Thermal Analysis of a Developed Hybrid Nanofluid as a Sustainable Coolant for Automobile Radiator Application

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ABSTRACT

The automobile radiator's internal components are prone to scale accumulation, rust, and corrosion, which impede coolant flow and reduce efficiency. The operation of the cooling fan and pump increases the vehicle's energy consumption, which affects the battery life of electric vehicles and the fuel efficiency of conventional vehicles. To overcome these challenges, this study aimed to develop mono- and hybrid nanofluids as sustainable coolants for radiator applications. The current study used mono nanoparticles of Graphene and TiO_2, and a 50% graphene/TiO_2 hybrid was created. SEM-EDS XRD was employed to characterize the nanoparticles and ascertain the mass ratio of constituents in the noodles. The mass flow rate of the temperature from the various regions and the heat transfer rate of the nano-coolant were then measured experimentally. It was shown in the present study that hybrid and mono-particulate nanoparticles incorporated within pH and thermal conductivity W Mk improved the coolant. The heat transfer rate was increased when the mass concentration of TiO_2 nanoparticles in the water-based TiO_2 nano coolants. The heat transfer rate rose from 13186.91 W (0.3 g) to 14893.43 W (0.7 g) with the increase of the concentration of the nanoparticles from 0.3g to 0.7g it was observed from the parametric analysis of the mono and the hybrid nano coolants that the TiO_2 nano-coolant performed very well compared to the graphite, having a percentage deviation of 8.2%, the hybrid nano-coolants 2.7% and the other two were reinforced. In addition, the TiO_2 50% plus Graphene 50% hybrid nano coolants were superior to the graphene nano coolants by 6.3%. It follows that the development of coolants at the nanoscale — specifically, the use of nanoparticles — is a technique that contributes to the longevity of automotive parts. This also suggests less intensive maintenance and fewer changes to automotive components. Furthermore, high-conductivity nanoparticles, such as tri-hybrid (carbon/metallic) or carbon-based nanoparticles, prevent particle agglomeration and require fewer surfactants, leading to cleaner environmental conditions.

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1. Introduction

Most coolants are non-biodegradable and extremely harmful; their application in automotive radiators has contributed to pollution. In recent years, using nanofluids as coolants has significantly improved radiator heat exchange efficiency (Arora & Gupta, 2020). Nanofluid refers to a fluid that contains particles of the order of a few nanometers in size, which significantly enhance its thermal properties, making these fluids more efficient in cooling and facilitating heat transfer. .'To increase cooling efficiency, a new type of coolant, hybrid nanofluid, has been developed by adding conventional coolant to nanoparticles. The application of hybrid nanofluids in car radiators would be beneficial for controlling the engine temperature and decreasing emissions (Ramalingam et al., 2020). Graphene, a two-dimensional material with single-layer carbon atoms packed in hexagonal lattices. Graphene, with its excellent mechanical and electrical properties and great thermal performance, is reported to be of great use in various technologies (Dada & Popoola, 2025). Manufacturers of graphene typically produce sub-millimetre flakes, 5–10 nm thick, through the purification of chemical extracts and then use liquid-phase chemical routes (e.g., liquid-phase exfoliation) or electrochemical techniques to expand them. These functional flakes with unique properties make them appealing for sensors, power electronics, energy storage materials, and biosensing applications. Graphene, due to its stiffness, high thermal conduction values, and electronic conductive properties, remains at the cutting edge in nanoelectronics with respect to manufacturability of transistors (as long as device scale is larger than this value) (Yusaf et al., 2022). Durability, fuel economy, and engine performance all play a part in the radiator's efficiency. Serious damage can occur if the engine is overheating, which may result from inadequate heat radiation by the radiator because of blockages or clogs in the radiator.

Furthermore, overheating may result in mechanical failure of the car. Along with these, the coolant's efficacy diminishes over time, whether due to pollution, oxidation, or simply poor maintenance, which lowers the efficiency of heat transfer. As the coolant becomes soured, it tends to lower its dissolution. The study goal was delineated in vitro by Yaw et al. (2023) who assessed the impact of mono- or hybrid metal oxides, Al_2O_3 and TiO_2, used with or without plant-extracted cellulose nanocrystals (CNC) at varying concentrations. The plant-extracted CNC was posed as a potential bioinspired nanofluid. The base fluid in which the nanocellulose is dispersed is 60% ethylene glycol and 40%. Titanium Dioxide, Aluminium Oxide, Cellulose Nanocrystal, Alumina/Titanium Dioxide, and Alumina/Cellulose Nanocrystal Nanofluids were found to have maximum absorption peaks at 0.9% volume concentration, which is indicative of better suspension stability. Mono nanofluids were no exception to this trend, where it was noted that the Al_2O_3 nanofluids outdid the rest in thermal conductivity, followed by the CNC and TiO_2 nanofluids. It was seen that the Al_2O_3/CNC hybrid nanofluids, at 0.9% concentration, possess higher thermal conductivity than the Al_2O_3/TiO_2 hybrid nanofluids. The results indicate that Al_2O_3/CNC hybrid nanofluids surpass other mono and hybrid nanofluids in viscosity at any given concentration.

Kumar and Arivazhagan (2024) used a new hybrid nano-coolant (HyNc), and a car radiator with a hybrid nano-phase change material (HyN-PCM) cooler was created and experimentally examined for the manufacture of hybrid nanoparticles. Graphene nanoplatelets (GnP) and multi-walled carbon nanotubes (MWCNT) nanoparticles were chosen and taken in a 50:50 ratio. Both HyNc and HyN-PCM were prepared using the non-covalent technique. In five steps, nano-coolants were made for varying volume proportions ranging from 0.1 to 0.5%. Two methods—a radiator and a radiator with a PCM cooler—were compared in the experiments. Compared to the base coolant, the prepared HyNc's thermal conductivity (TC) increases to 59%. At 70 °C intake temperature and 0.5% volume proportion, the largest improvements in convective heat transfer coefficient (CHTC) and overall heat transfer coefficient (OHTC) were noted, at approximately 75% and 125%, respectively. The radiator with a HyN-PCM cooler has a maximum effectiveness increase of roughly 1% compared to a radiator without a cooler.

Satpute et al. (2026) investigated CFD methodology to assess engine cooling performance at different copper nanoparticle concentrations and validate the results through experimentation. The analysis was performed under steady-state conditions, and the influence on engine cooling and pressure drop was identified. In terms of engine cooling, Cu-EG nanofluid was determined to be superior to base EG. The study also found that the degree of cooling is a linear function of nanofluid concentration. The findings demonstrated a 13.17% improvement in cooling at a 5% concentration as compared to EG coolant, while the nanofluid cooling produced a marginally larger pressure drop of 8.85%. Nanofluids, including TiO_2, Al_2O_3 and CuO, are discussed earlier where it was observed that the nanofluids have significant heat transfer performance enhancement. Recent studies have also touched upon hybrid nanofluids, especially mixtures of metal-oxide nanoparticles, with additional improvements in thermophysical characteristics and radiator efficiency. Nonetheless, despite the high thermal conductivity and stability of graphene-based nanomaterials, fewer experimental studies have investigated the formation and thermal efficiency of TiO2-graphene hybrid nanofluids for use as radiators in automobiles. Thus, the current research will fill this gap by creating and experimentally testing a TiO2-graphene hybrid nanofluid as a sustainable coolant in an automobile radiator. Therefore, this study focuses on the thermal analysis of a developed hybrid nanofluid made up of TiO_2 and Graphene nanoparticles with a base fluid (water) as a sustainable coolant for radiator application. The study investigates the developed nano-coolant in terms of the Volume Concentration of Graphene and TiO_2 Nanoparticles, and the physicochemical properties of both the mono and hybrid nano-coolants via an automobile ring setup. The uniqueness of this study is the ability to produce sustainable coolant that is a hybrid with complementary nanoparticles which is more effective in terms of thermal conductivity and stability to improve the cooling performance of radiator automobiles. It also exploits the synergy of nanoparticles to obtain high levels of heat transfer efficiency and stability compared to traditional single- or past hybrid nanofluids. The nanoparticles were studied at various concentration values for optimisation, which helps prove the viability of the developed nanoparticles compared with past research work, including the ability of TiO2 to increase the functionality of the coolant by over 40%. It discusses gaps in research on sustainable hybrid nanofluids that have been developed and thermally tested for practical use in automobile radiators. Also, the blend of TiO_2 and Graphene nanoparticles is very significant for corrosion reduction in radiator processes. As this blend has not been wildly considered in other literature. A good alternative is Titanium Dioxide (TiO_2) and graphene nanoparticle used in the development of superior radiator coolants which show a considerable enhancement in thermal conductivity compared to normal water. The TiO_2 is very stable, chemically resistant and non-toxic whereas graphene nanoplatelets are characterized by the highest thermal conductivity. They serve as high-performance hybrid nanofluids together that bridge a gap in the literature of the creation of a sustainable hybrid nanofluid.

2. Methodology

2.1 Materials

This section outlines the reasons for choosing the specific nanoparticle used in this study, including:

i. Titanium oxide nanoparticles (TiO_2) are interesting compounds made of titanium and oxygen, as presented in Figure 1a. Their unique properties allow them to be used in various applications, from sunscreen to coatings and even catalysts.
ii. Graphene (Gr) nanoparticles consist of a single layer of carbon atoms arranged in a two-dimensional structure, as presented in Figure 1b. They are well-known for their exceptional electrical conductivity, strength, and versatility, which makes them suitable for energy storage and electronics.
iii. Distilled water is made by removing minerals and impurities through distillation. It is often used in labs and experiments that need pure water.
iv. Equipment for mixing or dispersing materials includes an ultrasonic bath or a magnetic stirrer. An ultrasonic bath uses high-frequency vibrations to agitate and distribute particles, while a magnetic stirrer uses a rotating magnetic field to create stirring action.
v. Beakers or containers for mixing: Glass or plastic vessels hold and mix liquids or substances during experiments or laboratory processes. They come in various sizes and are essential tools in scientific research.

(a) (b)

Figure 1: (a) Titanium Oxide and (B) Graphene Nanoparticles

2.2 Method

2.2.1 Procedure for Developing the Hybrid Radiator Nano-Coolant

The developed mono nano-coolant and the hybrid nano-coolant begin by weighing the desired amounts of titanium oxide (TiO_2) nanoparticles and graphene (Gr) nanoparticles separately, considering the desired concentration in the coolant. The concentrated value for the preparation is 500ml of distilled water in a beaker, and the various nanoparticle concentrations are 0.3, 0.4, 0.5, 0.6, and 0.7, while ensuring their high quality and prior characterization of size and properties for nanoparticle dispersion measure an appropriate volume of distilled water based on the desired coolant quantity. Considering sufficient volume to accommodate the nanoparticles and facilitate thorough mixing, then pour the distilled water into a clean beaker or container, gradually add the titanium oxide (TiO_2) nanoparticles to the distilled water while continuously stirring to achieve uniform dispersion, employing a magnetic stirrer and ultrasonic bath was employed to enhance the dispersion process and prevent aggregation, and once the titanium oxide (TiO_2) nanoparticles are well-dispersed, introduce the graphene (Gr.) nanoparticles to the mixture and continue stirring or employing the chosen dispersion method until both types of nanoparticles are uniformly dispersed.

Thereafter, take samples of the mono and the hybrid nano-coolant are taken for characterization and stability testing, thermal conductivity testing, and viscosity measurement to assess its properties, and monitor its stability by observing sedimentation or agglomeration of nanoparticles over time, aiming for minimal settling in a stable coolant; during application and evaluation stages, flush the existing coolant from the radiator system to ensure proper cleaning and residue removal, fill the radiator system with the hybrid nano-coolant using suitable filling techniques to prevent air pockets, run the radiator system and evaluate its performance in terms of cooling efficiency and temperature regulation, while monitoring for indications of clogging, corrosion, or adverse effects resulting from the coolant, making necessary adjustments to the coolant formulation or concentration for optimization; throughout the entire process, strictly adhere to safety guidelines for handling nanoparticles, including wearing protective equipment, working in a well-ventilated area, and following proper disposal procedures for nanoparticle waste. Figure 2 shows the radiator application's mono- and hybrid-coolant preparation flow chart.

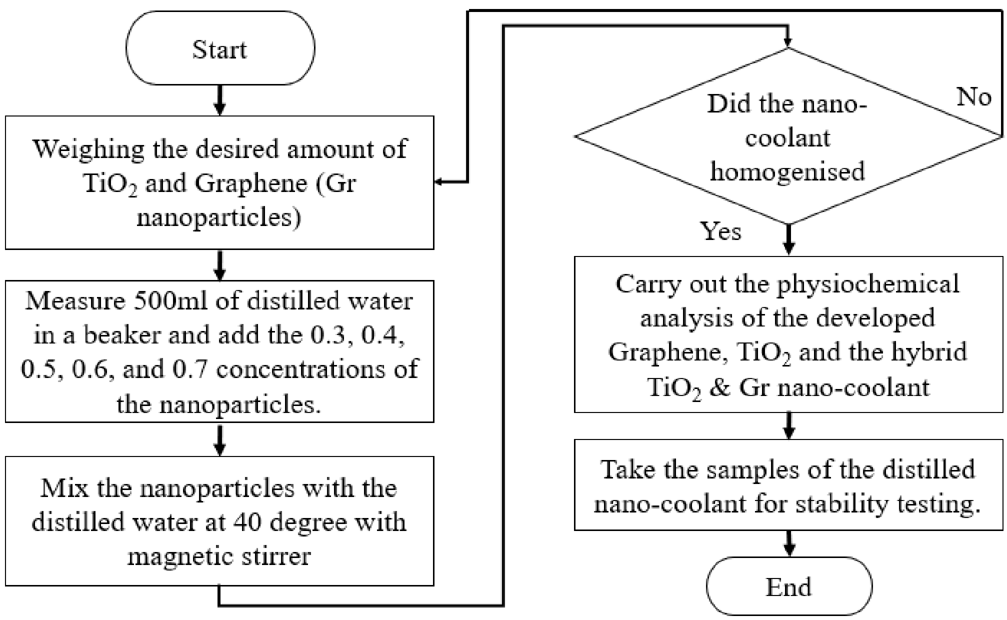


Figure 2: The Experimental Flow Chart for Developing the Nano-Coolant for the Radiator Application

2.2.2 Determination of the Nano-Coolant Stability

The study investigates the stability of a nano-coolant, i.e. how far properties and characteristics are preserved as time goes on with the following method:

First of all, an initial sample of the nano-coolant was prepared, according to the proposed formulation and mixing process, in order to obtain a representative sample. Then, mix well until the ingredients are combined. The next step was to study the initial features of nano-coolant as a reference point. This consisted of finding its thermal conductivity, density, viscosity, and other characteristics. Then select the storage conditions for the nano-coolant stability test. These conditions will be designed to represent the anticipated coolant or intended storage environment. Taking into account factors such as humidity, light exposure, temperature, and duration of the stability test. The samples, as a part of nano-coolant, were transferred into suitable beakers. Then keep the jars tightly closed to prevent evaporation and contamination. Store the vials under storage conditions as defined in 2-8. Note when you started the test.

2.2.3 Method for Developing the Hybrid Nano-coolants and Determining Density, Viscosity, and Thermal Conductivity

In this paper, density, viscosity and thermal conductivity of both mono and hybrid nano-coolants are quantified to understand which use case will be appropriate for each formulation. The experimental and computational procedure to obtain these performance figures of merit is described in the following sections. The authors first discuss a mono-coolant, and then hybrid-coolants consisting of mass-formulated composite dispersions of ultra-pure distilled water and various nano-material systems (graphene, TiO_2, and some other metal content) in the carrier fluid. A high-shear mixer provides the agitation necessary to achieve particle stabilization and homogeneity. After each batch, density and viscosity are recorded with a vibrating-tube densimeter and a cone-plate viscometer, respectively. Both instruments are operated at the same controlled laboratory temperature to minimize thermal drift. The thermal conductivity is assessed by a guarded heat-flow meter calibrated against certified reference materials across a temperature span of 30 to 70 °C. Following instrument stabilization, the hybrid nano-coolants are poured into the guarded meter chamber with care to expel entrained air. A thermoelectric heat source creates a known thermal gradient; the resulting steady-state power is measured and, combined with the temperature difference across the sample, provides the conductivity coefficient at the measured density and viscosity.

To measure the densities of the pure and hybrid nano-coolants, the authors employ a high-precision density meter or a calibrated pycnometer. Each instrument is first calibrated using reference liquids of precisely known density, typically distilled water at room temperature. Precautions are taken to eliminate any entrained air or particulate matter in the hybrid nano-coolant; after vacuum degassing, the samples are introduced into the instrument. The instrument then stabilizes, and the density value is securely recorded from the digital display. Viscosity tests of the pure nanocoolant as well as that of the blended hybrid-coolant are carried out with a rotational spindle viscometer. The calibrations are made using distilled water and a series of standard glycerin solutions. Experimental parameters (rotational speed, constant shear stress, and temperature remained at 40C) are adopted according to the instrument manual, followed by recording of viscosity measurements. Moreover, the three individual measurements of each sample are tested for replicability. Then the average density, viscosity, as well as consequential thermal conductivity values, are collected based on these replicates to increase reliability.

2.3 Procedure for the Radiator Cooling Experiment

All the experiments of density, viscosity, and thermal conductivity are repeated three times in our research; thus, the data is reliable and reproducible. Average values are then calculated based on these multiple trials. In performing a bench-scale radiator-cooling test, an overall approach is used to ensure that the results are repeatable and reproducible enough for good-faith performance comparison with a methodology to measure the cooling propensity and hydraulic resistance of the nano-coolant mixture in flow conditions.

In this study, the centrality of the experimental process is dissected stage by stage. The first part of a study is the setup step, which is a condition for obtaining any significant results at all. It is important, therefore to confirm that the radiator is mounted properly and plumbed into this thermal management circuit within the device so that when fluids are issued in an investigation unobstructed passage of coolant occurs at all times. Then the radiator must be flushed to remove any surface debris, mineral scale, or other pollutants that could impede heat transfer and flow. The study uses four thermocouples for temperature capture to obtain accurate thermal point readings during the trial; these are as follows. This configuration facilitates continuous monitoring of temperature dynamics. Below are the steps to be followed in installing the radiator pattern graffiti:

i. Fill the nano-coolant tank with 30 litres of water, then add pre-mix nano-coolant.
ii. Column: as shown in Figure 3 arrange your four thermocouples in this precise fashion. T1 measures the nano-coolant temperature at the reservoir, T2 records the radiator reservoir temperature, T3 observes the wall temperature of the radiator and finally, T4 registers the coolant temperature leaving from it.
iii. Hook up the car's loop system to a power source to start it up.
iv. While at it also record room-ambient temp. right by the rad with a separate thermocouple. To examine the cool-down characteristics of the graphene-containing nano-coolant, as shown in Figure 3, the test rig fills the reservoir and switches on the heater for 20 minutes, followed by driving the automobile ring for five minutes. Simultaneously, the experimental team has access to real-time cooling data.

Researchers constantly record the input and output temperatures of the nanofluid during flow inside the heat exchanger. Observations are carried out until enough thermal equilibrium and/or performance data is gathered—the observation length depends on the radiator test configuration used (Thirumaran et al., 2026). After the measuring task, personnel move on to natural analysis and calculate the exchanged thermal power using rates of heat transfer equations and radiator effectiveness. The study determined how well a radiator cools a fluid by comparing the temperature of the fluid entering and leaving. Also, various flow rates and other factors could affect radiator performance. These are useful inputs analysis that influences the radiator's operation.

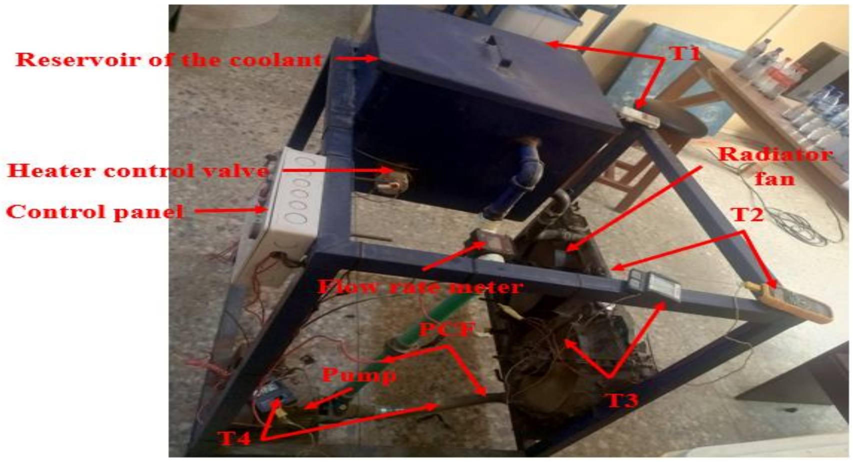


Figure 3: The Automobile Ring Setup for the Research

2.3.1 Estimation of Thermal Transfer Parameters

The study carried out calculations using the standard equations for heat flow to take a closer look at the results obtained from our experiments. Equations (1) to (10) give us the formula for Tb, the bulk temperature, which is found by averaging the inlet and outlet temperatures of the fluid as it moves through the radiator (Feng et al., 2026).

$$T_b = \frac{T_2 + T_1}{2} \tag{1}$$

T_w is the wall temperature, which is the average of the temperature of the two surface thermocouples and is expressed as;

$$T_w = \frac{T_3 + T_4}{2} \tag{2}$$

The heat gain is calculated using equation (3)

$$\dot{Q} = \dot{m}c_p \Delta T \tag{3}$$

The mass flow rate of the working fluid is given in equation (3.4);

$$\dot{m} = \rho V \tag{4}$$

From Newton's law of cooling, heat transfer can be calculated using equation (5);

$$\dot{Q} = hA_s(T_b - T_w) \tag{5}$$

When equations (3) and (5) are compared, h was obtained and expressed as shown in equation (6).

$$h = \frac{\dot{m}C_p(T_1 - T_4)}{A(T_b - T_w} \tag{6}$$

Estimation of R_e, P_e and P_r were as follows

$$R_e = \frac{\rho\, VD_h}{\mu} \tag{7}$$

$$P_e = \frac{VD_h}{\alpha} \tag{8}$$

$$P_r = \frac{V}{\alpha} \tag{9}$$

Where V is estimated as;

$$V = \frac{K}{\rho C_p} \tag{10}$$

The experimental N_u was expressed as;

$$N_u = \frac{\mathrm{h}D_h\mathrm{k}}{\kappa} \tag{11}$$

The overall h was given by

$$\frac{1}{U} = \left(\frac{1}{h_i A} + \frac{1}{2\pi k L}\ln\frac{r_2}{r_1} + \frac{1}{h_o A}\right) \tag{12}$$

The heat transfer based on the overall h was estimated as given in equation (13);

$$\dot{Q} = UA\Delta T \tag{13}$$

2.3.2 Uncertainty and error analysis

The sources of error in this project were principally from temperature and flow rate measurements. These errors were propagated using the following equations to estimate the uncertainty of $m^{\cdot}$, $Q^{\cdot}$, Nu, h, and Re, shown in equations (14) to (18) (Luo et al., 2026),

$$\delta\dot{m} = \left(\left(\frac{\partial\dot{m}}{\partial\rho}\delta\rho\right)^2 + \left(\frac{\partial\dot{m}}{\partial V}\delta V\right)^2\right)^{\frac{1}{2}} \tag{14}$$

$$\delta\dot{Q} = \left(\left(\frac{\partial\dot{Q}}{\partial\dot{m}}\delta m\right)^2 + \left(\frac{\partial\dot{Q}}{\partial C_p}\delta c_p\right)^2 + \left(\frac{\partial\dot{Q}}{\partial\Delta T}\delta\Delta T\right)^2\right)^{\frac{1}{2}} \tag{15}$$

$$\delta h = \left(\left(\frac{\partial h}{\partial Q}\delta\dot{Q}\right)^2 + \left(\frac{\partial h}{\partial A}\delta A\right)^2 + \left(\frac{\partial h}{\partial U}\delta U\right)^2\right)^{\frac{1}{2}} \tag{16}$$

$$\delta Nu = \left(\left(\frac{\partial Nu}{\partial h}\delta h\right)^2 + \left(\frac{\partial\dot{Q}}{\partial D_h}\delta D_h\right)^2 + \left(\frac{\partial\dot{Q}}{\partial\kappa}\delta\kappa\right)^2\right)^{\frac{1}{2}} \tag{17}$$

$$\delta Re = \left(\left(\frac{\partial Re}{\partial\rho}\delta\rho\right)^2 + \left(\frac{\partial Re}{\partial D_h}\delta D_h\right)^2 + \left(\frac{\partial Re}{\partial\mu}\delta\mu\right)^2 + \left(\frac{\partial Re}{\partial V}\delta V\right)^2\right)^{\frac{1}{2}} \tag{18}$$

To ascertain the validity of the experimental results, an uncertainty analysis was conducted based on the accuracy of the measuring devices. The root-sum-square method was used to calculate the combined uncertainty of the calculated parameters, as shown in Table 1. In each experimental condition, the researchers repeated the experiment three times, and the reported values indicate the average values with standard deviations. To demonstrate measurement variability and experimental repeatability, the plots also included error bars.

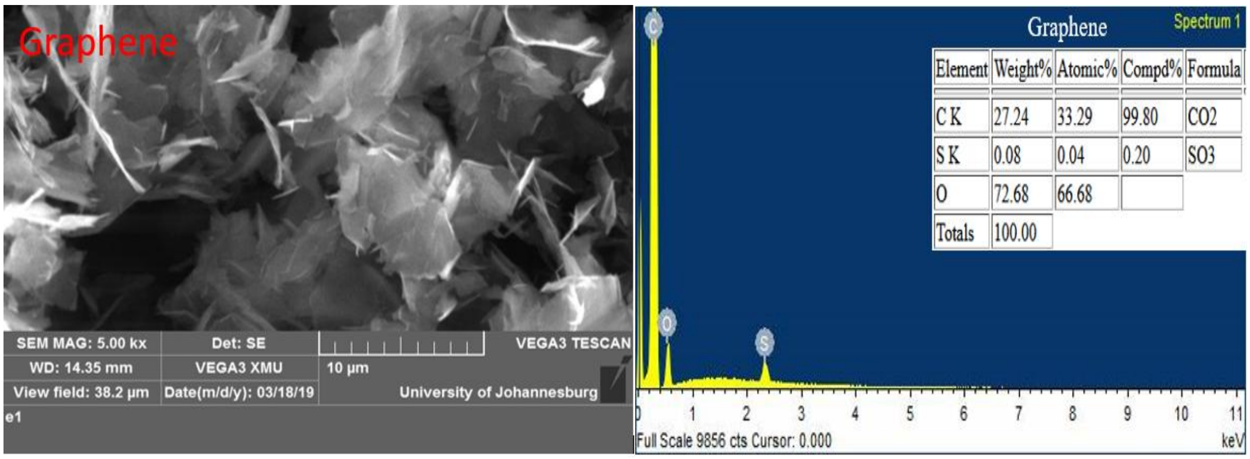
Table 1: The Variable with the Uncertainty Analysis for this Research Work

Variable	Symbol	Units	Instrument	Typical Uncertainty
Mass Flow Rate	$\dot{m}$	kg/s	Flow meter	±1.5 %
Specific Heat	C_p	kJ/kg	Calorimeter	±0.5 %
Inlet Temperature	(T_1 and T_2)	°C	Thermocouple	±0.2 °C
Outlet Temperature	(T_3 and T_4)	°C	Thermocouple	±0.2 °C
Heat Transfer Rate	Q	W	Calculated from of $\dot{m}$, C_p, and ΔT	±3.1–3.5 %

3. Results and Discussion

3.1 The Characterization Results of the Nanoparticles Used for Developing the Nano-Coolants for the Radiator Application

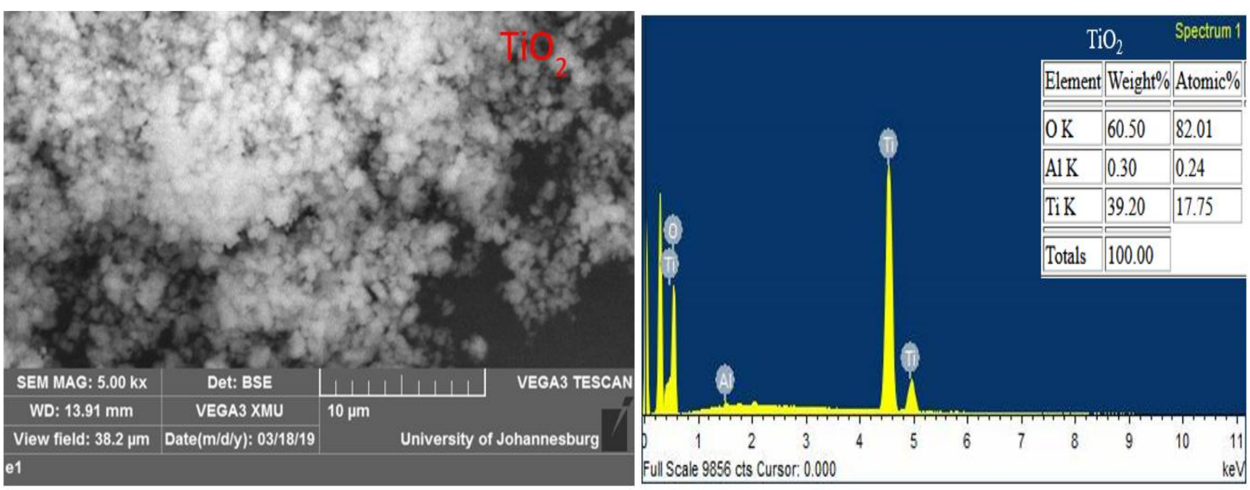
Graphene is a non-metallic nanoparticle with 98% purity, with particle sizes ranging from 10 nm ± 1 nm to 4.5 ± 0.5 nm, with 3-6 µm. The EDS analysis of the chemical composition of the graphene nano-powder (characterised under SEM) (Figure 4a and Figure 4b) revealed the presence of carbon in high amounts based on the percentage weight. The morphology of the graphene is stable based on the SEM micrograph. The stability of graphene morphology is very significant for developing the nano-coolant because the homogenization process of the nanoparticles with the water needs a stable nanoparticle size (Tawalbeh et al., 2024). The scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) examination of the TiO_2 nano-powder used in manufacturing the nano-coolant are shown in Figures 5a and 5b. Since the homogenization procedure involving nanoparticles and base fluid necessitates homogeneous nanoparticle sizes, nanoparticle size stability is critical for the formation of the nano-lubricant (Gosavi et al., 2023). The EDS analysis confirmed that the chemical composition of the nano-powders is 99.7% Titanium-oxide (TiO_2). The SEM study reports that the TiO2 has a stable morphology, with a specific area of 240 m/g and a particle size of 15 nm.



(a) (b)

Figure 4: (a) SEM Structure and (b) the EDX of the Graphene Particles Employed in the Study

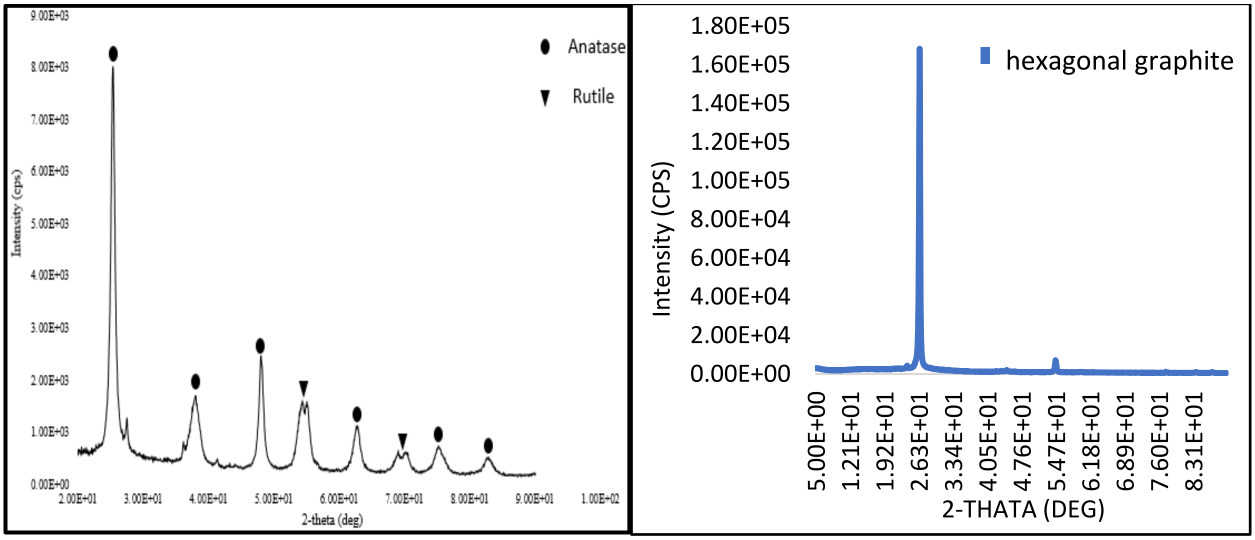
X-ray diffraction is a non-destructive technique for evaluating crystalline materials' phases, structures, crystal orientations, and other structural details (XRD). It is widely applied to characterise and evaluate the crystallinity of artificial nanoparticles. The crystal size has an inverse relationship with peak width. A thinner peak represents a larger crystal. A wider peak indicates the possibility of a smaller crystal, a crystalline structure flaw, or an amorphous sample—a solid without perfect crystallinity.



(a) (b)

Figure 5: (a) SEM Structure and (b) the EDX of the TiO_2 Particles Employed in the Study

The graphene nanoparticles are hexagonal graphite in nature, as shown in Figure 6a. Figure 6b displays the X-ray diffraction (XRD) investigation of the TiO_2 nanoparticle's phase transition. The result shows that the TiO_2 nanoparticles are anatase in nature, as indicated by the strong peaks at $2\theta = 25.4\,°$ and $48\,°$, with intensities of 8000 and 2400 cps. The absence of spurious diffraction in the XRD plot indicates the degree of crystallographic purity of the TiO2 nanoparticles. Additionally, the XRD result shows that the TiO_2 nanoparticles meet the Joint Committee on Powder Diffraction Standards (JCPDS, card no 21-1272) specifications (Venkataramana et al., 2024).



(a) (b)

Figure 6: (a) The Graphene Nanoparticles' XRD Analysis and (b) the TiO_2 Nanoparticles used to Create the Nano-Coolant for the Radiator Application

3.2 Physiochemical Results of the Developed Nano-Coolant

One essential element of nano-coolant is density. Density fluctuations affect Reynolds number (Re), frictional variables, pressure loss, and Nusselt number (Nu). As nanoparticles disperse in base fluids, nano-coolant density increases, as shown in Figure 7. When nanoparticles were added, the density of the nano-coolant rose, and the volume level inside the original fluid rose as well. However, as the temperature variable increased, the volume level fell. These results are supported by the study of Singh and Sood (2024). The fluid's shear resistance to flow is known as its viscosity. It is a characteristic that shows a fluid's resistance to deformation at a certain pace. A liquid's viscosity drastically decreases with increasing temperature. The viscosity of the hybrid Gr/TiO_2 nanocoolant is the highest of the three samples, as depicted in Figure 8. The viscosity of the nanofluid reduces as the inlet temperature rises. As a result, the study can say that in comparison to the base fluid, temperature and viscosity are directly related in all tests and situations. The physicochemical properties of the three coolants are depicted in Table 2 for graphene nano-coolants, Table 3 for TiO_2 nano-coolants, and Table 4 for the hybrid coolants.

Table 2: Graphene Nanoparticles Physiochemical Properties Test

S/N	Vol. Concentration of Gr. Nanoparticle	Density	Viscosity	Ph Value	Thermal Conductivity (W/Mk)
1.	0.03	1.11148	0.068	6.73	154.76
2.	0.04	1.1223	0.066	6.10	147.64
3.	0.05	1.1264	0.078	5.55	120.03
4.	0.06	1.1332	0.066	5.15	110.4
5.	0.07	1.1260	0.074	5.20	98.16

Table 3: Titanium-Oxide Nano-Particles Physiochemical Properties Test

S/N	Vol. Concentration of Nanoparticle	Density	Viscosity	Ph Value	Thermal Conductivity (W/Mk)
1.	0.3	1.1136	0.034	7.62	120.96
2.	0.4	1.1168	0.1112	7.96	146.47
3.	0.5	1.1244	0.137	8.37	148.85
4.	0.6	1.254	0.147	8.38	150.65
5.	0.7	1.1288	0.185	5.96	153.64

Table 4: Hybrid (TiO_2 & Gr) Nano-Particles Physiochemical Properties Test

S/N	Vol. Concentration of Nanoparticle (50%-50%)	Density	Viscosity	Ph Value	Thermal Conductivity (W/Mk)
1.	0.3	1.1252	0.208	5.36	109.83
2.	0.4	1.1124	0.196	5.68	110.97
3.	0.5	1.1136	0.194	5.39	125.78
4.	0.6	1.1172	0.177	5.78	134.42
5.	0.7	1.1184	0.198	5.45	167.78

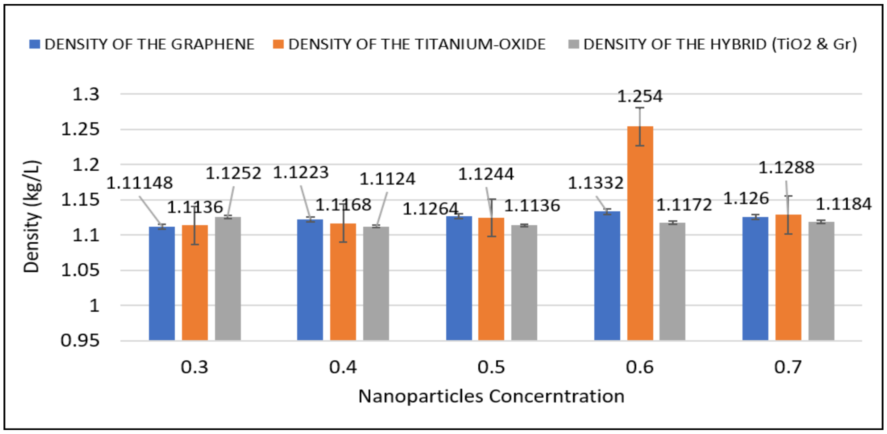


Figure 7: Comparative Analysis of the Density of the Developed Radiator Coolant for Graphene, Tio_2, and the Hybrid Tio_2 & Gr)

The effects of nanoparticle concentration on the development of nano coolant at different pH values show that graphene nanoparticles at 0.3% and 0.4% have pH values of 6.73 and 6.1, indicating low acidic content. However, as the concentration of the nanoparticles increases from 0.5% to 0.7%, the pH value decreases to below the neutral state, such as 5.55 to 5.45 (Shankara et al., 2022). The TiO_2 nano-coolant increases as the concentration value increases from 0.3% to 0.6%, and the pH value increases from 7.62 to 8.38, which confirms that the nanocoolant is eco-friendly and has high corrosion resistance that enables the operation to be free from rust on the walls of the reservoir, as shown in Figure 9. The findings show that as the TiO2 nanoparticle concentration increases to 0.7%, the pH value decreases, supported by the studies by Pusat et al. (2024) and Afolalu et al. (2024). However, as the concentration of TiO_2 nanoparticles increases to 0.7%, the pH value decreases drastically to 5.96. Therefore, the experimental analysis shows that the maximum concentration value needed for a sustainable coolant involving the TiO_2 nanoparticles is 0.6%. Also, the hybrid nano coolant analysis shows the percentage concentration of the Gr and TiO_2 nanoparticles in the essential fluid (water); the pH value decreases slightly, as shown in Figure 9 (Mousavi et al., 2024).

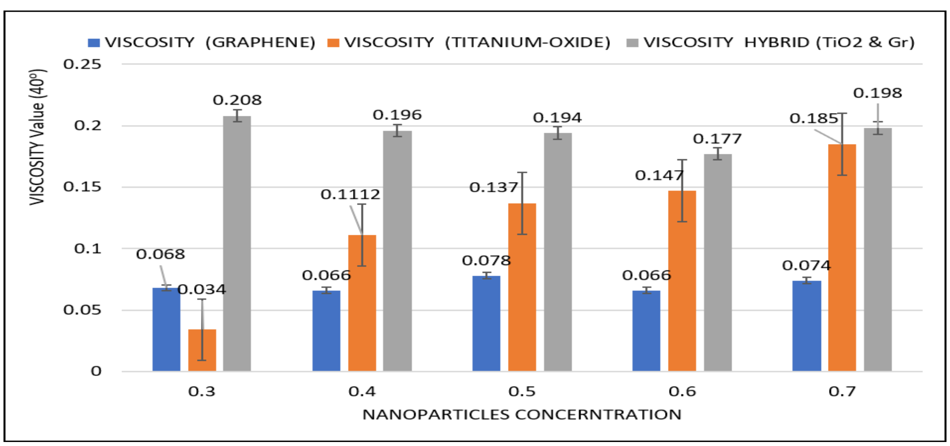


Figure 8: Comparative Analysis of the Viscosity at 40° of the Developed Radiator Coolant for Graphene, Tio_2 and the Hybrid Tio_2 & Gr)

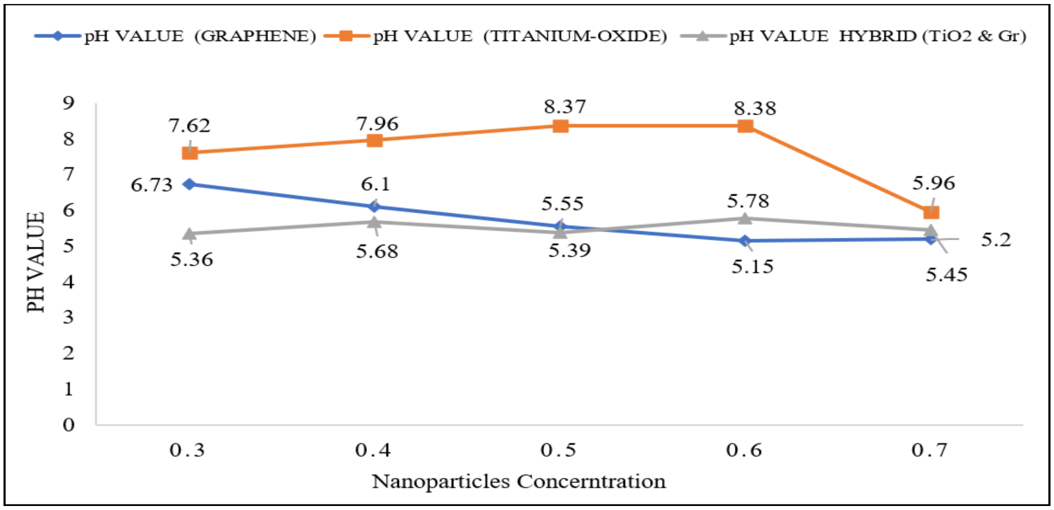


Figure 9: Comparative Analysis of the pH Value of the Developed Radiator Coolant for Graphene, TiO_2, and the Hybrid TiO_2 – Gr

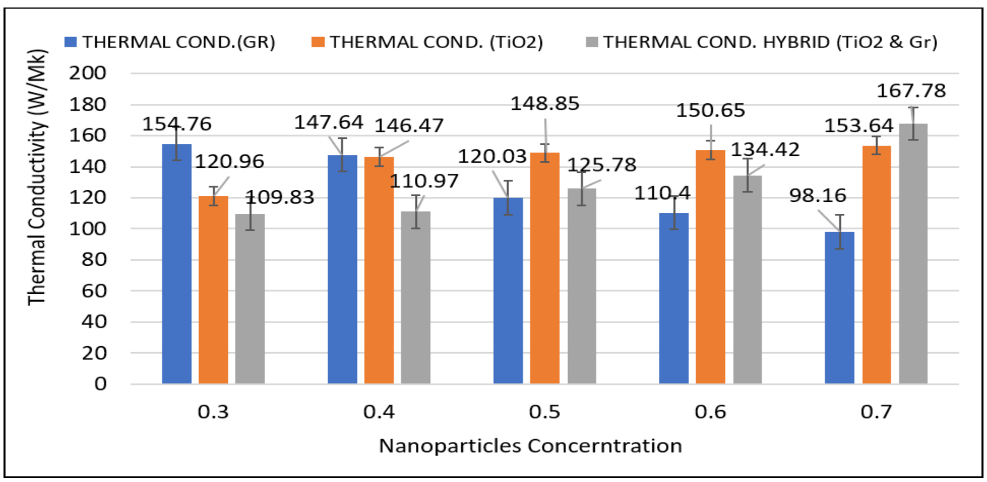


Figure 10: Comparative Analysis of the Thermal Conductivity of the Developed Radiator Coolant for Graphene, TiO_2, and the Hybrid TiO_2 & Gr)

Figure 10 shows the analysis of the nano-coolant on the thermal conductivity. The experimental values of thermal conductivity of TiO_2-water nanofluids show high deviation when compared to those estimated from the Maxwell Model. However, they are in good agreement with estimations from the Choi Model. When the results of TiO_2 and $A1_2O_3$ systems are compared using the base fluid as a reference, the former shows significantly higher thermal conductivity despite its smaller particle size of 15 nm (Khare & Tyagi, 2025). The experimental values of the thermal conductivity of nanofluids agree with those found in the literature. Figure 10 shows that thermal conductivity increases nearly linearly with each incremental increase of nano-concentration for the TiO_2 nano-coolant ranging from 0.3% to 0.7%. The thermal conductivity also increased from 120.96 W/Mk to 153.64 W/Mk, which agrees with research conducted by Ahmed et al. (2018). For the graphene nano-coolant, the reverse is the case; as the nanoparticle concentration increases in the water radiator coolant from 0.3% to 0.7%, there was a reduction process linearly as 154.76 W/Mk to 98.16 W/Mk (Bandarra Filho et al., 2025; Shijina et al., 2025). which also depicted in Figure 10. This trace is observed in the experimental analysis of the TiO2 & Gr mixture at 50% at every concentration level. In contrast, as the nanoparticle concentration increases, the thermal conductivity increases. It has been confirmed in the literature that metallic nanoparticles increase the thermal conductivity of radiator coolant, which is in line with the study of Esfe et al. (2023).

3.3 The Radiator Performance Analysis with the Various Nano-coolant

The performance analysis was carried out in a design prototype of an automobile system in an Air conditioning laboratory at Afe Babalola University in Ado Ekiti, Nigeria. The system is made up of different compartments such as the reservoir tank for the coolant, the valve for the regulation of the coolant, the radiator, the flowing metal, the heating system, the control system that is connected to the power source, pipes which the coolant flows through, the pumping system, and the implementation of four (4) thermocouple for the temperature measurement such as T_1 to T_4. Table 5 shows the control used, which is water (H_2O). The density of water = 1 kg/L; Specific heat capacity of water = 4190J/kg.

Table 5: The Control Coolant for Experimental Analysis

Water Coolant	Mass Flow Rate	$T_1^{/}$ ^{O}C	$T_2^{/}$ ^{O}C	$T_3^{/}$ ^{O}C	$T_4^{/}$ ^{O}C	Specific Heat	Heat Transfer Rate (W)
30L	518.24	39.7	22	35.5	26	4.21	8727.1616

$T_1^{/}$ is the final temperature at the reservoir, $T_2^{/}$ is the final temperature at the inlet radiator, $T_3^{/}$ is the final temperature at the outlet radiator, and $T_4^{/}$ is the final temperature at the outlet pipe. The initial temperature at reservoir T_1 is 27 ^{O}C, the initial temperature at inlet radiator T_2 is 22 ^{O}C, the initial temperature at outlet radiator T_3 is 25.5 ^{O}C, and the initial temperature at outlet pipe T_4 is 26 ^{O}C.

Table 6: The Results of the Mass Flow Rate and Heat Transfer Rate Obtained from the Graphene Nano-Coolant

Vol. Conc. of Nanoparticle Graphene (g)	T_1^{1} ^{O}C	T_2^{1}^{O}C	T_3^{1} ^{O}C	T_4^{1}^{O}C	Mass Flow Rate	Specific Heat	Heat Transfer Rate
0.3	40	19	33.6	24	519.56	4.265	11079.62
0.4	45	18	33.3	23	519.04	4.252	11034.79
0.5	50	17	33.3	23	522.43	4.243	13300.02
0.6	55	17	33.3	23.5	506.13	4.241	13952.23
0.7	60	16	33.9	23.5	468.29	4.235	14874.06

Table 6 shows the results obtained from the graphene nano-coolant; it can be seen that as the graphene nanoparticles increase in the base fluid, the mass flow rate decreases; this can be attributed to the fact that graphene nanoparticles are organic, so their ability is not as good as that of metallic nanoparticles. However, the graphene nano-coolant still performs well when compared to the base fluid due to its biocompatibility. Before carrying out the experimental study, the initial information is recorded for 0.3g Graphene nano-coolant: the initial temperature at reservoir T_1 is 65 ^{O}C, the initial temperature at inlet radiator T_2 is 26 ^{O}C, the initial temperature at outlet radiator T_3 is 29.9 ^{O}C, the initial temperature at outlet pipe T_4 is 25 ^{O}C (Lin et al., 2025). For 0.4g Graphene nano-coolant, the Initial temperature at reservoir T_1 is 78.5 ^{O}C, the initial temperature at inlet radiator T_2 is 23 ^{O}C, the Initial temperature at outlet radiator T_3 is 37.7 ^{O}C, and the Initial temperature at outlet pipe T_4 is 23 ^{O}C. For 0.5g Graphene nano-coolant, the initial temperature at reservoir T_1 is 77.1 ^{O}C, the initial temperature at inlet radiator T_2 is 24 ^{O}C, the initial temperature at outlet radiator T_3 is 27.3 ^{O}C, and the initial temperature at outlet pipe T_4 is 24 ^{O}C. For 0.6g Graphene nano-coolant, the Initial temperature at reservoir T_1 is 79.4 ^{O}C, the Initial temperature at inlet radiator T_2 is 21 ^{O}C, the Initial temperature at outlet radiator T_3 is 29.9 ^{O}C, and the Initial temperature at outlet pipe T_4 is 23 ^{O}C. For 0.7g Graphene nano-coolant, the initial temperature at reservoir T_1 is 77.5 ^{O}C, the initial temperature at inlet radiator T_2 is 21 ^{O}C, the initial temperature at outlet radiator T_3 is 29.9 ^{O}C, and the initial temperature at outlet pipe T_4 is 22 ^{O}C. It can be observed that T2 decreases due to the effects of the nanoparticles present in the coolant, compared with the initial temperature, which has a minimum of 16 °C.

For 0.3g of Titanium Oxide TiO_2, the initial temperature at reservoir T_1 is 37.9 ^{O}C, the initial temperature at inlet radiator T_2 is 26 ^{O}C, the initial temperature at outlet radiator T_3 is 31.7 ^{O}C, and the initial temperature at outlet pipe T_4 is 27 ^{O}C. For 0.4g of Titanium Oxide TiO_2, the initial temperature at reservoir T_1 is 25.9 ^{O}C, the initial temperature at inlet radiator T_2 is 23 ^{O}C, the initial temperature at outlet radiator T_3 is 27.5 ^{O}C, and the initial temperature at outlet pipe T_4 is 25 ^{O}C. For 0.5g of Titanium Oxide TiO_2, the initial temperature at reservoir T_1 is 30.9^{O}C, the initial temperature at inlet radiator T_2 is 28 ^{O}C, the initial temperature at outlet radiator T_3 is 25.9 ^{O}C, and the initial temperature at outlet pipe T_4 is 27 ^{O}C. For 0.6g of Titanium Oxide TiO_2, the initial temperature at reservoir T_1 is 38.9 ^{O}C, the initial temperature at inlet radiator T_2 is 22 ^{O}C, the initial temperature at outlet radiator T_3 is 29.7 ^{O}C, the initial temperature at outlet pipe T_4 is 24 ^{O}C. For 0.7g of Titanium Oxide TiO_2, the initial temperature at reservoir T_1 is 45.1 ^{O}C, the initial temperature at inlet radiator T_2 is 23 ^{O}C, the initial temperature at outlet radiator T_3 is 37.4 ^{O}C, and the initial temperature at outlet pipe T_4 is 26 ^{O}C when compared to the final temperature as shown in Table 7.

Table 7: The Results of the Mass Flow Rate and Heat Transfer Rate Obtained from the Tio_2 Nano-Coolant

Vol. Concentration of Nanoparticle (TiO_2) (g)	Mass Flow Rate	T_1/ ^OC	T_2/ ^OC	T_3/ ^OC	T_4/ ^OC	Specific Heat	Heat Transfer Rate
0.3	512.91	34.9	20	33.5	26	4.285	13186.9161
0.4	521.51	36.2	19	34.1	25	4.272	13367.3443
0.5	549.33	41.3	19	34.7	25	4.253	14017.8029
0.6	559.44	52.2	18	34.7	24	4.251	14269.0766
0.7	583.37	59.1	18	33.5	24	4.255	14893.4361

For 0.3g Hybrid (Graphene + TiO_2), the initial temperature at reservoir T_1 is 80.1 ^OC, the initial temperature at inlet radiator T_2 is 28 ^OC, the initial temperature at outlet radiator T_3 is 27.3 ^OC, and the initial temperature at outlet pipe T_4 is 28 ^OC. For 0.4g Hybrid (Graphene + TiO_2), the initial temperature at reservoir T_1 is 75.6 ^OC, the initial temperature at inlet radiator T_2 is 22 ^OC, the initial temperature at outlet radiator T_3 is 37.4 ^OC, and the initial temperature at outlet pipe T_4 is 24 ^OC.

Table 8: The Results of the Mass Flow Rate and Heat Transfer Rate Obtained from the Graphene 50%+Tio_2 50% Nano-Coolant

Vol. Concentration of Nanoparticle (Graphene 50%+TiO_2 50%)	Mass Flow Rate	T_1/ ^OC	T_2/ ^OC	T_3/ ^OC	T_4/ ^OC	Specific Heat	Heat Transfer Rate
0.3	455.38	83.7	19	34.1	25	4.289	11718.75
0.4	553.31	82.9	19	34.9	24	4.282	11846.37
0.5	560.79	83.5	18	33.9	24	4.273	14377.53
0.6	582.9	83.6	17	33.9	23	4.272	14940.89
0.7	610.37	82.9	17	33.3	23	4.275	15655.99

The mass flow rate and heat transfer rate of the Graphene (50%) + TiO2 (50%) hybrid nanofluid were determined through uncertainty and error analysis to ascertain the reliability and reproducibility of the experimental measurements. The measurements were taken three times, and the values reported in Table 7 are the average of these measurements. To measure variability in the experiment, the standard deviation of repeated measurements was determined. To show the variability in measurements and the repeatability of the experiment, the graphical representations of the rate of heat transfer versus nanoparticle concentration contained error bars representing the standard deviation. This discussion establishes that the reported increase in heat transfer rate and mass flow rate with the rise in nanoparticle concentration is statistically significant and accurate, which gives confidence in the performance study of the hybrid nanofluid developed.

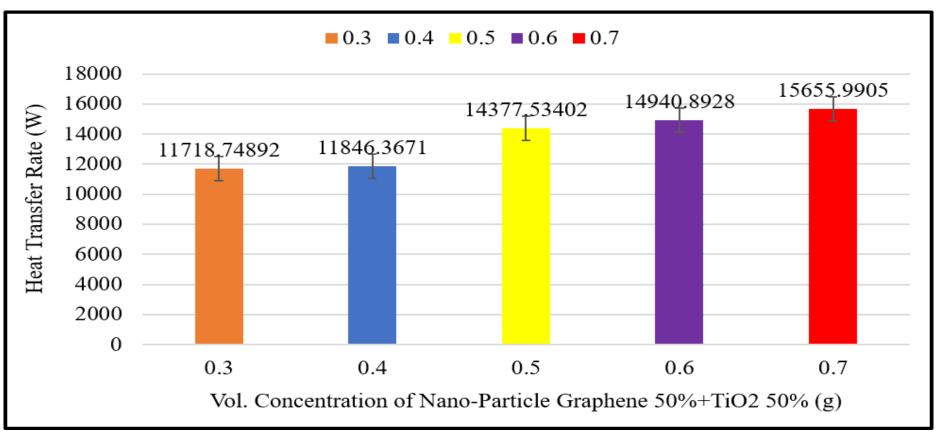


Figure 11: Influence of the Volume Concentration of the Nanoparticles on the Heat Transfer Rate under the Hybrid Nano-Coolant

For 0.5g Hybrid (Graphene + TiO_2), the initial temperature at reservoir T_1 is 74.3 ^OC, the initial temperature at inlet radiator T_2 is 22 ^OC, the initial temperature at outlet radiator T_3 is 37.3 ^OC, and the initial temperature at outlet pipe T_4 is 24 ^OC. For 0.6g Hybrid (Graphene + TiO_2), the initial temperature at reservoir T_1 is 76.4 ^OC, the initial temperature at inlet radiator T_2 is 22 ^{O}C, the initial temperature at outlet radiator T_3 is 37.5 ^{O}C, and the initial temperature at outlet pipe T_4 is 23 ^{O}C. For 0.7g Hybrid (Graphene + TiO_2), the initial temperature at reservoir T_1 is 76.2 ^{O}C, the initial temperature at inlet radiator T_2 is 21 ^{O}C, the initial temperature at outlet radiator T_3 is 37.9 ^{O}C, and the initial temperature at outlet pipe T_4 is 23 ^{O}C. The results show a significant reduction in the radiator temperature T_2, as depicted in Table 8. As the hybrid nanoparticles increase, there is a trace of an increase in the heat transfer rate, as shown in Figure 11. Compared to pure water (8727.16 W), the heat transfer rate dramatically improves at a TiO2 nano-coolant concentration of 0.3 g, with 13186.91 W. TiO2 has a higher thermal conductivity, aspect ratio, lower specific gravity, better thermal resistance, and a larger specific area. Compared to the essential fluid, the heat transfer coefficient increased with the addition of metal oxide nanoparticles (TiO_2 nanoparticles are a part of metallic nanoparticles). According to several studies, higher concentrations of metal oxide nanoparticles have been linked to increased thermophoresis effects, Brownian motion, and thermal conductivity, which causes the ability to transfer high heat to the environment (Lin et al., 2025).

However, the increasing process of the TiO_2 nanoparticles from o.3 g to 0.7 g shows a significant increase in the heat transfer rate achieved by the TiO_2 nano-coolant from 13186.91 W to 14893.43 W, as shown in Figure 12. From experimental observation, the three (3) nano-coolants have a higher heat transfer rate than water. Furthermore, the percentage deviation of the three coolants shows that the TiO_2 performs better than the graphene nano-coolant at all concentration values, with about 8.2%. In contrast, the hybrid nano-coolant is made of 50% of each graphene, and the TiO_2 nano-coolant is 6.3% compared to the graphene nano-coolants. It is observed that the thermal conductivity of graphene nanofluids rises with an increase in temperature and volume concentration and that graphene nanoparticles greatly improve the base fluid's (water) thermal conductivity, viscosity, and heat transfer capacity (Ramezani et al., 2025). From the analysis, the Percentage validation shows that TiO2 performed at 8.2%, then graphene nano-coolant, when compared. However, the hybrid nano-coolant performed 6.3% when compared with the hybrid as depicted in Table 9.

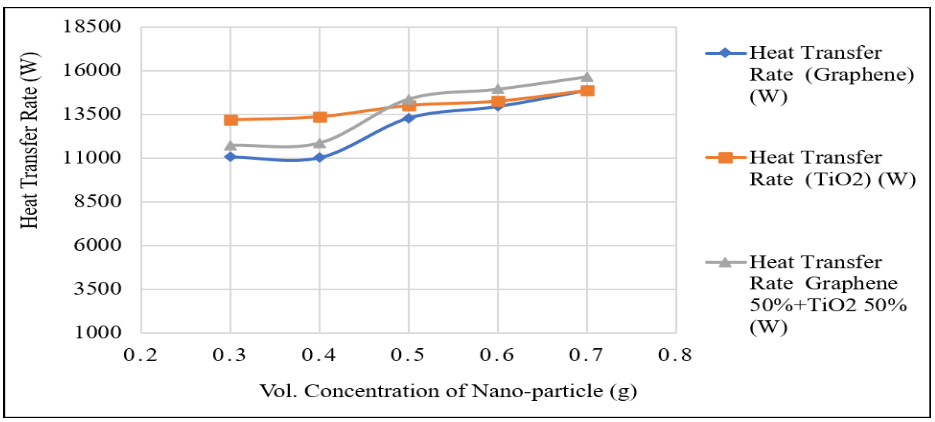


Figure 12: Comparative Analysis of the Nano-Coolant Effects on the Heat Transfer Rate for the Mono and Hybrid Nano-Coolants

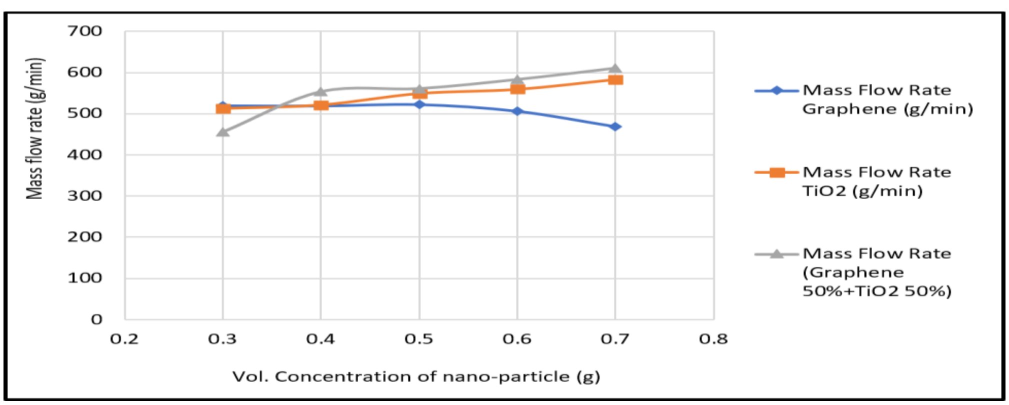


Figure 13: Comparative Analysis of the Nano-Coolant Effects on the Mass Flow Rate for the Graphene, Tio_2, and Hybrid Nano-Coolants

Figure 13 depicts the comparative analysis of the mass flow rate of the graphene, TiO_2, and the hybrid nano-coolant. As the volume concentration of the graphene nano-coolants increased from 0.3 g to 0.4 g, there was a slight increase in the mass flow rate. However, as the volume concentration increases from 0.4 to 0.7, the mass flow rate decreases because graphene nanoparticles tend to react with water. Graphene disrupts hydrogen connections between water molecules when touching them, substituting a weaker dispersion attraction to carbon atoms (Ramezani et al., 2025). However, it has been discovered that neat graphene has modest hydrophilia. In general, hydrophobic molecules in water tend to agglomerate, reducing their surface contact and related surface energy, thereby causing a reduction in the mass flow rate of the graphene nano-coolants (Wang et al., 2025).

Table 9: The Percentage Validation of the Comparative Heat Transfer Rate of the Nano-Coolants

Vol. Concentration of Nanoparticle (g)	Heat Transfer Rate Graphene (W)	Heat Transfer Rate TiO_2 (W)	Heat Transfer Rate Graphene 50%+TiO_2 50% (W)	Percentage Validation (Hybrid and TiO_2	Percentage Validation (TiO_2 and Graphene	Percentage Validation (Hybrid and Graphene
0.3	11079.62	13186.91	11718.75	-12.5284	15.9802	5.453909
0.4	11034.79	13367.34	11846.37	-12.8392	17.44965	6.850875
0.5	13300.02	14017.80	14377.53	2.502009	5.120509	7.494403
0.6	13952.23	14269.07	14940.89	4.496475	2.220512	6.617143
0.7	14874.06	14893.43	15655.99	4.870685	0.130098	4.994446
				-2.7%	8.2%	6.3%

Findings in this study were also compared with what previous studies on the use of nanofluids and hybrid nanofluids have reported on thermal management purposes. Previous research has shown that traditional nanofluids like TiO2, Al2O3, MgO, CNTs, MWCNTs, and CuO suspended in water or ethylene glycol have the potential to boost heat-transfer efficiency in automotive radiators because of better thermal conductivity and convective heat-transfer properties. Equally, recent studies of hybrid nanofluids have proven that the overall increase in the thermophysical properties of the nanoparticles can be further increased by combining two nanoparticles to work in synergy with each other (Satpute et al., 2026). The findings of the current experiment are also in the same manner, in which the addition of nanoparticles results in enhanced thermal performance relative to the base fluid. Nevertheless, the TiO_2-Graphene hybrid nanofluid has a relatively higher level of heat transfer that can be explained by the high thermal conductivity of graphene and the enhanced dispersion of the TiO_2 nanoparticles (Taşkesen, 2026). These results are in line with earlier studies on nanofluids and also show additional performance enhancement attributed to the hybrid nanoparticle combination employed in the current study. Also, one of the primary reasons why enhanced heat transfer performance is attained are due to enhanced thermal conductivity, increase in surface area of nanoparticles, Brownian motion, and synergistic interaction between TiO_2 and graphene nanoparticles in the base fluid (Hai et al., 2025).

4. Conclusion

In this study, an experimental analysis has been carried out using a developed sustainable nano-coolant to enhance the heat transfer rate in automobile radiator applications. The nano-coolant was developed using a two-step method via magnetic stirring and ultrasonication, homogenising graphene, TiO_2, and the hybrid of graphene and TiO_2 nano-coolants with the base fluid (water). The water-based TiO_2 and graphene nano-coolant were evaluated for their physicochemical properties using a refractometer, an Ostwald viscometer, and a pH meter. The nanoparticles were characterised using SEM, EDS, and XRD to determine the elemental composition and understand the phase transformation of the nanoparticles used in the research. After the physicochemical characterization, the developed mono- and hybrid coolants were tested using a standard automobile ring to conduct the experiments. The physicochemical characteristics measured are density, Viscosity, pH value, and Thermal Conductivity (W/Mk) at various concentration values of the mono and hybrid nano-coolants: 0.3g, 0.4 g, 0.5 g, 0.6 g, and 0.7 g. Also, for the automobile radiator analysis, the temperature at the different regions were recorded, such as $T_1^{/}$ is the final temperature at the reservoir, $T_2^{/}$ is the final temperature at the inlet radiator, $T_3^{/}$ is the final temperature at the outlet radiator, and $T_4^{/}$ is the final temperature at the outlet pipe, alongside the mass flow rate and the heat transfer rate. Therefore, the following conclusions were drawn;

i. The mono and hybrid nanoparticles implemented in the study enhance the Thermal Conductivity (W/Mk) and pH value for the TiO_2 nano-coolant; however, for the graphene and the hybrid nano-coolant, the increase in the concentration affects the pH values, making it slightly acidic.

ii. The increase in the volume concentration of the TiO_2 nanoparticles in the water-based TiO_2 nano-coolants increases the heat transfer rate. The heat transfer rate obtained at the 0.3 g TiO_2 nano-coolant is 13186.91 W. When the volume increases to 0.7 g, the heat transfer rate increases to 14893.43 W.
iii. The statistical analysis of the comparison of the mono and hybrid nano-coolants shows that the TiO_2 nano-coolant performed excellently well when compared with the graphene, having a percentage deviation of 8.2% and the hybrid nano-coolants with 2.7%. Additionally, the hybrid nano-coolant of TiO_2 (50%) + Graphene (50 %) performed better at 6.3% compared to the graphene nano-coolant.

References

Afolalu, S. A., Ikumapayi, O. M., Ogedengbe, T. S., Emetere, M. E., Jen, T.-C., & Akinlabi, E. T. (2024). Experimental approach to bio-waste nanoparticles suitable for radiator coolant. *Advances in Materials and Processing Technologies*, *10*(4), 2968-2982. https://doi.org/10.1080/2374068X.2023.2192388

Ahmed, S. A., Ozkaymak, M., Sözen, A., Menlik, T., & Fahed, A. (2018). Improving car radiator performance by using TiO2-water nanofluid. *Engineering Science and Technology, an International Journal*, *21*(5), 996-1005. https://doi.org/10.1016/j.jestch.2018.07.008

Arora, N., & Gupta, M. (2020). An updated review on application of nanofluids in flat tubes radiators for improving cooling performance. *Renewable and sustainable energy reviews*, *134*, 110242. https://doi.org/10.1016/j.rser.2020.110242

Bandarra Filho, E. P., do Nascimento, E. O., Farooq, M., & Cabezas-Gómez, L. (2025). Numerical Investigation on Heat Transfer and Pressure Drop in Silver/Water Nanofluids Flowing Through Tubes with Variable Expansion–Contraction Ratios. *Energies*, *18*(1), 161. https://doi.org/10.3390/en18010161

Dada, M., & Popoola, P. (2025). Surface modification of two-dimensional materials: techniques and applications. In *Polymers and Two-Dimensional Nanocomposites* (pp. 155-179). Elsevier. https://doi.org/10.1016/B978-0-443-14131-7.00007-9

Esfe, M. H., Alidoust, S., Tamrabad, S. N. H., Toghraie, D., & Hatami, H. (2023). Thermal conductivity of MWCNT-TiO2/Water-EG hybrid nanofluids: Calculating the price performance factor (PPF) using statistical and experimental methods (RSM). *Case Studies in Thermal Engineering*, *48*, 103094. https://doi.org/10.1016/j.csite.2023.103094

Feng, Y.-q., Wang, X.-x., Song, J., Liu, Z.-n., Wu, Y.-z., Tian, S.-l., Sapin, P., Yu, H.-s., & Markides, C. N. (2026). Machine learning approach for the prediction and optimization of heat transfer performance of ZnO/TiO2-R123 in ORC evaporator. *International Communications in Heat and Mass Transfer*, *172*, 110391. https://doi.org/10.1016/j.icheatmasstransfer.2025.110391

Gosavi, G., Sivamurugan, P., Shende, M., & Pingale, A. D. (2023). Recent developments of sonication process in stability and efficiency of nanofluid-based coolants: A review. *Materials Today: Proceedings*. https://doi.org/10.1016/j.matpr.2023.07.068

Hai, T., Omar, I., Alizadeh, A. a., Varshney, N., Dixit, S., Sultan, A. J., Anqi, A. E., Bhatnagar, S., Rajab, H., & Singh Sawaran Singh, N. (2025). Optimization of nano-finned enclosure-shaped latent heat thermal energy storage units using CFD, RSM, and enhanced hill climbing algorithm. *Scientific reports*, *15*(1), 12486. https://doi.org/10.1038/s41598-025-96599-y

Khare, R., & Tyagi, D. (2025). Examine the Heat Transfer Characteristics in Car Radiator Utilizing the Water/Anti-Freezing and Al2O3/Cuo/Tio2 Based Nanofluid as Coolant. *International Journal of Innovations in Science, Engineering And Management*, 17-30. https://doi.org/10.69968/ijisem.2025v4i117-30

Kumar, V. A., & Arivazhagan, S. (2024). Influence of hybrid nano-coolant on the performance of engine radiator coupled with nano-composite-assisted PCM cooler. *Journal of Thermal Analysis and Calorimetry*, *149*(21), 11941-11961. https://doi.org/10.1007/s10973-024-13529-2

Lin, B., Ali, A. B., Babadoust, S., Al-Zahy, Y. M. A., Castaneda, J. L. Y., Abdullaeva, B., Salahshour, S., & Esmaeili, S. (2025). Investigating the effect of volume fraction on Brownian displacement, thermophoresis, and thermal behavior of graphene/water nanofluid by molecular dynamics simulation. *International Communications in Heat and Mass Transfer*, *162*, 108648. https://doi.org/10.1016/j.icheatmasstransfer.2025.108648

Luo, Z., Fan, J., Hao, P., & Bao, C. (2026). Numerical investigation of dry spot evolution and heat transfer degradation in falling film evaporation over tube bundle. *International Journal of Thermal Sciences*, *223*, 110599. https://doi.org/10.1016/j.ijthermalsci.2025.110599

Mousavi, M., Pouranfard, A., & Darvishi, P. (2024). Experimental study and modeling of thermal and rheological characteristics of water-based CuO/CaCO3/SiO2 ternary hybrid nanofluid. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *686*, 133367. https://doi.org/10.1016/j.colsurfa.2024.133367

Pusat, S., Karagöz, Y., Attar, A., & Karagoz, S. (2024). A study of TiO2-enhanced nanofluids in internal combustion engines using neural networks. *Scientific reports*, *14*(1), 19251. https://doi.org/10.1038/s41598-024-68701-3

Ramalingam, S., Dhairiyasamy, R., & Govindasamy, M. (2020). Assessment of heat transfer characteristics and system physiognomies using hybrid nanofluids in an automotive radiator. *Chemical Engineering and Processing-Process Intensification*, *150*, 107886. https://doi.org/10.1016/j.cep.2020.107886

Ramezani, A., Khorasani, A. F., & Ayoobi, A. (2025). Effect of concentration and period on the transient pool boiling heat transfer of Fe3O4-based aqueous nanofluids. *Experimental Thermal and Fluid Science*, *163*, 111404. https://doi.org/10.1016/j.expthermflusci.2024.111404

Satpute, J., Campli, S., Sonawane, P., Gade, S., Yadav, S., Channapattana, S., Dey, T., & Hakizimana, E. (2026). Analysis of ethylene glycol (EG) based nanofluid coolant for enhancing cooling capacity of engine. *Discover Applied Sciences*, *8*(1), 1. https://doi.org/10.1007/s42452-025-07812-6

Shankara, R. P., Banapurmath, N., D'Souza, A., Sajjan, A., Ayachit, N., Khan, T. Y., Badruddin, I. A., & Kamangar, S. (2022). An insight into the performance of radiator system using ethylene glycol-water based graphene oxide nanofluids. *Alexandria Engineering Journal*, *61*(7), 5155-5167. https://doi.org/10.1016/j.aej.2021.10.037

Shijina, S. S., Akbar, S., & Sajith, V. (2025). Graphene functionalized nano-encapsulated composite phase change material based nanofluid for battery cooling: An experimental investigation. *Applied Thermal Engineering*, *259*, 124893. https://doi.org/10.1016/j.applthermaleng.2024.124893

Singh, B., & Sood, S. (2024). Hybrid nanofluids preparation, thermo-physical properties, and applications: a review. *Hybrid Advances*, *6*, 100192. https://doi.org/10.1016/j.hybadv.2024.100192

Taşkesen, E. (2026). Experimental thermal and hydrolic behavior of CuO/water and Cr/water nanofluids in a production passenger-car radiator. *Environmental Progress & Sustainable Energy*, e70296. https://doi.org/10.1002/ep.70296

Tawalbeh, M., Shomope, I., & Al-Othman, A. (2024). Comprehensive review on non-Newtonian nanofluids, preparation, characterization, and applications. *International Journal of Thermofluids*, *22*, 100705. https://doi.org/10.1016/j.ijft.2024.100705

Thirumaran, B., Dhasan, M. L., & Selvam, C. (2026). Modeling on heat transfer behavior of carbon-based nanofluids for electronics cooling applications. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *48*(1), 2611145. https://doi.org/10.1080/15567036.2025.2611145

Venkataramana, P., Kumar, V. M., Ram, N. R., & Chinka, S. S. B. (2024). Experimental investigation of air jet impingement cooling in car radiator with hollow cone nozzle plate spacing using nanofluids. *Heat and Mass Transfer*, *60*(8), 1377-1391. https://doi.org/10.1007/s00231-024-03493-w

Wang, R.-T., Yang, C.-A., Chen, S.-L., Chang, T.-L., & Wang, J.-C. (2025). Investigations of thermoelectric properties in polymer-based hybrid nanofluids with various surfactants. *Journal of Physics and Chemistry of Solids*, *199*, 112557. https://doi.org/10.1016/j.jpcs.2025.112557

Yaw, C. T., Koh, S., Sandhya, M., Kadirgama, K., Tiong, S. K., Ramasamy, D., Sudhakar, K., Samykano, M., Benedict, F., & Tan, C. H. (2023). Heat transfer enhancement by hybrid nano additives—graphene nanoplatelets/cellulose nanocrystal for the automobile cooling system (radiator). *Nanomaterials*, *13*(5), 808. https://doi.org/10.3390/nano13050808

Yusaf, T., Mahamude, A. S. F., Farhana, K., Harun, W. S. W., Kadirgama, K., Ramasamy, D., Kamarulzaman, M. K., Subramonian, S., Hall, S., & Dhahad, H. A. (2022). A comprehensive review on graphene nanoparticles: Preparation, properties, and applications. *Sustainability*, *14*(19), 12336. https://doi.org/10.3390/su141912336