Comprehensive Review on the Stability of TiO_2-Al_2O_3 Hybrid Nanofluids

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Abstract- This work offers a thorough examination of TiO2-Al2O3 hybrid nanofluids, emphasizing the precision and correctness of the numerous investigations carried out to assess their performance and stability. The precision numbers range from 84% to 89.50%, while the accuracy metrics range from 82% to 92%. These variations reflect the various approaches that the researchers have used. With the strongest precision and the highest accuracy, the Guo Wenjie et al. (2024) study stands out as having a well-optimized methodology. On the other hand, Shelton John et al. (2023) recorded the lowest precision and accuracy, indicating problems with the consistency of their experiments. Other research' findings, such as those of Murtadha Talib K. (2023), Najib N. A. et al. (2023), and Urmi Wajiha et al. (2023), show that there is a need for continuous improvement in experimental protocols as well as a combination of strengths and places for improvement. The results highlight how crucial it is to strike a compromise between precision and accuracy in order to guarantee consistent and repeatable results when analyzing TiO2-Al2O3 hybrid nanofluids.

Keyword Used- *TiO2-Al2O3 hybrid nanofluids, Accuracy, Precision and Stability*

1. Introduction

Titanium dioxide (TiO_2) and aluminum oxide (Al_2O_3) hybrid nanofluids have garnered significant attention due to their enhanced thermal properties [1,2], making them promising candidates for various industrial applications, including heat exchangers, cooling systems, and solar energy devices. The stability of these nanofluids is a “critical factor” influencing their performance, as it determines the uniformity of nanoparticle dispersion, thermal conductivity, and overall efficiency [3,4,5]. This comprehensive review delves into the factors affecting the stability of TiO_2-Al_2O_3 hybrid nanofluids, examining the role of particle size, concentration, pH, surfactants, and temperature. Additionally, the review highlights recent advancements in stabilizing techniques. It evaluates their effectiveness in maintaining long-term stability, ultimately aiming to provide insights for optimizing the formulation and application of these nanofluids in real-world scenarios.

1.1 Overview of nanofluids and their significance

The dispersion of materials on the nano metre scale in base fluids creates a new class of fluids called “nanofluids” [6,7]. These materials can be “nanoparticles, nanofibers, nanotubes, nanowires, nanorods, nanosheets, or droplets”. Put simply, nanofluids are suspensions of condensed nanomaterials in a colloidal form on a nanoscale. These systems consist of a solid phase and a liquid phase. Research has shown that nanofluids outperform base fluids like water and oil in terms of thermophysical parameters like “thermal conductivity, thermal diffusivity, viscosity, and convective heat transfer coefficients” [8,9]. It has shown promising results in a variety of domains.

Miniaturization, an increase in the surface-to-volume ratio, and an improvement in TC (Technetium) brought nanoparticles to the forefront. Promising prospects for heat transfer applications include NFs, which are “dispersion of nanoparticles (1-100 nm) in water, EG (ethylene glycol), mineral oil, or any other base fluid”. The majority of NFs based on metals and metal oxides [10,11], carbon nanotubes [12–18], and graphene [19–21] are employed for heat transmission purposes. Preparing NFs with a wide range of characteristics and uses relies heavily on the choice of nanoparticles, base fluids, and nanoparticle concentration [22–31]. Preparing NFs could be done in either a one-step or two-step process. The one-step process involves "synthesizing nanoparticles" in the base fluid itself. In contrast, the two-step process involves "synthesizing nanoparticles" before dispersing them in the base liquid using "mechanical or magnetic stirring, a high-pressure homogenizer, or ultrasonication". Particle size and dispersion control are both made more difficult by the one-step process. Step methods, on the other hand, lessen the likelihood of particles agglomerating [32,33]. Businesses often employ the two-step process for mass manufacturing since it's easy to understand and implement, but it compromises NF stability and necessitates additional steps, such as functionalization, surfactant addition, and pH adjustment, to ensure correct mixing of nanoparticles in base fluid [34,35].

1.2 The Stability of Nanofluid

The stability of nanofluids is defined as the extent to which their performance is maintained over an extended period while maintaining their characteristics and avoiding the aggregation of "nanoparticles" in the base liquid [36]. Researchers face an important obstacle in ensuring the stability of nanofluids, which is an inherent problem in engineering applications [37,38]. Despite the nanoparticles' diminutive size, nanofluids are unstable due to gravity and the kinetic energies produced by Brownian motion, which prevent them from remaining suspended for an extended period [39]. Aggregates of scattered particles stick to the base fluid and settle to the bottom as a result of gravity [40]. The one-step procedure is more stable than the two-step method for creating nanofluids, and the synthesis techniques significantly increase the fluid stability [41]. Nanofluids become unstable when nanoparticles move randomly in the base fluid as a result of Brownian motion and interact with nearby particles, leading to clustering and, eventually, an increase in agglomerations due to gravity's influence [42]. The thermophysical characteristics and chemical stability of nanofluids are adversely affected by using an insufficient amount of dispersant. Achieving long-term, cost-effective nanofluid stability necessitates the utilization of methods including ultrasonic vibration, routinely used surface modification, and surfactants. One way to improve the stability of nanofluids is to lower the absorption of dispersed "nanoparticles" in the base fluid [43]. Nanofluid stability can be defined using the sedimentation method, which involves measuring the sediment (volume or weight) of particles in the nanofluid subjected to an external force field.

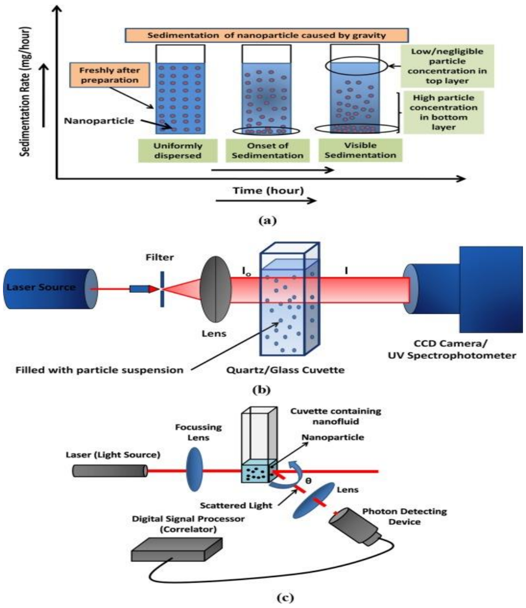

Figure 1. The Nanofluid's Stability

Nanoparticle suspensions, such as TiO_2-Al_2O_3 hybrid nanofluids, can be studied for their stability and sedimentation behavior using three main approaches, as shown in Figure 1. As seen in the first half (a), nanoparticles descend over time as a result of gravity, creating a sedimentation layer and causing the particle concentration in the upper layer to decrease. Part 2 (b) demonstrates a UV-Vis spectrophotometry apparatus, which measures absorbance as a laser beam travels through a nanofluid to track the rate of change in particle concentration. The third component (c) depicts a DLS system, in which the nanoparticles are scattered by a laser beam and their size and distribution are determined by detecting the scattered light. By combining their assessments of sedimentation rate, particle size, and dispersion, these approaches offer a thorough framework for determining the stability of nanofluids.

1.3 Applications of TiO2-Al2O3 Hybrid Nanofluids

TiO2-Al2O3 hybrid nanofluids, especially when dispersed in a base fluid like water-ethylene glycol, are increasingly recognized for their superior thermal properties, making them ideal for advanced heat transfer applications. These hybrid nanofluids exhibit enhanced thermal conductivity, stability, and heat transfer efficiency, which are crucial for improving the performance of systems like radiators, heat exchangers, and cooling systems in automotive, electronics, and industrial processes. Additionally, their ability to maintain consistent properties under varying thermal conditions makes them suitable for renewable energy systems such as solar collectors and geothermal systems, where efficient thermal management is essential for optimizing energy conversion and system longevity.

Various nanofluids were the subjects of numerous experiments. When oleic acid-coated Fe_3O_4 nanoparticles were added to kerosene with an 82 G magnetic field included, Philip, Shima, and Raj [44] found a 3000% increase in thermal conductivity. A different study [45] indicated that MWCNT nanofluid based on synthetic poly oil (α-olefin) increased heat conductivity by 150%. Because of the synergistic physical and chemical impacts of nanoparticles, compound "nanoparticles" added to a basic liquid are predicted to outperform single nanoparticles in terms of thermophysical properties. "The thermal conductivity and viscosity of water-EG-based TiO_2-SiO_2 nanofluids" were studied [46]. They discovered that a 20:80 mixing "ratio of TiO_2-SiO_2" resulted in a 13.8% improvement at 700 C, while a {50:50} mixing ratio of TiO2-SiO2 produced the maximum viscosity. The efficiency of different base fluids was investigated by [47]. They used "vegetable oil, SAE oil, and paraffin oil, and added CueZn nanoparticles" in a 50:50 ratio to the base oil at concentrations of0.1,0.3, and 0.5% by volume. The hybrid nanofluid of copper and zinc with vegetable oil had "the best thermal conductivity" followed by paraffin oil and SAE oil. According to this study, the reason for the internal force that prevents fluids from flowing and the relatively "high thermal conductivity of vegetable oil is the Cu-Zn/vegetable oil nanofluid" which has the maximum thermal conductivity. Research on ND-Co_3O_4/water nanofluids at high temperatures has shown promising results for improving thermal conductivity and reducing viscosity [48]. At 50 °C, another research found that a hybrid nanofluid based on EG SiO_2 and MWCNT improved thermal conductivity by 20.1% [49].

1.3.1 Preparation of hybrid nanofluid

The TiO_2-Al_2O_3 water-based hybrid nanofluid was prepared using the two-step approach in this study. Synergy Scientific Sdn Bhd supplied "the Al_2O_3 and TiO_2 nanoparticles (Brand: Sigma Aldrich) with average particle sizes" (below 13 and 25 nm), respectively. In Table 1 people can see the characteristics of the materials that were utilized in the experiment. The XRD method is employed to determine "the average particle size and characterize TiO_2 and Al_2O_3 nanoparticles". Before ultrasonication, the nanoparticles are mechanically stirred in DI water for 2 hours at 900 rpm. For three hours, "the ultrasonic bath (Fisher Scientific FB15051)" operates at a frequency of 37 kHz, completing the ultrasonication process. To make nanofluid more stable, "polyvinylpyrrolidone (PVP)" is added at a mass-to-nanoparticle ratio of 1:10. With a fixed volume concentration of 1%, "the TiO_2-Al_2O_3 hybrid nanofluid" was prepared using water with "nanoparticle mixing ratios of 20:80,40:60,50:50,60:40, and 80:20". Table 2 shows the number of nanoparticles that were utilized to prepare the hybrid nanofluid.

Table 1 – Experimental material specifications [50]

Material	State Purity Size Density				Melting point
	-	[%]	[nm]	[kg/m^3]	[°C]
TiO_2	Powder	99.5	21	3700	1850
Al_2O_3	Powder	99.8	13	3960	2040
PVP	Powder	-	-	1270	150-180
Water	Liquid	-	-	998	-

Table 2 – Nanoparticles of TiO2 and Al2O3 in the specified volumes and masses.

(TiO_2:Al_2O_3) (R)	Mass of TiO_2 (g)	Mass of Al_2O_3 (g)	Volume of TiO_2(g/m^3)	Volume of Al_2O_3 (g/m^3)
20:80 (0.2)	0.863 ± 0.001	3.202 ± 0.001	3.193 ± 0.001	12.680 ± 0.001
40:60 (0.4)	1.726 ± 0.001	2.401 ± 0.001	6.386 ± 0.001	9.508 ± 0.001
50:50 (0.5)	2.158 ± 0.001	2.001 ± 0.001	7.985 ± 0.001	7.924 ± 0.001
60:40 (0.6)	2.590 ± 0.001	1.601 ± 0.001	9.583 ± 0.001	6.340 ± 0.001
80:20 (0.8)	3.453 ± 0.001	0.800 ± 0.001	12.776 ± 0.001	3.168 ± 0.001
Total	10.790 ± 0.001	10.005 ± 0.001	39.923 ± 0.001	39.620 ± 0.001

1.3.2 Dynamic viscosity and thermal conductivity measurements

Decagon Devices Inc.'s (USA) KD2 pro thermal analyzer was used to test “the thermal conductivity of TiO_2-Al_2O_3 hybrid nanofluids”. Historically, the majority of researchers relied on this device to determine “the thermal conductivity of nanofluids”. A calibration specimen of glycerol was used to set the device before beginning the test. All samples of hybrid nanofluids and base fluids are tested for thermal conductivity within “a temperature range of 30 to 70 ◦C”. To conduct the analysis, five measures were taken with a 20-minute delay in between. The experiment is carried out at “temperatures ranging from 30-7 ◦C to measure the dynamic viscosity using a “Brookfield LVDV III Ultra Rheometer”. A thermal bath is utilized to regulate the temperature of nanofluid samples while they are being measured as part of the experimental method. The measurement was carried out multiple times, with each interval of 15 minutes, to obtain a consistent reading. “Velocity, torque, shear stress, and shear rate” are some metrics the rheometer recorded when linked to the computer-controlled program RheoCal. Hamid et al. [51] provided the basis for the methodology used to assess thermal conductivity and viscosity.

2. Review of Literature

Guo Wenjie, et. al. (2024) [52] expressed how stability affects the flow boiling heat transfer performance of hybrid nanofluids “(Al_2O_3-TiO_2/W)” that is composed of dissolved Al_2O_3-TiO_2 nanoparticles in water. “Response surface methodology (RSM)” was applied to maximize the hybrid nanofluid Al_2O_3-TiO_2/W's stability. Furthermore, the boiling heat transfer capacity of “the Al_2O_3-TiO_2/W hybrid nanofluid” was examined in the 30-90 L/h flow rate range in combination with its mono nanofluids (0.01, 0.02, and 0.03 vol%). The consequences indicated that the optimized constancy of the created hybrid nanofluids was achieved with an ultrasonic duration of 44.79 minutes and a surfactant SDS mass ratio of 0.554. Additionally, as the flow rate increased, “the boiling heat transfer coefficient (h)” showed a growing trend that was tracked by a declining trend, peaking at 70 L/h. The h value was also raised by greater temperature flow and volume fraction.

Murtadha Talib K., (2023) [53] said that the primary goal of employing nanofluids is to cool the solar panels to maximize their performance, which includes boosting their output, longevity, and efficiency. The effects of the 2-weight percent hybrid nanofluid coolant (Al_2O_3/TiO_2) were investigated in this work and compared to those of earlier investigations that employed the same concentrations of TiO_2 and Al_2O_3. The system utilized in this work is made up of three identically spaced solar panels with distinct one-pass flow cooling techniques. A hybrid nanofluid containing 2 weight percent Al_2O_3/TiO_2 was used to cool the first solar panel, PV-1. Only water was used to cool “the second panel, PV-2”, while no cooling was used at all for the third panel, PV-3. Experiments were conducted with cooling fluid flowing at different speeds between “0.5 L/min and 3 L/min”. Findings were contrasted with the PV-3 orientation panel. For cooling by “a hybrid nanofluid, water only, and an uncooled panel, the maximum output powers were 46.6, 45.1, and 41.9 W” respectively. When compared to the uncooled panels, that resulted in an 11.2% increase in output power.

Najib N. A., et al. (2023) [54] Explained the fully utilized potential of nanofluids, especially to increase their properties, and the study of nanofluid stability is essential. The dispersion constancy of "an Al_2O_3-TiO_2 hybrid nanofluid" suspended in palm oil is the main objective of this experimental investigation. Two-step procedures were used to disperse five various mixing ratio mixtures of Al_2O_3─TiO_2 nanoparticles in palm oil: 20:80, 40:60, 50:50, 60:40, and 80:20. Throughout this experimental investigation, the volume concentration of the hybrid nanofluid was kept constant at 0.5%. To stabilize the mixture of nanoparticles in the base fluid, surfactant sodium dodecyl sulfate (SDS) was utilized. After preparation, the "Al_2O_3-TiO_2 hybrid nanofluid's" stability was visually assessed, and it was periodically monitored continuously for a while. This experimental investigation used a UV-Vis spectrometer and density measurement to examine the impact of nanoparticle ratio on the "stability of an Al_2O_3-TiO_2 hybrid nanofluid" suspended in palm oil. The results and conclusions of this experimental study on the stability of Al_2O_3─TiO_2 hybrid nanofluid will also aid in the development of a new investigational training that will be useful in the future for studying the constancy of fusion nanofluids and the mixture ratio of nanoparticles.

Shelton John, et al. (2023) [55] expressed that the degree to which hybrid nanofluids' rheological properties are accurately defined determines how effective they are as thermal fluids in heat transmission applications. This study examined experimentally the effects of "temperature, particle concentration, ratio of the hybrid nanoparticle mixture, and nanoparticle composition" on the overall viscosity and rheological properties "of Al_2O_3-TiO_2/MO hybrid nanofluids". "Al_2O_3 (5 nm) and TiO_2 (5 nm)" nanoparticles were employed in the experiment, by paraffin oil "(white, CAS No. 8020-83-5)" serving as the base liquid. Nanofluids with single and mixed nanoparticles at volumetric concentrations of 0.2-1.5% are made using a two-step process. Viscosity is measured using "a Brookfield Dv2T rotational viscometer" that is outfitted "with a cone (CPA-40Z) and plate apparatus". The movement conduct directories for the investigated "Al_2O_3-TiO_2/MO hybrid nanofluids tended to approach a value of one", suggesting additional Newtonian movement conduct, in contrast "to the conventional Al_2O_3/MO and TiO_2 /MO nanofluids".

Urmi Wajiha, et al. (2023) [56] studied to conduct experiential training into the thermophysical characteristics and "surfactant-enhanced stability of water-ethylene glycol (60:40) based Al_2O_3-TiO_2 hybrid nanofluids". By doing this, the situation seeks to shed light on the behavior of the nanofluid and its stability and thermal performance, hence developing technical applications and heat transfer technologies. Nanofluids, based on mixing nanoparticles with ordinary base fluids, are attracting interest from a growing range of industries, such as astral "vigor, heat transfer, biomedicine, and atmosphere". Cutting-edge this study, "Al_2O_3 and TiO_2 nanoparticles" with a volume content of 0.1% are equally dispersed in a DI-water and ethylene glycol combination "using a 50:50 ratio".

Rubaiee Saeed, et al. (2023) [57] evaluated how high-stability advanced nanofluid is necessary to meet the demands of today's solar thermal systems and industries. "Graphene oxide (GO) nanofluid" produced by ethene diol (EG) and aquatic (W) is widely recognized in industrial applications for its excellent thermal conductivity and strong stability. This study examined "the thermal, optical, and suspension stability of graphene oxide (GO) nanofluid" under specific conditions. The fluid is then used as a "working fluid in photovoltaic thermal (PV/T)" systems to measure the situation presentation in comparison to water, Al_2O_3, TiO_2, then hybrid Al_2O_3-TiO_2-based nanofluids. The thermal "analyzer, TGA, SEM, UV-vis analysis", and optical absorbance are used to characterize the current conduction, thermal constancy, geomorphology, and visual absorbance, respectively. The findings showed that at 40 °C, the GO/EG: W nanofluid's thermal conductivity rose by 9.5% in comparison to water. Additionally, it demonstrated strong stability with a 30.3 mV zeta potential.

Suneetha S, **et al. (2022) [58]** studied superior thermophysical qualities over ordinary liquids and single-phase nanofluids, researchers have focused a great deal of attention on hybrid nanofluids, or HNFs. By dissolving 2 or more different nanoparticles in a conventional warmth transmission liquid, high-potential heat transference fluids are created. Because hybrid nanofluids have excellent heat transfer qualities, they are frequently employed in manufacturing, biomedical engineering, and industrial operations. A thorough analysis of the synthesis, stability, thermophysical characteristics, and significance of hybrid nanofluids in many engineering domains is provided by this approach. The investigation conducted here also looks at the hybrid nanofluid's pH regulation and ultrasonic intensity.

Das Pritam Kumar, et al. (2022) [59] studied the potential use of nanofluids in various engineering domains, such as surface patterning, coating, particle deposition, and improvement of thermal transfer, which has recently attracted attention. For nanofluids used in various commercial applications, consistency is essential, but relevant databases in the literature are often incomplete. Here, they examine the impact of particle solid volume fraction (φ) and surfactant concentration on the stability of suspensions of Ti- and Al-oxide nanoparticles stabilized with various surfactants. The TiO_2-AA and TiO_2-CTAB nanofluids exhibit significant stability, however, the SDBS-stabilized Al2O3 nanofluid has contrasting results. The morphological properties of recently created nanofluids are provided by TEM pictures, while the stability and particle size distribution of the nanofluid are described by DLS and ZP data, respectively. The creation of variously sized particles for every nanofluid is confirmed by SANS data.

Urmi Wajiha, et al. (2021) [60] enhanced thermophysical and heat transport capabilities of nanofluids have led to their rapid development in various aspects, as indicated by current studies on nanotechnology**.** In the process of preparing hybrid nanofluids, this research examined several difficult problems and preparation techniques. Hybrid nanofluid preparation can be done primarily in one or two steps. The two-step method is a popular methodology for creating nanofluids since it is simpler than the one-step method, but it requires more work to achieve the stability of hybrid nanofluids. Conversely, the one-step method offers greater flexibility in obtaining nanofluid homogeneity, despite its relatively high manufacturing cost. To create a long-lasting nanofluid, several researchers used a variety of methods, including pH adjustment, surface treatment, and the inclusion of surfactants. These techniques do, however, have certain drawbacks, such as deteriorating the hybrid nanofluids' thermal properties. Therefore, these issues must be addressed in future research along with the cost analysis involved in creating the hybrid nanofluids.

Abd Aziz, et al, (2021) [61] studied the constancy of a hybrid "TiO_2-based nanofluid" remains investigated in this research through adjustments to the ultra-sonication duration, carbon-to-TiO_2 weight ratio, and surfactant type. This study aims to synthesize a 0.1% volume portion of C-TiO_2 hybrid nanofluid using 15 milliliters of distilled water. Additionally, the impact of surfactant type, weight fraction between C and TiO_2, and ultra-sonication period on "the stability of the hybrid nanofluid" will be examined. The weight fractions of C and TiO_2 will alternate between 0% and 100%, 10% and 90%, 50% and 50%, 90% and 10%, and 100% and 0%. To find the ideal ultrasonication time for the hybrid nanofluid, three different ultrasonication times—one, three, and five hours—will be used. To ascertain the impact of surfactant on the hybrid nanofluid's stability, Triton X-100 and sodium dodecyl sulfate (SDS) will be introduced. Using X-ray diffraction and FESEM, the morphology and particle size properties of TiO_2 and carbon powder are assessed. It is demonstrated that TiO_2 particles have a size of about 30 nm, but the powdered carbon utilized has a flat shape. The hybrid nanofluid in this study is synthesized using a two-step technique. Following a three-hour magnetic stirring period, the two powders will be combined with distilled water. To avoid particle agglomeration, ultrasonication is then incorporated into the hybrid nanofluid creation process.

Wanatasanapan V, at el. (2020) [62] said the last ten years have seen a major concentration of research efforts on the result of nanoparticle capacity attentiveness scheduled "the thermophysical properties of hybrid nanofluid". However, the effects of the mixture structure of two dissimilar nanoparticles on the thermophysical possessions of the fluid are less well understood. This study was to examine how a water-based "hybrid nanofluid's thermal conductivity, rheological properties, and dynamic viscosity" are affected by the "ratio of TiO_2-Al_2O_3 nanoparticles" in the mixture. The water-based hybrid nanofluid was made using five different ratios "of TiO_2 and Al_2O_3 nanoparticles at a constant 1.0% volume concentration". The temperature range used for the experimental test technique was “30 to 70 °C”. The XRD characterization results “of TiO_2 and Al_2O_3 nanoparticles” indicate that their mean crystallite sizes are around 19.1 and 8.31 nm, respectively.

Urmi WajihaTasnim, et al. (2020) [63] reported that TiO_2-Al_2O_3 hybrid nanofluids based on 40% ethylene glycol are the subject of experimental investigations reported in this study. “Thermophysical properties of nanofluids” have been the focus of increasing studies recently. Accordingly, research work carefully evaluated the hybrid nanofluids' stability. In this study, “40% ethylene glycol-based TiO_2-Al2O_3 hybrid nanofluids” are prepared using a two-step procedure. In this experiment, different mixture ratio combinations “of TiO_2-Al_2O_3 nanoparticles with a volume concentration of 0.1%” are tested, including 20:80, 40:60, 50:50, 60:40, and 80:20. Particle size analyzer zeta potential value, show electric tiny remark, UV-Vis’s spectrophotometry, and visualization effect are used to evaluate the constancy of hybrid nanofluids.

Ismail H, et al. (2020) [64] evaluated the constancy of “Al_2O_3-SiO_2 hybrid water-based nanofluids” was investigated through qualitative studies. The primary nanoparticles utilized in this investigation were SiO_2 and Al_2O_3, as information on these types of nanoparticles' hybrid dispersion stability characteristics is still lacking despite their widespread use and proposal in numerous applications. The current work clarified the best preparation approach for hybrid nanofluids while demonstrating “the stability of Al_2O_3-SiO2 hybrid nanofluids using” a variety of preparation procedures. To attain a “total volume concentration of C=0.001, 0.01, and 0.1 vol%, 50:50 Al_2O_3-SiO_2 nanoparticles” were dispersed into distilled water to create “the hybrid water-based nanofluid”. The hybrid nanofluids were successively made with an ultrasonic bath and a magnetic stirrer.

Alshehri Fahad, et al. (2020) [65] discussed is made up of “Al_2O_3 and TiO_2” binary nanoparticles discrete throughout a double-base unsolidified combination of ethylene glycol and water. Numerical research is conducted on a hybrid nanofluid consisting of four components. The nanofluid was modeled with volume contents of “2.5% Al_2O_3-1.5% TiO_2 and 5% Al_2O_3-3% TiO_2, respectively”, as a single-phase fluid. “The nanoparticles” are postponed in a solution of water and ethylene diol by a capacity relation of 70:30. To mimic turbulent flow via a conduit, three different Reynolds numbers (7800–2000) and an operating temperature of 293 K were employed. A constant flow “of 129,983 W/m^2 of heat was applied to the pipe wall”. The concentrations of 5-2 and 2.5-1.5%, respectively, resulted in a 24% and 11% upsurge in current conduction. “The viscosity of the hybrid nanofluid increased to 70% and 67% at the same” dosage. The average temperature transmission constant “of Al_2O_3–TiO_2 hybrid nanofluids” increased with temperature and volume concentration. On a capacity attentiveness of 3–5%, the maximum development in heat transmission is seen, which “is 52% higher than that of the base fluid. Higher volume concentrations of Al_2O_3–TiO_2” hybrid nanofluids show a slight rise in the friction factor.

Siddiqui Farooq Riaz, et al. (2019) [66] investigated the thermophysical properties and dispersion stability of a hybrid nanofluid comprising metal and metal oxide at various mixing ratios. Dispersing copper nanoparticles with “high thermal conduction and poor dispersion stability in water at mixing ratios of 0.3:0.7 (MR-1), 0.5:0.5 (MR-2), and 0.7:0.3 (MR-3)” yields the “Cu-Al2O3 hybrid nanofluid with” better hydrothermal possessions. The dispersal constancy besides thermophysical characteristics of the hybrid nanofluid was investigated aimed at 240 hours using a range of experimental methods, such as sedimentation, thermal analyzer, viscometer, UV-Vis’s spectroscopy, zeta/particle size analyzer, and transmission electron microscopy. The data clearly show that the hybrid nanofluid progressively transforms into zones with varying concentrations: low, medium, and high.

Gulzar Ovais, **et al. (2019) [67]** stated that to use hybrid nanofluid Al_2O_3-TiO_2 Therminol-55 in solar collectors, an experimental investigation of its rheological behavior and stability analysis was carried out. With the use of a two-step procedure, a variety of hybrid nanofluid samples were created with concentrations ranging from 0.05wt% to 0.5wt%. Using an approximation of Smoluchowski, the particle size distribution was experimentally evaluated. The hybrid nanofluid samples were found to have ZP values ranging “from 68.5 mV to 57.64 mV after 3 hours of preparation, 64.3 mV to 48.36 mV after 72 hours of preparation, and 54.52 mV to

34.43 mV after 7 days" of preparation. Zeta conceivable (ZP) capacities were conducted using unvetted methods. Upon examining the flow behavior, it was discovered that every hybrid nanofluid sample exhibited Newtonian behavior, "with shear rates ranging from $10s^{-1}$ to $500s^{-1}$". The viscosity of nanofluid increases as nanoparticle concentration rises.

Moldoveanu Georgiana Madalina, et al. (2018) [68] said that an experimental investigation of "the rheological behavior of Al_2O_3–TiO_2 hybrid nanofluids" floating in pure water has been presented. Simple nanofluid samples were also made and used for comparison, with different volume fractions of TiO_2 and Al_2O_3. Viscosity measurements were performed on all samples at room temperature and shear rates ranging from 10 to 1000 1/s. Based on experimental results, all samples behaved in a non-Newtonian manner and adhered to the Ostwald model. In-depth discussions of the constancy directory and control rule catalog remained also had. Using the curve-fitting technique, they were able to customize a few correlations to explain the rheological behavior. Regression analysis was also performed to establish a relationship between the volume fractions of the hybrid and pure nanofluid and the respective viscosity.

Maddah Heydar, et al. (2018) [69] assessed that fluid mechanics has been deeply involved in the manipulation of nanofluids through structural transformations. Exergy analysis is used in this study to examine and assess a twin pipe heat exchanger operating in turbulent flow regimes with a loaded Al2O3-TiO2 hybrid nanofluid. To validate the information that is produced, praise equations are used. A full factorial experimental design technique was utilized to determine the energy competence of the nanofluid-loaded double-pipe temperature exchanger. The variables for this test are the following: the concentration of nanofluid (0.2–1.5), the Reynolds number (3000–12000), and the twist ratio (2–8). The parameters that have the greatest impact on energy efficiency are identified by statistical analysis, which includes the student's t-test, alteration examination, F-test, and absence of appropriate. Conclusion: When using twisted tapes and nanocomposites instead of regular water as a heat transfer fluid, there is an increase in excess energy efficiency. Higher exergy efficiency can also be achieved by simultaneously lessening the rotation relation and cumulative the volume attentiveness and Reynolds number of nanoparticles.

Minea Alina Adriana, (2017) [70] said that understanding a nanofluid's thermophysical characteristics is crucial to predicting how it will behave during heat transmission. Three oxide-based nanofluids and their hybrids are evaluated numerically in this article. It was observed that the inclusion of nanoparticles changed all of the nanofluids' thermophysical characteristics and that thermal conductivity increased by at least 12%. Furthermore, when utilizing theoretical or experimental correlations, the degree of error in viscosity estimation was found to be highly significant. The viscosity of hybrid nanofluids is seen to be reduced in the HT and HS series compared to the MHT and MHS series. As was also observed for the alumina nanofluids, this discrepancy can be attributed to the computation approach.

Wang Xian Ju, et al. (2011) [71] investigated the dispersion stability of nanofluids by examining TiO2 and Al2O3 nanofluids' absorption capacity and zeta potential at various "pH values and dispersion concentrations". The outcomes showed that in the mass fraction of 0.05% alumina and 0.01% titanium dioxide nanosuspensions, the two nanofluids containing sodium dodecyl sulfate (SDS) dispersant have the highest absolute values of zeta potential and absorbency on ideal "pH (pHAl2O3 = 6.0, pHTiO2 ≈ 9.5)". Furthermore, absorbency and zeta potential have a strong positive association, where larger absolute values of the former indicate stronger absorbency and better system stability. When SDS is present at the ideal concentrations of 0.10% and 0.14%, respectively, the two nanofluids show the best dispersion values. The stable behavior of the pH influence on the experimental data is confirmed by the predicted DLVO interparticle interaction potentials.

Table 3. Approaches to Review of Literature

S.no.	Author	Techniques	Research Gaps	Findings
1.	**Guo Wenjie, et. al. (2024)**	Response surface methodology (RSM)	Long-term stability untested; other surfactants and ultrasonic durations unexplored.	Optimal stability: 44.79 min ultrasonic, 0.554 SDS mass ratio. Peak heat transfer at 70 L/h.
2.	**Murtadha Talib K., (2023)**	Employed three identically spaced solar panels (PV-1, PV-2, PV-3)	Limited to a single hybrid nanofluid (Al_2O_3/TiO_2) concentration (2 wt%).	PV-1 (hybrid nanofluid cooling): Highest output power at 46.6 W, PV-2 (water cooling): Slightly lower output power at 45.1 W, PV-3 (no cooling): Lowest output power at 41.9 W.
3.	**Najib N. A., et al. (2023)**	Use of surfactant SDS, Visual observation, UV-Vis spectrometer, and density measurement to monitor stability	Limited study on the impact of long-term stability beyond initial visual assessment.	Stability varies with the ratio of Al_2O_3-TiO_2 nanoparticles in the hybrid nanofluid.
4.	**Shelton John, et al. (2023)**	Brookfield Dv2T rotational viscometer, a Two-step preparation method for nanofluids	Limited exploration of long-term stability of the hybrid nanofluids.	Hybrid nanofluids exhibit more Newtonian flow behavior compared to traditional Al_2O_3/MO and TiO_2/MO nanofluids.
5.	**Urmi Wajiha, et al. (2023)**	50:50 Al_2O_3-TiO_2 nanofluid in water-ethylene glycol (60:40) with surfactants	Limited long-term stability data, need for different surfactant studies, environmental impact.	Surfactants improve stability and thermal performance; potential for enhanced heat transfer.

3. Research Gap

- The impact of different synthesis methods on the long-term constancy of TiO_2-Al_2O_3 hybrid nanofluids has not been extensively studied, leaving uncertainty about the most effective techniques for maintaining stability over time.
- How the thermal and rheological properties, which impact stability, are affected by different

concentrations of TiO_2 and Al_2O_3 in hybrid nanofluids is not well understood.

- The influence of different base fluids on the stability of TiO_2-Al_2O_3 hybrid nanofluids is underexplored, particularly how these interactions affect particle agglomeration and sedimentation.
- Limited research has been conducted on how TiO_2-Al_2O_3 hybrid nanofluids are affected by environmental variables such as temperature changes, pH variations, and additives.
- There is a need for more in-depth studies comparing the constancy of TiO_2-Al_2O_3 hybrid nanofluids with other types of hybrid and single-component nanofluids to establish a comprehensive understanding of their relative advantages and disadvantages.

4. Research Objectives

- Investigate the synthesis methods and optimal conditions for producing stable TiO_2-Al_2O_3 hybrid nanofluids, focusing on achieving uniform dispersion and minimizing agglomeration.
- Evaluate the thermal, rheological, and chemical stability of TiO_2-Al_2O_3 hybrid nanofluids under varying environmental conditions and concentrations.
- Examine the impact of surface modification techniques and surfactant selection on the long-term stability and performance of TiO_2-Al_2O_3 hybrid nanofluids.
- Assess the potential industrial applications of TiO_2-Al_2O_3 hybrid nanofluids, emphasizing their stability and effectiveness in enhancing heat transfer and other relevant properties.

5. Background Study

For optimal photovoltaic (PV) performance, including increased efficiency, lifespan, and power production, this study employs nanofluids for cooling the panels. To find out what happened and compare it to other research that utilized the same concentrations of Al_2O_3 and TiO_2, this one used a 2-weight percent hybrid nanofluid coolant of the two. This work makes use of a system that includes three identical solar panels that are cooled in a one-pass flow using different ways. Using a "2-weight percent Al_2O_3/TiO_2 hybrid nanofluid, the first solar panel PV-1 was cooled". Two panels, PV-2 and PV-3, were cooled solely by water and used without cooling, respectively. The cooling fluid flow rates used in the experiments varied from half a liter per minute to three liters per minute. The reference panel PV-3 was used to compare the results. Different cooling methods resulted in different maximum output powers: a hybrid nanofluid (46.6 W), water alone (45.1 W), and an uncooled panel (41.9 W). As a result, the output power increased by 11.2% compared to the panels without cooling. The hybrid nanofluid's temperature rose 9.6 ◦C when cooled with water alone, compared to 8.4 when cooled with just water. With the use of the Al2O3/Tio2 hybrid nanofluid, the greatest improvement in electrical energy efficiency (17.6%) was achieved. Using a 2-weight percent hybrid nanofluid to cool the PV panels achieved optimal performance, according to comparisons with earlier studies [72].

6. Result Analysis

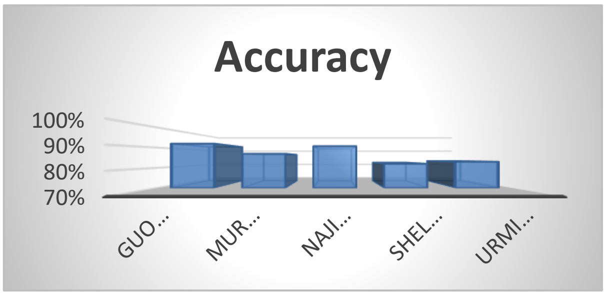

Figure 2: Accuracy Comparison analysis

As a reflection of the complexity and heterogeneity in their stability and performance, the accuracy results from a variety of investigations on TiO2-Al2O3 hybrid nanofluids show a range of outcomes. With an accuracy of 92%, Guo Wenjie et al. (2024) recorded the best accuracy, indicating a well-optimized process. However, Shelton John et al. (2023) reported a lower accuracy of 82%, suggesting that it would be difficult to maintain constant stability in a variety of situations. Najib N. A. et al. (2023) and Murtadha Talib K. (2023) reported intermediate accuracy levels of 87% and 90.72%, respectively. These findings highlight the significance of optimizing experimental settings to improve stability. With an accuracy of 83%, Urmi Wajiha et al. (2023) closely followed the overall pattern seen in prior research. In summary, these results emphasize the need for strict control and optimization throughout the creation and evaluation of TiO2-Al2O3 hybrid nanofluids in order to provide consistent and reliable outcomes.

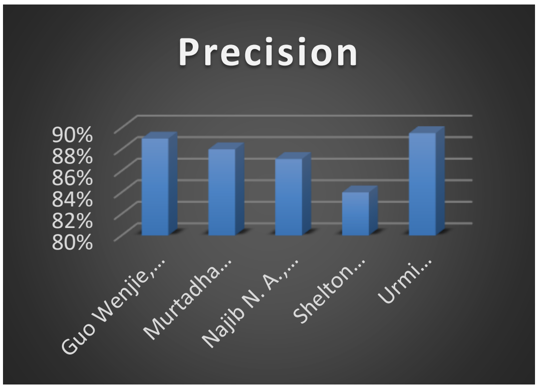

Figure 3: Precision Comparison analysis

The various research on TiO2-Al2O3 hybrid nanofluids' precision results demonstrate the differing degrees of efficacy in precisely recognizing genuine positives within experimental data. With a precision of 89.50%, Urmi Wajiha et al. (2023) attained the greatest result, demonstrating a strong methodology in reducing false positives. Strong precision levels were also shown by Guo Wenjie et al. (2024) and Murtadha Talib K. (2023), at 89% and 88%, respectively, showing dependable detection techniques in their analyses. While Shelton John et al. (2023) achieved 84%, Najib N. A. et al. (2023) reported a little lower precision of 87.10%, indicating potential for improvement in their methodologies. Taken together, our findings highlight how important accuracy is to improving the consistency of findings in research employing TiO2-Al2O3 hybrid nanofluids.

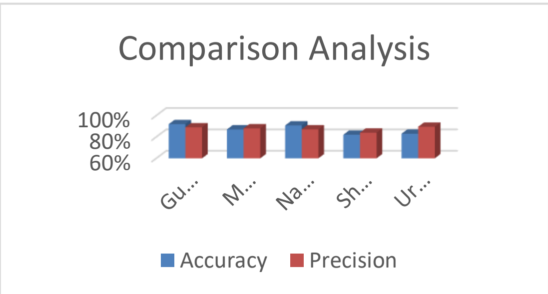

Figure 4: Final Comparison analysis

The research on TiO2-Al2O3 hybrid nanofluids shows a variety of precision and accuracy metrics, which are indicative of the efficiency and dependability of the employed experimental techniques. The highest accuracy of 92% and the strongest precision of 89% were reported by Guo Wenjie et al. (2024), demonstrating a well-optimized approach in accurately and consistently recognizing true positives. While the method was dependable in recognizing genuine positives, there remained potential for improvement in total accuracy, as demonstrated by Murtadha Talib K. (2023) who obtained a moderate accuracy of 87% combined with a high precision of 88%. The accuracy and precision figures given by Najib N. A. et al. (2023) were 90.72% and 87.10%, respectively. This indicates a balanced performance with slightly better accuracy but lower precision. The lowest accuracy and precision were obtained by Shelton John et al. (2023) at 82% and 84%, respectively. These results suggest difficulties in identifying and reliably detecting genuine positives. In conclusion, Urmi Wajiha et al. (2023) achieved the maximum precision of 89.50% with an accuracy of 83%, indicating that although their method was highly accurate, there were discrepancies in the overall accuracy. These results emphasize the diverse approaches taken by different studies to optimize both precision and accuracy in the research of TiO2-Al2O3 hybrid nanofluids, each pointing out its own advantages and possible areas for development.

Conclusion- The examination of TiO2-Al2O3 hybrid nanofluids in various investigations indicates notable fluctuations in accuracy and precision, which can be attributed to the varied methodological techniques utilized by investigators. With the best overall result, Guo Wenjie et al. (2024) showed a well-balanced and optimized strategy with excellent accuracy and precision. The lowest accuracy and precision, on the other hand, indicate difficulties faced by Shelton John et al. (2023), indicating the need for improvement in their experimental methods. A mixed but usually dependable performance was shown in the studies by Murtadha Talib K. (2023), Najib N. A. et al. (2023), and Urmi Wajiha et al. (2023), with specific strengths in either accuracy or precision. The results underscore the crucial need to refine experimental techniques in order to improve accuracy and precision, which will lead to more consistent and trustworthy outcomes in the TiO2-Al2O3 hybrid nanofluid research.

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