nanoparticle dispersion in the surrounding fluid, enhancing heat transfer. Smaller nanoparticles exhibit stronger Brownian motion which promotes micro convection and contributes to improved thermal conductivity and heat performance. Additionally, the small particle size can also reduce sedimentation, which contributes to improved stability of the nanofluid [22].

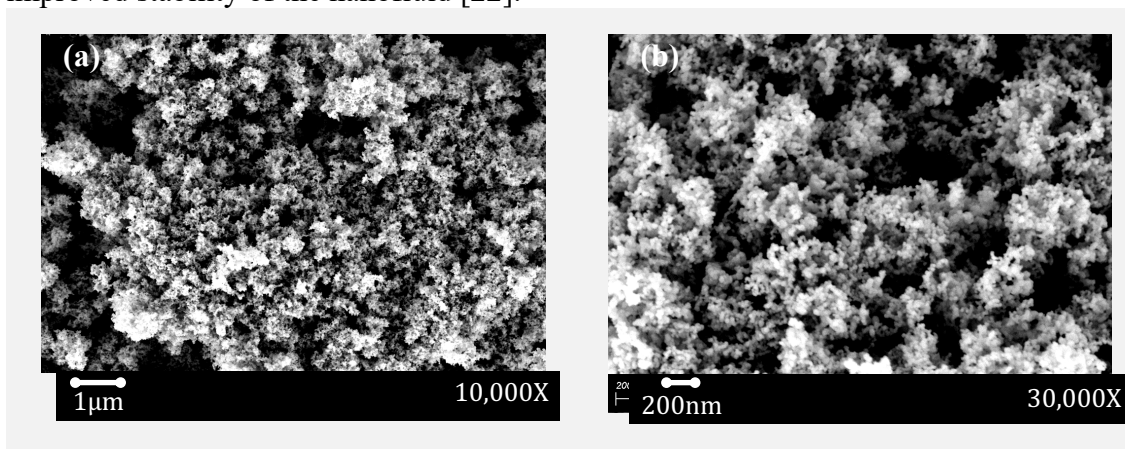


Figure 4. FESEM images of TiO₂ nanoparticles (a) 10,000× magnification (b) 30,000× magnification

EDX Analysis of TiO₂ Nanoparticles

The elemental composition of TiO₂ nanoparticles was analyzed using Energy Dispersive X-ray Spectroscopy and the corresponding spectrum and quantitative results are presented in Figure 5 and Table 2. The EDX spectrum in Figure 5(a) shows the presence of titanium (Ti) and oxygen (O) confirming the formation of single phase TiO₂ nanoparticles. The elemental mapping images of oxygen and titanium reveal the spatial distribution of the elements within the tested sample. The quantitative EDX analysis showed 50.22 wt.% titanium and 49.78 wt.% oxygen content of 49.78 wt.% confirming the successful formation of TiO₂ nanoparticles. The presence of Ti and O as the major elemental constituents is consistent with the expected elemental composition of titanium dioxide [18,19].

Table 2. EDX values of TiO₂ nanoparticles

Element	Apparent	Weight percent	Weight percent
Oxygen (O)	0.88	49.78	0.23
Titanium (Ti)	1.15	50.22	0.21

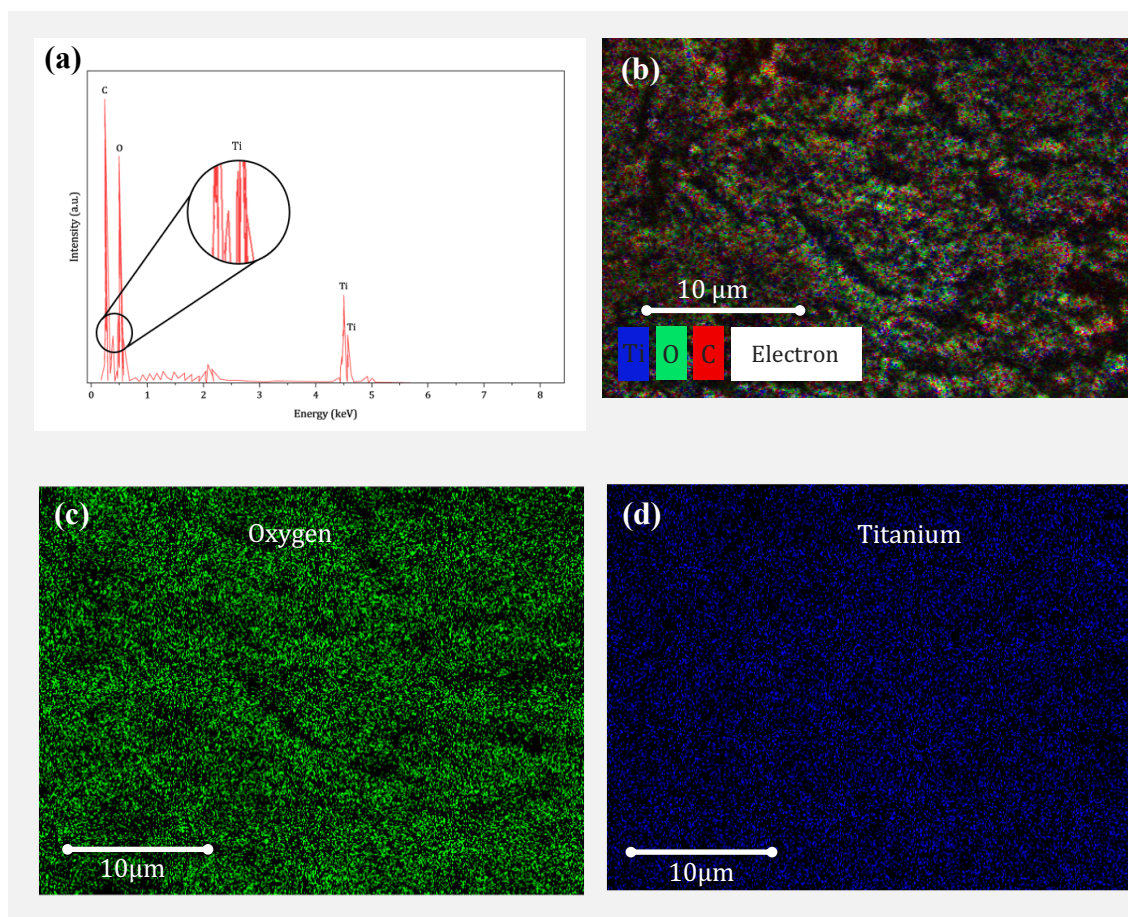


Figure 5. EDX spectrum and elemental mapping images of TiO₂ nanoparticles (a) EDX spectrum, (b) overall elemental mapping, (c) elemental mapping of oxygen and (d) elemental mapping of titanium

EDX Analysis of TiO₂ Nanoparticles

The thermal conductivity measurements in Table 3 and Figure 6 demonstrated a clear enhancement with increasing TiO₂ loading across all temperatures. The 0.5 wt.% nanofluid exhibited the highest thermal conductivity values across all temperatures (0.589 W/mK at 28 °C, 0.637 W/mK at 40 °C and 0.749 W/mK at 60 °C). This result is consistent with thermal conductivity trends reported in previous TiO₂ nanofluid studies [23]. The observed improvement can be attributed to the greater number of thermally conductive nanoparticles dispersed in the base fluid. This results in the proliferation of thermally conductive pathways through the fluid medium and elevates the thermal conductivity of

the nanofluid [7,24]. Consequently, nanofluids containing a higher amount of TiO_2 nanoparticles exhibits greater thermal conductivity.

The influence of temperature on thermal conductivity is also evident from the results. Most TiO_2 nanofluids displayed an increase in thermal conductivity with rising temperature. The greatest increase was observed for the 0.5 wt.%, where thermal conductivity increased from 0.589 W/mK at 28 °C to 0.637 W/mK at 40 °C and reached to 0.748 W/mK at 60 °C. Similar increases in thermal conductivity with temperature was also observed for 0.2-0.4 wt.%. In contrast, the 0.1 wt.% nanofluid showed little variation with temperature while the base fluid exhibited only negligible changes. The temperature induced enhancement maybe associated with intensified Brownian motion of the TiO_2 nanoparticles at elevated temperature. Increased nanoparticle movement promotes repeated particle collision and enhanced microscale fluid circulation which facilitates thermal energy transfer through the base fluid [1].

Table 3. Thermal conductivity of TiO_2 nanofluids measured at 28 °C, 40 °C and 60 °C

Temperature (°C)	Thermal Conductivity (W/m K)					
	Base fluid	0.1 wt.%	0.2 wt.%	0.3 wt.%	0.4 wt.%	0.5 wt.%
28	0.440	0.552	0.566	0.570	0.579	0.589
40	0.497	0.577	0.586	0.588	0.609	0.637
60	0.496	0.551	0.652	0.652	0.694	0.749

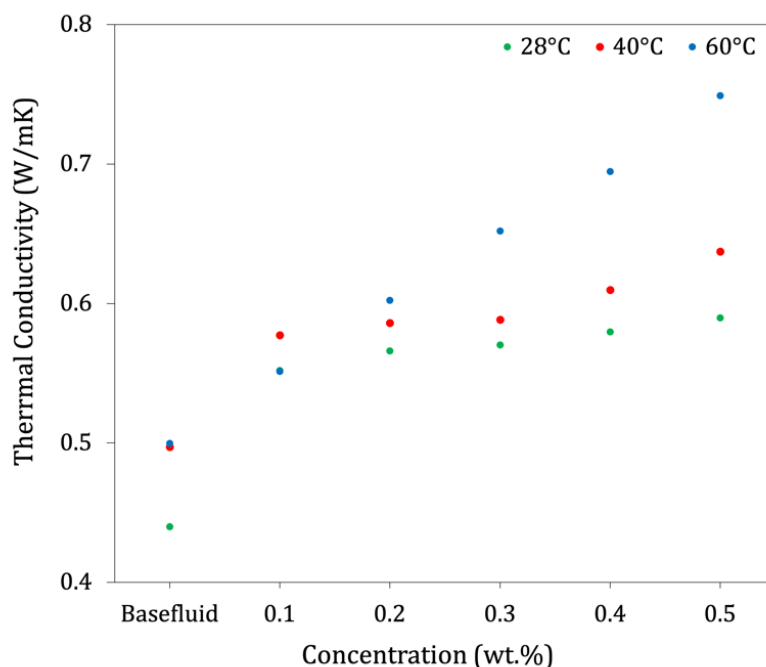


Figure 6. Thermal conductivity of TiO_2 nanofluids measured at 28 °C, 40 °C and 60 °C

Thermal conductivity enhancement also showed similar trends as depicted in Table 4 and Figure 7. The enhancement increased with increasing TiO₂ concentration at each temperature as shown in Table 4 and Figure 7. Among all concentrations, the 0.5 wt.% exhibited the highest thermal conductivity enhancement reaching 34.01% at 28 °C, 28.23% at 40 °C and 49.89% at 60 °C. The higher enhancement observed at greater concentrations is due to the increased availability of conductive pathways created by the larger number of dispersed nanoparticles [7,24]. Although the measured thermal conductivity increased with temperature, the enhancement values showed a different trend. The enhancement at 40 °C were lower than that at 28 °C for all nanoparticle concentrations. A significant increase in thermal conductivity enhancement was then observed at 60 °C, where the 0.5 wt.% exhibited highest enhancement of 49.89%. This behavior is likely as the enhancement percentage is calculated relative to thermal conductivity of the corresponding base fluid which also changes with temperature. Nevertheless, the result demonstrated that elevated temperature, particularly 60 °C further improves the heat transfer of TiO₂ nanofluids.

The presence of polyvinylpyrrolidone (PVP) may also have contributed to the observed thermal conductivity enhancement. PVP acts as a steric stabilizer which adsorbs onto the surface of the nanoparticle reducing particle agglomeration by creating repulsive barriers between the neighboring particles. Improved nanoparticle dispersion allows a larger fraction on nanoparticles to remain suspended within the base fluids, thereby maximizing the effective heat transfer area and promoting more efficient thermal transport [23].

Table 4. Thermal conductivity enhancement of TiO₂ nanofluids at 28 °C, 40 °C and 60 °C

Temperature (°C)	Thermal Conductivity Enhancement (%)				
	0.1 wt.%	0.2 wt.%	0.3 wt.%	0.4 wt.%	0.5 wt.%
28	25.45	28.63	29.62	31.74	34.01
40	16.16	17.09	18.37	22.53	28.23
60	10.34	20.54	30.48	39.02	49.89

To evaluate the effect of storage on thermal performance, additional measurements were conducted approximately 66 h after nanofluid preparation. Thermal conductivity values after storage are presented in Table 5 and Figure 8. While the corresponding thermal conductivity enhancement percentages are shown in Table 6 and Figure 9. Nanofluids with lower concentrations of TiO₂ nanoparticle (0.1 wt.% and 0.2 wt.%) showed minor changes in thermal conductivity with storage. Conversely, the higher TiO₂ concentrations showed a larger reduction in thermal conductivity with storage. The largest decreased was noted for the 0.5 wt.% nanofluid, where thermal conductivity decreased from 0.589 W/mK to 0.458 W/mK.

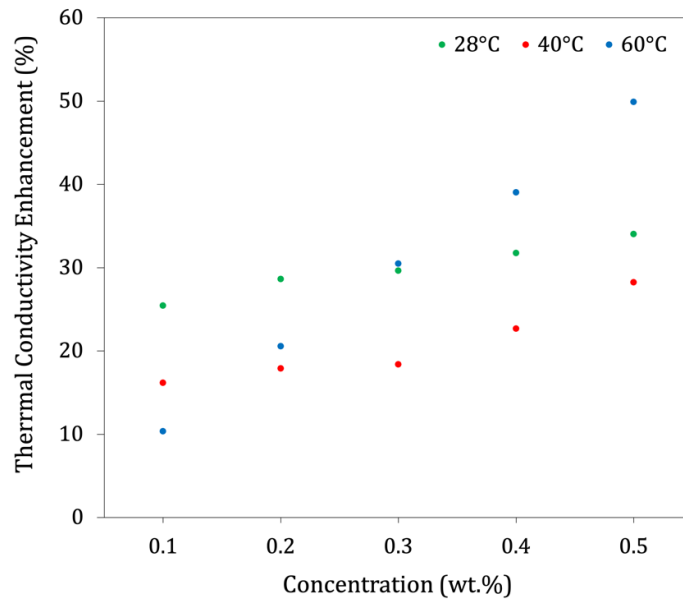


Figure 7. Thermal conductivity enhancement of TiO₂ nanofluids at 28 °C, 40 °C and 60 °C

This decline in thermal conductivity for the higher concentrations after storage is likely due to sedimentation of the nanoparticles. As the nanofluids remain undisturbed, the thermally conductive TiO₂ nanoparticles will gradually settle down and reducing their amount dispersed within the fluid. This reduces the formation of continuous heat transfer networks within the fluid, resulting in lower thermal conductivity. In addition, higher nanoparticle concentrations are more susceptible to interactions between the particles which promotes sedimentation and reduce long term dispersion stability [15]. These observations indicate that nanofluids exhibit better dispersion stability and thermal performance when freshly prepared.

A similar trend was observed in thermal conductivity enhancement which decreased significantly at higher concentrations. The 0.5 wt.% demonstrated the most significant decrease in enhancement, declining from 34.01 % before storage to 5.26% after 66 h. Even though thermal conductivity decreased after 66 hours of storage, all concentrations maintained higher thermal conductivity value compared with the base fluid of 0.436 W/mK. This confirms that although with storage the nanoparticle sedimentation reduces the thermal performance, the presence of TiO₂ nanoparticle continues to provide a thermal conductivity advantage over the base fluid.

Table 5. Comparison of thermal conductivity of TiO₂ immediately after preparation and after 66 h of storage

Storage time (h)	Thermal Conductivity (W/m K)					
	Base fluid	0.1 wt.%	0.2 wt.%	0.3 wt.%	0.4 wt.%	0.5 wt.%
0	0.440	0.552	0.566	0.570	0.579	0.589
66	0.436	0.547	0.576	0.495	0.477	0.459

Table 6. Thermal conductivity enhancement of TiO₂ nanofluid immediately after preparation and after 66 h of storage

Storage time (h)	Thermal Conductivity Enhancement (%)					
	Base fluid	0.1 wt.%	0.2 wt.%	0.3 wt.%	0.4 wt.%	0.5 wt.%
0	25.45	28.63	29.62	31.74	34.01	25.45
66	25.50	32.01	13.44	9.38	5.26	25.50

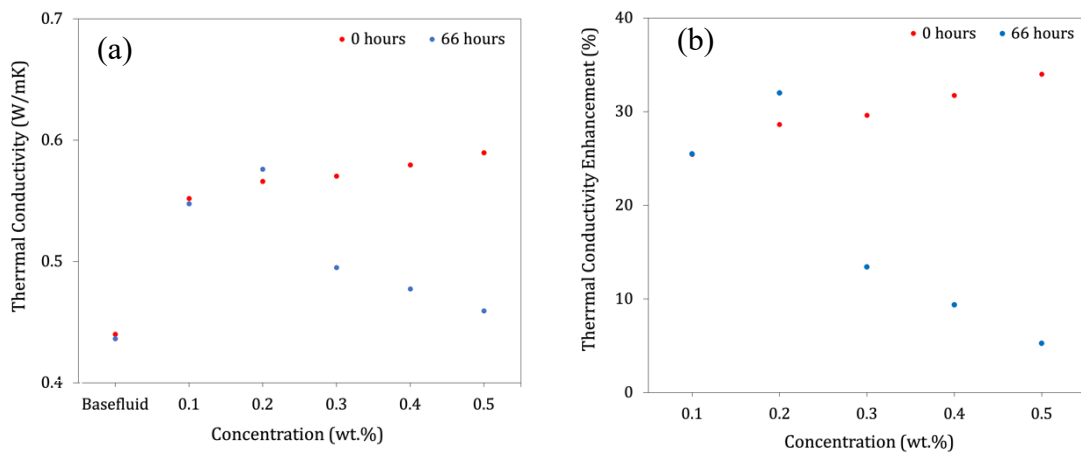


Figure 8. Influence of storage time on thermal performance of TiO₂ nanofluids measured immediately after preparation and after 66 h of storage (a) thermal conductivity (b) thermal conductivity enhancement

Overall, the findings show that increasing TiO₂ concentration improves the thermal conductivity of TiO₂/water-ethylene glycol (60:40) nanofluids. The 0.5 wt.% nanofluid exhibited the highest thermal conductivity and thermal conductivity enhancement immediately after preparation. Increasing temperature further improved thermal conductivity, with the greatest enhancement observed for 0.5 wt.% at 60 °C. However, storage for 66 h resulted in reduced thermal conductivity for the higher concentrations due to sedimentations. In contrast the lower concentrations maintained their thermal performance more effectively over time, while all nanofluids continued to exhibit higher thermal conductivity than the base fluid after storage.

Visual Observation of Nanofluid Stability

The visual appearance of the five different concentrations (0.1-0.5 wt.%) of TiO₂/water-ethylene glycol (60:40) nanofluids at different storage intervals is shown in Figure 9. The freshly prepared TiO₂ nanofluids exhibited excellent initial stability. A homogenous white appearance free of visible agglomeration or sedimentation was observed, indicating that initially the TiO₂ nanoparticles were well dispersed throughout the base fluid.

After being left undisturbed for 7 days, visible changes can be observed from the nanofluids. The top section of the nanofluid became more transparent compared to the lower part due to the phase separation as shown in Figure 9(b). The transparent region was most noticeable in the 0.1 wt.% nanofluid because it contained fewer dispersed TiO_2 nanoparticles than the higher concentrations samples. Similar sedimentation behavior was observed in all concentrations suggesting a gradual reduction in nanofluid stability during storage.

Following 14 days of storage, sedimentation became more pronounced in all samples. The transparent upper layer increased compared with the 7-day observation. These observations indicate that prolonged storage reduced the stability of the TiO_2 nanoparticles within base fluid causing them to sediment and settle under the influence of gravity and nanoparticle interactions [23]. The observed sedimentation with increasing storage time is consistent with previous findings which show that TiO_2 nanofluids gradually lose stability during storage due to nanoparticle settling [23,25]. Overall, the results suggest that prolonged storage reduces the uniform distribution of TiO_2 nanoparticles within the base fluid, thereby reducing nanofluid stability.

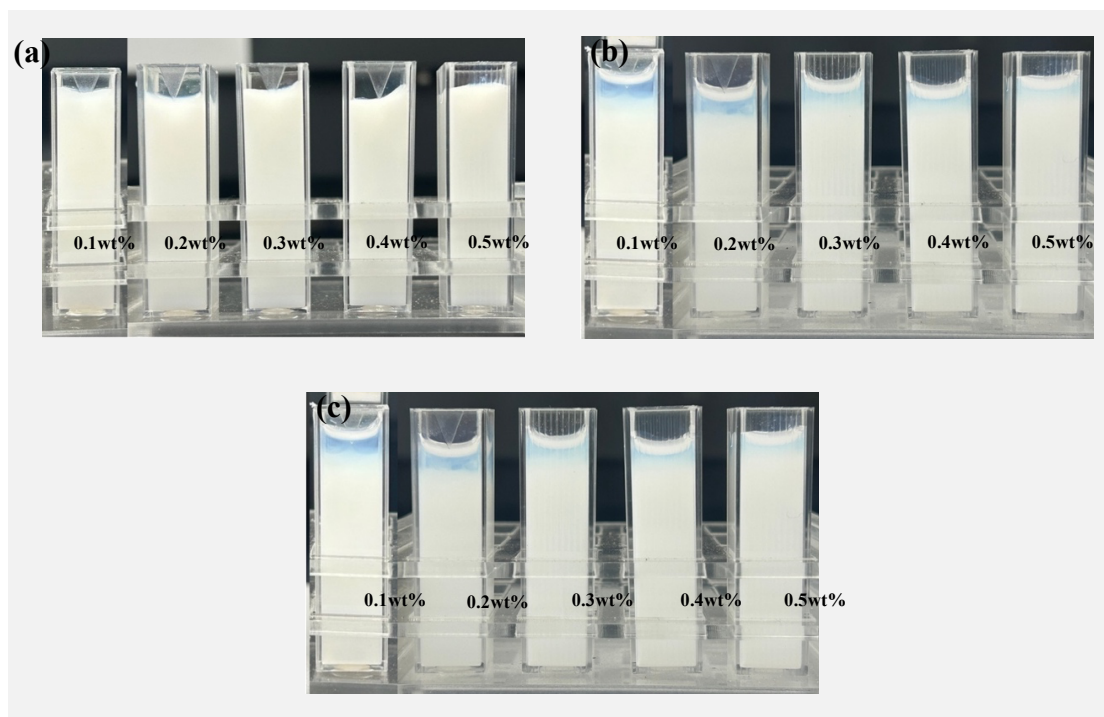


Figure 9. Visual observation of TiO_2 nanofluids at different intervals for five TiO_2 concentrations (0.1-0.5 wt.%): (a) freshly prepared, (b) after 7 days and (c) after 14 days

UV-Vis Spectroscopy

Figure 10(a) presents absorbance structure of the TiO_2 nanofluids. The absorbance increased with increasing nanoparticle concentrations across the measured wavelength range. This trend is expected as increase in concentration of TiO_2 nanoparticle results in a greater quantity of dispersed particles within the base fluid resulting in greater absorption and scattering of incident light. As a result, higher nanoparticle concentrations will produce higher absorbance values. Similar concentration dependent increases in

absorbance have been observed previously where higher nanoparticle concentration resulted in increase in absorbance [26].

For all concentrations the absorbance increased gradually from 800 nm to 400 nm. However, between 400 and 300 nm the absorbance reached the instruments maximum measurable limit and showed a flat plateau from until 200 nm. However, this plateau does not indicate constant absorbance, but rather it signifies detector saturation. The highly concentrated solutions absorb and scatter virtually all incident light leaving insufficient throughput intensity for the instrument to measure accurately. Consequently, the exact peak for TiO₂ in the UV region could not be measured. This intense UV-blocking behavior is characteristic of TiO₂ nanoparticles which exhibit stronger interaction with light in the UV region compared to the visible region [27].

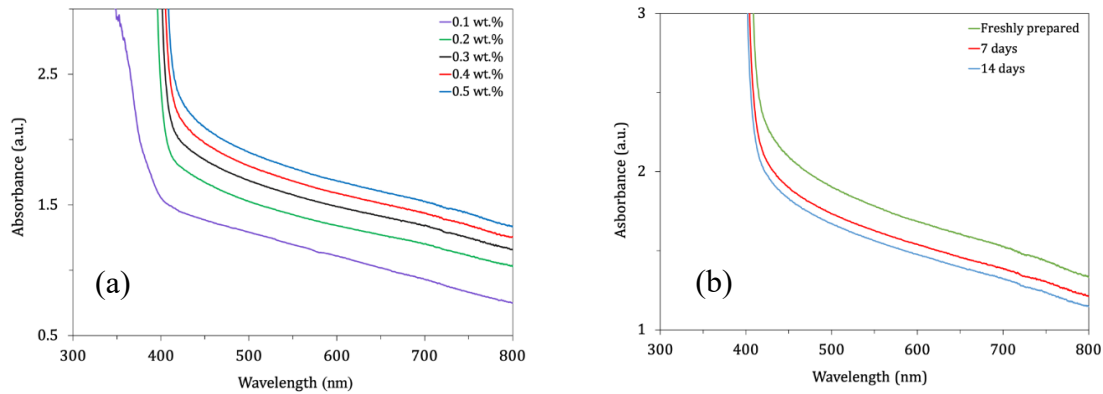


Figure 10. (a) UV-Vis spectra of freshly prepared TiO₂ nanofluids and (b) UV-Vis spectra of 0.5 wt.% of TiO₂ nanofluids immediately after preparation, after 7 days and after 14 days

Figure 10(b) shows the absorbance of 0.5 wt.% freshly prepared and after 7 and 14 days of storage. The freshly prepared sample showed highest absorbance throughout the measurement range. Absorbance gradually decreased (from 7 days to 14 days) as the storage time increased across the spectrum. The decrease in absorbance with increase in storage time is a direct indicator of sedimentation. As the nanofluid remains undisturbed overtime, the nano particles begin to fall out of the dispersed solution and sediment at the bottom. Due to this sedimentation, fewer nanoparticles remain well dispersed within the base fluid. Consequently, less light is absorbed and scattered during UV-Vis analysis reducing the absorbance and stability. Therefore, this reduction in absorbance indicates a gradual deterioration in nanofluid stability as storage period lengthens [28].

The UV-Vis results demonstrate that nanoparticle concentration has a significant influence on absorbance and stability of nanofluids. Prolonged storage reduces the amount of well-dispersed nanoparticles within the base fluid due to sedimentation reducing absorbance and stability. These findings indicate that although higher nanoparticle concentration results in greater absorbance, maintaining long-term dispersion stability still remains a challenge. To enhance long term stability of the nanoparticles overtime, the nanofluids can be homogenized during preparation. Increasing sonication period has also shown greater influence in achieving stable and high thermally preforming nanofluids [29].

Particle Size Analysis of TiO₂ Nanofluids

The hydrodynamic diameter of TiO₂ nanofluids ranged from 601.12-671.32, indicating the presence of agglomerates within the suspension. The hydrodynamic diameter is considerably larger than the primary TiO₂ nanoparticle size, suggesting nanoparticle-nanoparticle interactions and aggregation have occurred [30]. Among the samples, 0.2 wt.% showed the largest hydrodynamic diameter of 671.23 nm and the highest peak intensity of 730.22. These results suggest the presence of large particle agglomerates in the suspension as larger particles scatter more light than smaller ones. These larger agglomerates could have formed due to the increased collisions between TiO₂ nanoparticles [30]. The 0.1 wt.% nanofluid showed the smallest hydrodynamic diameter (602.12 nm) suggesting the presence of smaller particle agglomerates in the nanofluid compared to the other concentrations. Lowest Polydispersity Index (PDI) (0.189) was recorded for the 0.5 wt.% indicating a relatively uniform particle size distribution. Despite this, its large hydrodynamic diameter (625.24 nm), suggests that the nanoparticles must have formed uniformly sized aggregates than remaining as individual nanoparticles.

The PDI values between 0.189 and 0.239 indicates relatively uniform particle size distribution and acceptable dispersion stability of the nanofluids [31] Although the differences were relatively small, the variation in hydrodynamic diameter and intensity suggest that TiO₂ concentrations influence particle interactions within the suspension. Higher nanoparticle loading increases the likelihood of particle collisions which can promote aggregation [32]

Table 7. Particle size analysis of TiO₂ nanofluids at different concentration after five weeks of storage

Sample concentration (wt.%)	Polydispersity index (PDI)	Hydrodynamic diameter (nm)	Peak intensity
0.1	0.221	601.65	591.78
0.2	0.238	671.32	730.22
0.3	0.231	629.62	648.47
0.4	0.238	602.12	586.49
0.5	0.189	625.24	632.93

CONCLUSIONS

This study investigated the effect of TiO₂ nanoparticle concentration on the stability and thermal conductivity of TiO₂ nanofluids formulated using a 60:40 water-ethylene glycol-based fluid. The results demonstrated that increasing TiO₂ concentration enhanced the thermal conductivity of TiO₂ nanofluids. The 0.5 wt.% nanofluid exhibited the highest thermal conductivity, thermal conductivity enhancement and UV-Vis absorbance immediately after preparation indicating superior thermal conductivity and stability. An increase in temperature further enhanced thermal conductivity of the nanofluids, particularly at higher concentrations, due to increased Brownian motions of nanoparticles promoting more efficient heat transfer. After storage for 66 h, the higher concentrations exhibited reduced thermal conductivity due to nanoparticle sedimentations while lower concentrations maintained their thermal performance more effectively. Visual

observation confirmed that prolonged storage affected the homogenous distribution of nanoparticles within the base fluid resulting in sedimentation and reduced stability. Higher nanoparticle concentration produced greater absorbance because of the increased number of dispersed nanoparticles. However, maintaining dispersion stability remains a challenge as absorbance gradually decreased with time. Dynamic light scattering indicated the formation of large aggregates within the suspension due to more frequent collision between the nanoparticles with prolonged storage.

TiO₂ concentration is an influential factor in determining the thermal conductivity and stability of TiO₂/water-ethylene glycol (60:40) nanofluids. Although greater nanoparticle concentration provides greater thermal conductivity, further optimization is necessary to enhance the nanoparticle stability over prolonged periods. This can be achieved through optimized surfactant selection, sonication conditions or nanoparticle surface modifications. Based on the results obtained the freshly prepared 0.5 wt.% demonstrated the best thermal performance and stability and shows strong potential as an improved heat transfer medium for automotive cooling application.

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AUTHOR CONTRIBUTIONS STATEMENT

Hassan, A. H. (Methodology; Formal analysis; Data Curation; Writing – original draft), Azman, N. A. (Data Curation; Writing – review & editing), Abdullah, N. (Conceptualization; Validation; Funding acquisition; Supervision; Writing – review & editing), Mohd Nasir, N. A. A. (Draft manuscript preparation), Norizan, M. N. (Draft manuscript preparation), Jamari, N. L-A. (Draft manuscript preparation), Ahmad Syah, N. A. (Draft manuscript preparation), Mohd Noor, S. A. (Draft manuscript preparation), Chandramoulee Swaran, Y. (Draft manuscript preparation)

CONFLICT OF INTEREST

Author declares that there is no conflict of interest regarding the publication of the paper.

DATA AVAILABILITY

The raw and processed data required to reproduce these findings are available from the corresponding author upon reasonable request.

ETHICS APPROVAL

Not applicable.

REFERENCES

- [1] Rahman MA, Hasnain SMM, Pandey S, Tapalova A, Akylbekov N, Zairov R. Review on Nanofluids: Preparation, Properties, Stability and Thermal Performance Augmentation in Heat Transfer Applications. *ACS Omega* 2024;9:32328–49. <https://doi.org/10.1021/acsomega.4c03279>
- [2] Abbas F, Ali HM, Shah TR, Babar H, Janjua MM, Sajjad U, et al. Nanofluid: Potential evaluation in automotive radiator. *Journal of Molecular Liquids* 2020;297:112014. <https://doi.org/10.1016/J.MOLLIQ.2019.112014>
- [3] Kavitha R, Ravi S, Ladu NSD. Competitive roles of plasticity, elasticity, and radiation in heat/mass transfer of Casson–Williamson–Maxwell nanofluid over a porous stretching sheet. *Discover Nano* 2026;21:229. <https://doi.org/10.1186/s11671-026-04654-y>
- [4] Sofiah AGN, Samykano M, Pandey AK, Kadirgama K, Sharma K, Saidur R. Immense impact from small particles: Review on stability and thermophysical properties of nanofluids. *Sustainable Energy Technologies and Assessments* 2021;48:101635. <https://doi.org/10.1016/j.seta.2021.101635>
- [5] Pusat S, Karagöz Y, Attar A, Karagoz S. A study of TiO₂-enhanced nanofluids in internal combustion engines using neural networks. *Scientific Reports* 2024;14(1):19251. <https://doi.org/10.1038/s41598-024-68701-3>
- [6] Erkan A, Tüccar G, Tosun E, Özgür T. Comparison of effects of nanofluid utilization (Al₂O₃, SiO₂, TiO₂) with reference water in automotive radiators on exergetic properties of diesel engines. *SN Applied Sciences* 2021;3(3):365. <https://doi.org/10.1007/s42452-021-04368-z>
- [7] Hsu CY, Mahmoud ZH, Abdullaev S, Ali FK, Ali Naeem Y, Mzahim Mizher R, et al. Nano titanium oxide (nano-TiO₂): A review of synthesis methods, properties, and applications. *Case Studies in Chemical and Environmental Engineering* 2024;9:100626. <https://doi.org/10.1016/J.CSCEE.2024.100626>
- [8] Ahmed SA, Ozkaymak M, Sözen A, Menlik T, Fahed A. Improving car radiator performance by using TiO₂-water nanofluid. *Engineering Science and Technology, an International Journal* 2018;21:996–1005. <https://doi.org/10.1016/J.JESTCH.2018.07.008>
- [9] Chandoliya R, Sharma S, Sharma V, Joshi R, Sivanesan I. Titanium Dioxide Nanoparticle: A Comprehensive Review on Synthesis, Applications and Toxicity. *Plants* 2024;13(21):2964. <https://doi.org/10.3390/plants13212964>
- [10] Ramadhan AI, Azmi WH, Mamat R. Heat transfer characteristics of car radiator using tri-hybrid nanocoolant. *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 863, Institute of Physics Publishing; 2020;863(1):012054. <https://doi.org/10.1088/1757-899X/863/1/012054>
- [11] Zubair MM, Seraj M, Faizan M, Anas M, Yahya SM. Experimental study on heat transfer of an engine radiator with TiO₂/EG-water nano-coolant. *SN Applied Sciences* 2021;3(4):333. <https://doi.org/10.1007/s42452-021-04441-7>
- [12] Guerrero EE, Portilla ÁA, Pontón PI. The effect of TiO₂/ethylene glycol-based nanocoolant on the pollutant emissions from a diesel passenger van at Quito

- ambient conditions. *Materials Today Proceedings* 2022;49:129–34. <https://doi.org/10.1016/J.MATPR.2021.07.483>
- [13] Hilmin MNHM, Remeli MF, Singh B, Affandi NDN. Thermoelectric power generations from vehicle exhaust gas with TiO₂ nanofluid cooling. *Thermal Science and Engineering Progress* 2020;18:100558. <https://doi.org/10.1016/J.TSEP.2020.100558>
- [14] Senejani AK, Mehdipour R. Investigating the effect of nanofluids of aluminum oxide and titanium dioxide on the heat transfer of the engine cooling coil by considering the boiling phenomenon. *Heat Transfer* 2020;49:2868–86. <https://doi.org/10.1002/htj.21750>
- [15] Nieh HM, Teng TP, Yu CC. Enhanced heat dissipation of a radiator using oxide nano-coolant. *International Journal of Thermal Sciences* 2014;77:252–61. <https://doi.org/10.1016/J.IJTHEMALSCI.2013.11.008>
- [16] Saidi NM, Abdullah N, Norizan MN, Janudin N, Mohd Kasim NA, Osman MJ, et al. Surface-Oxidised Carbon Nanofibre-Based Nanofluids: Structural, Morphological, Stability and Thermal Properties. *Nanomaterials* 2022;12(21):3922. <https://doi.org/10.3390/nano12213922>
- [17] Wu J, Li Z, Jian W, Ma D. Experimental Investigation into Stability, Heat Transfer, and Flow Characteristics of TiO₂-SiO₂ Hybrid Nanofluids Under Multiple Influencing Factors. *Nanomaterials* 2026;16(6):359. <https://doi.org/10.3390/nano16060359>
- [18] Al-Darkazali WN, Hamood SS, Aldaher N, Harbi NS. Studying the effect of using metal oxide nanofluids on the performance of a single-tube heat exchanger. *Chinese Journal of Analytical Chemistry* 2025;53(3):100497. <https://doi.org/10.1016/j.cjac.2025.100497>
- [19] Surakasi R, Sripathi S, Nadimpalli SP, Afzal S, Singh B, Tripathi M, et al. Synthesis and Characterization of TiO₂-Water Nanofluids. *Adsorption Science and Technology* 2022;2022:3286624:1–9. <https://doi.org/10.1155/2022/3286624>
- [20] Praveen P, Viruthagiri G, Mugundan S, Shanmugam N. Structural, optical and morphological analyses of pristine titanium di-oxide nanoparticles - Synthesized via sol-gel route. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy* 2014;117:622–9. <https://doi.org/10.1016/j.saa.2013.09.037>
- [21] Lal M, Sharma P, Ram C. Synthesis and photocatalytic potential of Nd-doped TiO₂ under UV and solar light irradiation using a sol-gel ultrasonication method. *Results in Materials* 2022;15:100308. <https://doi.org/10.1016/j.rinma.2022.100308>
- [22] Miseo E V, Larkin Peter J. Fourier Transform Infrared Spectroscopy (FT-IR) Diamond Attenuated Total Reflection (ATR) Measurements: The Good, the Bad, and the (Really) Ugly. *Applied Spectroscopy Practica* 2025;3:27551857251336264. <https://doi.org/10.1177/27551857251336262>
- [23] Razzaq I, Xinhua W, Rasool G, Sun T, Shflot AS, Malik MY, et al. Nanofluids for Advanced Applications: A Comprehensive Review on Preparation Methods, Properties, and Environmental Impact. *ACS Omega* 2025;10:5251–82. <https://doi.org/10.1021/acsomega.4c10143>
- [24] Heshmatian S, Aligholami M, Shafiei S, Madiba IG, Azizi S, Hussein AA, et al. Size effect on thermal conductivity and stability of TiO₂/MWCNT-based hybrid

- nanofluids synthesized via probe ultrasonication. *RSC Advances* 2025;15(46):37939-53. <https://doi.org/10.1039/d5ra06184a>
- [25] Ulhakim MT, Sukarman, Khoirudin, Nazar Fazrin, Tomas Irfani, Amri Abdulah. The Qualitative Stability and Thermal Properties Investigation of TiO₂-EG/W Nanofluids Through Experimental Validation. *Jurnal Asimetrik: Jurnal Ilmiah Rekayasa & Inovasi* 2024;143–52. <https://doi.org/10.35814/asiimetrik.v6i1.5882>
- [26] Nanan K, Chuwattanakul V, Pramuanjaroenkij A, Eiamsa-Ard S. Effect of a TiO₂/Water Nanofluid on the Thermal Cooling of a Central Processing Unit. *Chemical Engineering Transactions* 2024;109:595–600. <https://doi.org/10.3303/CET24109100>
- [27] Induranga A, Galpaya C, Vithanage V, Koswattage KR. Thermal Properties of TiO₂ Nanoparticle-Treated Transformer Oil and Coconut Oil. *Energies* (Basel) 2024;17(1):49. <https://doi.org/10.3390/en17010049>
- [28] Ramadhan AI, Azmi WH, Mamat R, Hamid KA, Norsakinah S. Investigation on stability of tri-hybrid nanofluids in water-ethylene glycol mixture. *IOP Conference Series Materials Science and Engineering* vol. 469, 2019;469(1):012068. <https://doi.org/10.1088/1757-899X/469/1/012068>
- [29] Ghamarpoor R, Fallah A, Jamshidi M. Investigating the use of titanium dioxide (TiO₂) nanoparticles on the amount of protection against UV irradiation. *Scientific Reports* 2023;13(1):10057. <https://doi.org/10.1038/s41598-023-37057-5>
- [30] Nugroho A, Bo Z, Mamat R, Puranto P, Ghazali MF, Supriyatna YI, et al. Optimization and stability analysis of TiO₂-palm olein nano-biolubricants using one-factor-at-a-time. *Journal of Molecular Liquids* 2025;438. <https://doi.org/10.1016/j.molliq.2025.128525>
- [31] Izzati N, Rafaizul AM, Afzanizam M, Rosli M, Norizan MN, Aisyah N, et al. Effect of Mechanical Technique on the Stability and Thermal Conductivity of MgO/Commercial Coolant-Based Nanofluid. *Solid State Science and Technology* 2025;33:162–78.
- [32] Johnson L, Gray DM, Niezabitowska E, McDonald TO. Multi-stimuli-responsive aggregation of nanoparticles driven by the manipulation of colloidal stability. *Nanoscale* 2021;13(18):8345-78. <https://doi.org/10.1039/d1nr01190a>
- [33] Tofan G, Țuguî AC, Atanase L, Bejan D, Minea AA. Experimental Investigation of Surfactant Addition Influence on the Properties of Titanium Oxide Water Nanofluid. *International Journal of Thermophysics* 2026;47(3)47. <https://doi.org/10.1007/s10765-026-03747-1>
- [34] Mancardi G, Alberghini M, Aguilera-Porta N, Calatayud M, Asinari P, Chiavazzo E. Multi-Scale Modelling of Aggregation of TiO₂ Nanoparticle Suspensions in Water. *Nanomaterials* 2022;12. <https://doi.org/10.3390/nano12020217>