Mono and Hybrid Nanofluids' Preparation, Characterization and Stability

Subjects: Nanoscience & Nanotechnology

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Nanofluids are colloidal mixtures of nanosized particles (10–100 nm) suspended in base fluids. They possess good physical or chemical properties and thermal or rheological properties. Hybrid nanofluids are suspensions of a mixture of dissimilar nanoparticles or nanocomposites infused in the conventional base fluid, which yield better thermal conductivity and heat transfer characteristics due to hybridization.

nanofluids heat transfer rate Prandtl number pressure drop

1. Hybrid Nanofluids

Industries with cooling solution requirements have focused on the use of modified fluids with various additives [1] to obtain improved thermal properties. Nanofluids are colloidal mixtures of nanosized particles (10–100 nm) suspended in base fluids [2]. They possess good physical or chemical properties and thermal or rheological properties [3][4]. Hybrid nanofluids are suspensions of a mixture of dissimilar nanoparticles or nanocomposites infused in the conventional base fluid, which yield better thermal conductivity and heat transfer characteristics due to hybridization [5]. They are used in phase change materials, heat exchangers, solar energy, electronics, agriculture, chemical, manufacturing, and automobile industries [6][7][8][9][10][11][12][13][14][15][16][17][18][19]. The two-step method is used for preparing hybrid nanofluids. Different nanoparticles are prepared and mixed in the primary liquid through magnetic or mechanical stirring. The solution is sonicated and characterized to ensure stable and homogeneous mixing, providing improved heat transfer characteristics [20]. Enhanced heat transfer is due to increased surface area, collision, interactive effect, and proper mixing of nanoparticles in base fluids (causing micro turbulences). Hybrid nanofluids play four roles (used as refrigerant, lubricant, absorbent, and secondary refrigerant) in improving the thermal system performance in low-temperature applications. The effects of nanoparticle concentration and size on the performance of water-based CuO nanofluids were investigated in [21]. The synthesis, stability, and thermo-physical properties of hybrid nanofluids were studied in [22]. Zaynon and Azmi [23] presented the influence of nanoparticle type, concentration, temperature, shape, and size on the nanofluid properties. The amount of grapheme required in the base fluid to improve thermal performance was suggested in [24].

2. Preparation of Mono/Hybrid Nanofluids

Nanofluids are organized according to their preparation using one- or two-step methods (**Figure 1**). In a one-step approach, nanoparticles are prepared and mixed directly in a base fluid using physical or chemical processes. In the two-step method, nanoparticles are obtained using physical or chemical methods and then effectively infused in an essential base liquid [25]. Several investigators have reviewed the preparation of different mono/hybrid nanofluids based on various base fluids [26][27][28][29][30][31][32][33][34][35][36]. Spherical ZnO particles were synthesized using a sol–gel annealing process at 500–600 °C in [37]. The ball milling process was used to grind aluminum nitride carbon nanocomposite (a nontoxic ceramic) for heat transfer experiments [38]. Making nanofluids through a single-step method is expensive and time-consuming. The control of particle agglomeration is the primary problem in the two-step method. Ultrasonication minimizes nanoparticle sedimentation and improves nanofluid stability [39]. Due to simplicity, 95% of researchers used a two-step method when preparing nanofluids (see **Table 1**).

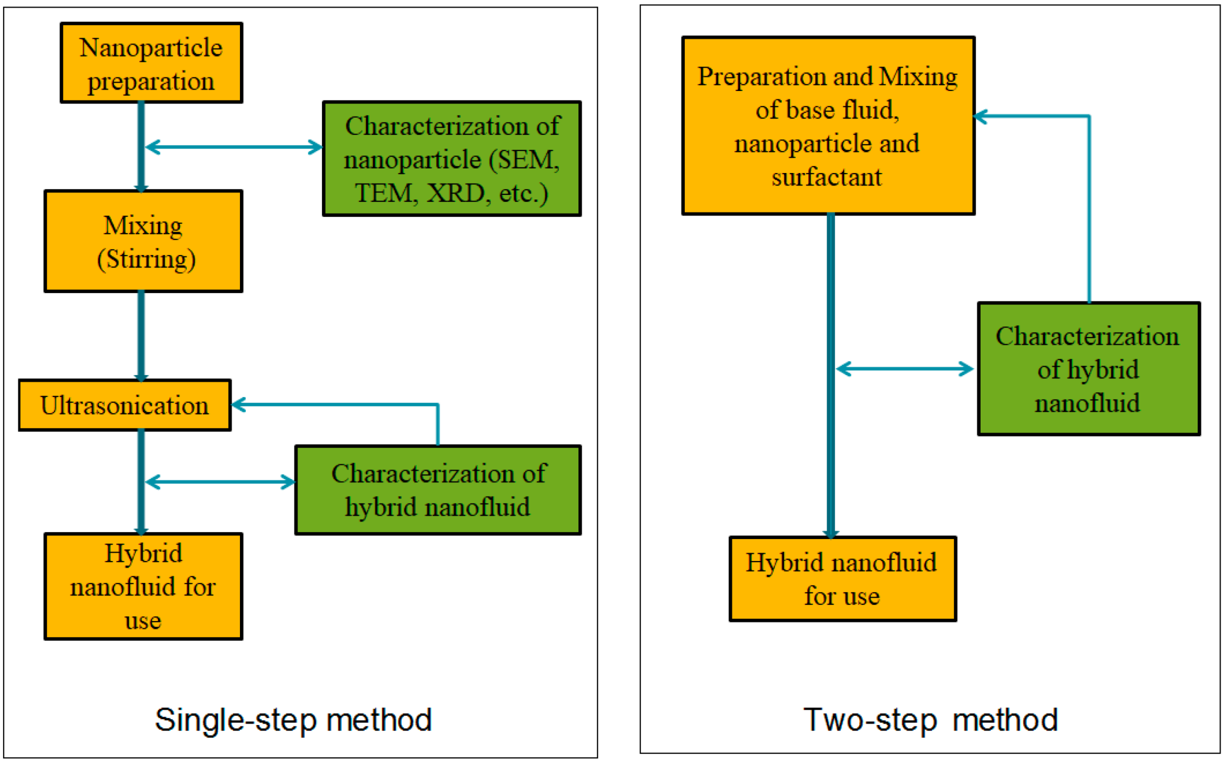

Figure 1. Flowchart for producing hybrid nanofluids [40].

Table 1. Examples of hybrid nanofluids adopting two-step preparation.

Author(s)	Nanoparticle	Base Fluid
Jana et al. [41]	Au–CNT, Cu–CNT	Water
Han et al. [42]	Sphere–CNT	Oil
Turcu et al. [43]	Fe_3O_4–polypyrrole	Water
Jha and Ramaprabhu [44]	Cu–MWCNT	Water/EG

Author(s)	Nanoparticle	Base Fluid
Han and Rhi [45]	Ag–Al_2O_3	Water
Baby and Sundara [46]	CuO–HEG	Water/EG
Paul et al. [47]	Al–Zn	EG
Suresh et al. [48]	Al_2O_3–Cu	Water
Botha et al. [49] *	Ag–SiO_2	Oil
Ho et al. [50]	Al_2O_3–PCM	Water
Baby and Sundara [51]	Ag–HEG	Water/EG
Amiri et al. [52]	Ag–MWCNT	Water
Chen et al. [53]	Ag–MWCNT	Water
Aravind and Ramaprabhu [54]	Graphene–MWCNT	Water and EG
Bhosale and Borse [55]	Al_2O_3–CuO	Water
Balla et al. [56]	CuO–Cu	Water
Abbasi et al. [57]	ϒ-Al_2O_3–MWCNT	Water
Nine et al. [58]	Cu–Cu_2O	Water
Munkhbayar et al. [59] *	Ag–MWCNT	Water
Sundar et al. [60]	Nanodiamond–nickel	Water/EG
Parameshwaran et al. [61]	Ag–TiO_2	PCM
Batmunkh et al. [62]	Ag–TiO_2	Water
Madhesh et al. [63]	Cu–TiO_2	Water
Chen et al. [64]	MWCNT–Fe_3O_4	Water
Parekh [65]	$Mn_{0.5}Zn_{0.5}Fe_2O_4$	Oil
Luo et al. [66]	Al_2O_3–TiO_2	Lubricating oil
Madhesh and Kalaiselvam [67]	Cu–TiO_2	Water
Zubir et al. [68]	Graphene oxide–CNT	Water
Qadri et al. [69]	Graphene–Cu_2O	Water/EG

Author(s)	Nanoparticle	Base Fluid
Karimi et al. [70]	$NiFe_2O_4$	Water
Chakraborty et al. [71]	Cu–Al	Water
Megatif et al. [72]	CNT–TiO_2	Water
Abbasi et al. [73]	MWCNT–TiO_2	Water
Toghraie et al. [74]	ZnO–TiO_2	EG
Bhanvase et al. [75]	PANI–CuO	Water
Asadi et al. [76]	CuO–TiO_2	Water
Chen et al. [77]	Al_2O_3	Liquid paraffin
Asadi et al. [78]	MWCNT	Water
Gulzar et al. [79]	Al_2O_3–TiO_2	Therminol-55
Alarifi et al. [80]	MWCNT–TiO_2	Oil
Akram et al. [81]	CGNP	DI Water
Sharafeldin and Grof [82]	WO_3	Water
Chen et al. [83]	MWCNT	Water
Ali et al. [84]	Al	Water
Mahbubul et al. [85]	Al_2O_3	Water
Mahyari et al. [86]	GO–SiC	Water/EG
Chen et al. [87]	Fe_3O_4–MWCNT	Brine water
Okonkwo et al. [88]	Al_2O_3–Fe	Water
Terueal et al. [89]	$MoSe_2$	Water
Li et al. [90]	SiO_2	Liquid paraffin
Geng et al. [91]	ZnO–MWCNT	Oil
Li et al. [92]	SiO_2	EG

* Single-step method.

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[74] 2 EG hybrid nanofluids by dispersing equal volumes of ZnO and titanium dioxide (TiO_2) nanoparticles in a given amount of pure EG as a base liquid. The stability of the prepared nanofluid was confirmed, ensuring no sedimentation. Paul et al. [47] synthesized Al–Zn nanoparticles by stirring. They prepared hybrid nanofluids through a two-step process. Al–Zn nanoparticles were added to ethylene glycol (base fluid), followed by sonication and magnetic stirring. Suresh et al. [48] obtained a hybrid powder of alumina–copper using a thermochemical method, including spray-drying, oxidation of the precursor powder, hydrogen reduction, and homogenization. They used different volume fractions (0.1%,

0.33%, 0.75%, 1.0%, and 2.0%). Baby and Sundara [46] used a hydrogen-induced exfoliation and chemical reduction process of graphite oxide (GO) to synthesize grapheme decorated with CuO (CuO/HEG). The HEG obtained was functionalized by acid treatment and coated with CuO nanoparticles. CuO/HEG was dispersed in the base liquid (water/EG) by ultrasonication. Nine et al. [58] reported an economical and beneficial process for synthesizing Cu_2O and Cu/Cu_2O nanoparticles with a mean size of less than 30 nm. A ball milling process was used to synthesize Cu/Cu_2O–water hybrid nanofluids. Madhesh et al. [63] prepared a copper–titania hybrid nanofluid by uniformly dispersing an aqueous solution of titania (5 g) and copper acetate (0.5 g) in an ultrasonic vibrator for 2 h using reducing agents at 45 °C and atmospheric pressure. A one-step method was described for a hybrid nanofluid containing silver and silica nanoparticles by Botha et al. [49]. Ho et al. [50] prepared phase change material (PCM) suspensions using interfacial poly-condensation and emulsion techniques. Nanofluid Al_2O_3–water was obtained by adding Al_2O_3 nanoparticles in water (base liquid). Chen et al. [53] prepared Ag/MWCNT nanocomposites using the silver mirror reaction. Functionalized MWCNTs were used to fabricate Ag/MWCNT nanocomposites using sodium dodecyl sulfate (SDS) as a surfactant and formaldehyde as a reducing agent.

3. Characterization and Stability of Mono/Hybrid Nanofluids

Several forces, such as van der Waals attraction, buoyancy, gravity, and electrostatic repulsion, cause destabilization and sediment formation. Van der Waals attraction and gravity decrease the stability of colloidal suspensions. Stability is a critical factor in the effectiveness of nanofluids for technological applications. All thermo-physical properties of nanofluids depend on their stability. The instability of nanofluids can reduce their effectiveness in many heat transfer applications. It is caused by the tendency of nanoparticles to form clusters in liquids. An SEM image of the Al_2O_3–MWCNT/water hybrid nanofluid is shown in **Figure 2** [93].

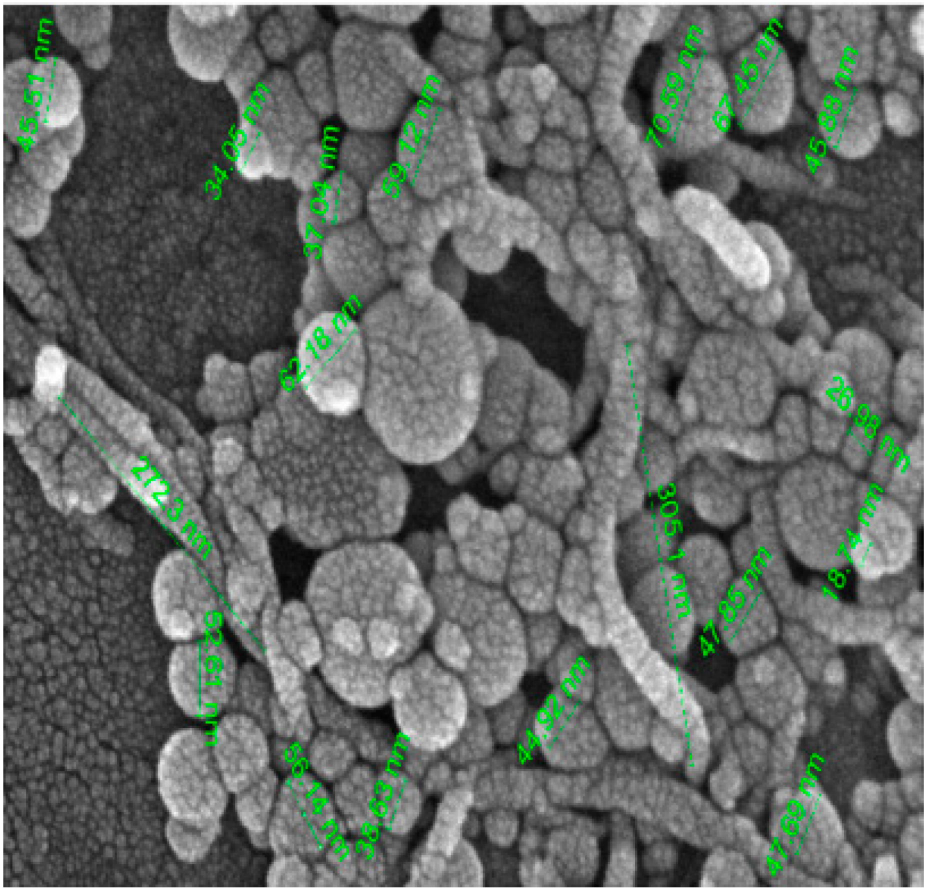


Figure 2. SEM image of Al_2O_3–MWCNT/water hybrid nanofluid [93].

The particle aggregation causes the separation of nanoparticles from base fluids and forms sedimentation [94]. The coagulation rate is determined from the collision frequency of particles in Brownian motion and cohesion probability [95]. Removal of agglomeration propensity yields stable nanofluids. Methods adopted for assessing the stability of nanofluids are the sedimentation method, spectral absorbance, centrifugation method, transmittance measurement, zeta potential measurement, and dynamic light scattering [96]. For long-term stable and homogenous nanofluids, the following surfactants can be added [97][98]: anionic (sodium dodecyl sulfate and sodium dodecyl benzene sulfonate), cationic (cetyl trimethyl ammonium bromide), nonionic (Span-80 and Tween-20), and polymer (polyvinyl pyrrolidone, polyvinyl alcohol, and gum Arabic). Surfactants improve the wettability of the nanoparticles and the base fluids by reducing the base fluid’s surface tension and improving the nanoparticles’ dispersibility [99].

Ultrasonic mills, baths, stirrers, and high-pressure homogenizers are used for the dispersion of nanoparticles. Baby and Sundara [51] used an economical method to synthesize hydrogen-functionalized, exfoliation-induced silver-decorated graphene (Ag/HEG) and prepared nanofluids. Ag/HEG was distributed in a mixture of deionized water/ethylene glycol using ultrasonic agitation without surfactant. The hybrid nanofluid was observed to be stable for more than 3 months. Aravind and Ramaprabhu [54] prepared MWCNT nanocomposites with graphene shells and synthesized them by chemical vapor deposition. The prepared hybrid nanofluid was stable for an extended period. Megatif et al. [72] prepared a CNT–TiO_2 hybrid nanocomposite and dispersed it in water to obtain a hybrid nanofluid. The surfactant SDBS was added to the suspension for proper dispersion. They sonicated the solution for 15 min and tested its stability. The solution was stable for 2 days.

Although most (95%) of the researchers adhered to the two-step method, nanofluids synthesized by the expensive and complex one-step method improve the stability of nanoparticle suspensions in base oils due to high sedimentation rates with short sonication times [100]. Ultrasonication lessens the sedimentation of nanoparticles, resulting in enhanced nanofluid stability. A better understanding of the mechanisms of nanofluids at the atomic level is required to address particle transport, aggregation, and stability issues with minimal experimentation.

No sophisticated equipment is required to produce nanofluids using a simple two-step method. Dispersion of nanoparticles requires sonication times of 3–10 h [101]. Amin et al. [102] critically reviewed the properties of single and hybrid nanofluids based on organic and synthetic materials. Malika and Sonavan [103] used a two-step method to prepare CuO–ZnO/water hybrid nanofluids. Ultrasonication provided nanofluid stability. FESEM/EDS, dynamic light scattering, and zeta potential measurements provide insight into nanoparticle morphology, shape, and size. The stability of Al_2O_3–CuO/(50/50) EG/W (ethylene glycol/water) hybrid nanofluids at 60 °C was confirmed by zeta potential measurements [104].

The stability of trihybrid nanofluids was tested by mixing three types of nanoparticles (i.e., Al_2O_3, TiO_2, and SiO_2 with volume concentrations of 0.05–0.3%) in a water/ethylene glycol-based fluid [105] and a recommended sonication time of 10 h at a zeta potential of 25.1 mV. To improve the stability of nanofluids, Afshari et al. [106] highlighted properties such as the acidity degree of the nanofluid, ultrasonication, nanoparticle material, base fluid type, nanoparticle concentration, surfactants, and surface modification of nanoparticles. Arora and Gupta [107] reviewed stability evaluation techniques (spectral absorbance, sedimentation, zeta-potential, and electron microscopy) and enhancement techniques (ultrasonication, surfactant addition, particle surface modifications, and pH change). Future research should focus on industrial applications to minimize pressure losses, the concentration of nanoparticles, and the long-term stability of hybrid nanofluids.

The stability characteristics of mono and hybrid nanofluids have been studied using zeta potential measurements and vibrating sample magnetometry (VSM) analysis [108]. To maintain nanofluid stability, Zainon and Azmi [23] recommend analysis by sonication, pH modification, surfactant, TEM, field emission scanning electron microscopy (FESEM), XRD, zeta potential, and UV/visible spectroscopy techniques. Bumataria et al. [109] used single and hybrid nanofluids to study heat transfer consider in heat pipe technologies. The use of dispersing agents and sonication increases the stability of nanofluids [110]. Excellent suspension stability could be obtained by adding small amounts of SDBS and PEG to DW (hybrid nanofluid 25% Al_2O_3 + 75% TiO_2) [111]. The hybrid nanofluid’s stability was high, as the zeta potential value (i.e., the electrostatic repulsive force between the nanoparticle and the base fluid) was 42.6 mV compared to the reference value of 30 mV. Said et al. [112] investigated the stability of carbon nanofibers (CNF), functionalized carbon nanofibers (F-CNF), reduced graphene oxide (rGO), and F-CNF/rGO nanofluids. Hybrid nanofluids (FCNF/rGO) showed higher stability than CNF, F-CNF, and rGO nanofluids.

Muthoka et al. [113] investigated the stability of hybrid nanofluids with two nanoparticles in PCM/DI water. The stability of surfactant-free MgO and 24 wt.% primary liquid was poor after 24 h, whereas the functionalized MWCNT solution showed no separation after 24 h. It was confirmed that the nanofluid's low-temperature stability was increased using a surfactant. Acid treatment with CNF was used to test stability [114]. The zeta potential of 0.02 vol.% F–CNF nanofluids measured after 2 and 90 days was −42.9 and −41.8 mV, indicating improved stability compared to the −16.3 and −15.5 mV UNV zeta potentials, which were characterized by relatively unstable dispersion. Alawi et al. [115] synthesized aqueous nanofluids PEG–GnP, PEG–TGr, Al_2O_3, and SiO_2. The dispersion stability of the carbon-based nanofluid and the metal oxide nanofluid was observed for 30 days, and the high dispersibility of PEG–HNP and PEG–TGr in an aqueous medium with low sedimentation was confirmed. Compared to GnP/DW nanofluids, TiO_2/DW nanofluids showed superior stability [116]. The addition of CTAB surfactant showed excellent stability of ternary hybrid nanofluids [117]. Uysal [118] used a 500 rpm homogenizer to mix and stabilize nano-graphene in vegetable oil. Al-Waeli et al. [119] demonstrated high nanofluid stability (over 80 days) with CTAB and tannic acid + ammonia solution. The stability of Al_2O_3/water nanofluids using CTAB and SDBS surfactants was investigated for various pH values [120]. Kazemi et al. [121] visually observed the stability of SiO_2/water and G/water nanofluids. SiO_2/water nanofluids were found stable at all pH values (see **Table 2** for the stability of various nanofluids).

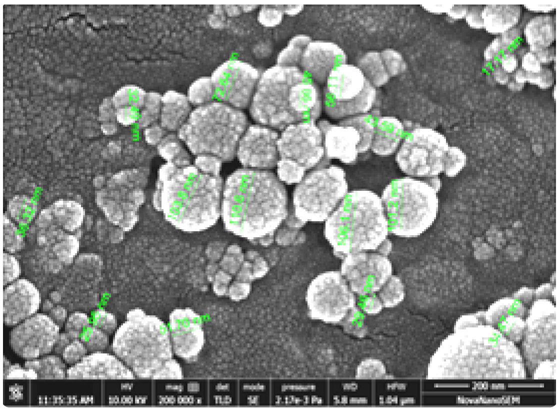
Table 2. Stability of different nanofluids with surfactants.

Author(s)	Nanoparticle	Base Fluid	Surfactant (s)
Xian et al. [122]	COOH-GnP, TiO_2	DW/EG	SDC, CTAB *, SDBS
Almanassra et al. [123]	CNT	Water	GA *, PVP, SDS
Cacua et al. [124]	Al_2O_3	Water	CTAB, SDBS *
Kazemi et al. [121]	SiO_2, graphene	Water	CMC *
Ouikhalfan et al. [125]	TiO_2	DW	CTAB *, SDS
Siddiqui et al. [126]	Cu-Al_2O_3	DI water	
Cacua et al. [120]	Al_2O_3	DI water	CTAB, SDBS *
Etedali et al. [127]	SiO_2	DI water	CTAB *, SLS *
Giwa et al. [128]	Al_2O_3-Fe_2O_3	DW	SDS *, NaDBS *
Kazemi et al. [129]	G-SiO_2	DW	CMC *
Gallego et al. [130]	Al_2O_3	Water	SDBS *
Shah et al. [131]	(rGO)	EG	CTAB *, SDBS, and SDS
Ilyas et al. [132]	GnP	Saline water	SDS *

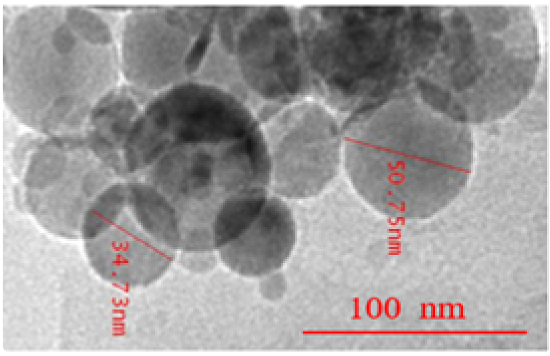
* Recommended surfactant for improved stability of hybrid nanofluids

Brownian motion of nanoparticles, microconvection, clustering, and pH value strongly affect the thermal properties of hybrid nanofluids [133]. Solidification and clustering of nanocomposites of different sizes in nanofluids affect their thermal properties [134][135]. The stabilization and evaporation of single and hybrid nanofluids have been studied in specific systems from a statistical point of view [136][137]. Bhattad et al. [138] investigated with Al_2O_3 - TiO_2 - water hybrid solution. Commercially purchased nanoparticles were mixed with the primary fluid (DI Water) using a mechanical stirrer followed by ultrasonication. Afterward, the solution was characterized to verify the shape, size, proper mixing and stability.

SEM (Scanning electron microscopy) and TEM (Transmission electron microscopy) tests were performed and measured the mean size of Al_2O_3 and TiO_2 nanoparticles by ImageJ 2.0.0-rc-3 as 45 nm and 20 nm, respectively. The small-size particles in **Figure 3** represent TiO_2 nanoparticles, whereas larger ones are the Al_2O_3 nanoparticles. Both types of nanoparticles were found to be spherical, with a shape factor of 1. One of the key challenges in studying nanofluids is ensuring their stability and homogeneity. A stability test involving gravitational settling was performed to address this issue, and images of the test tube were taken at different intervals (**Figure 4**). The results showed that there was no sedimentation throughout the 7-day investigation.



(**a**)



(**b**)

Figure 3. (**a**). SEM image of Al_2O_3- TiO_2/water hybrid nanofluid; (**b**). TEM image of Al_2O_3- TiO_2/water hybrid nanofluid.

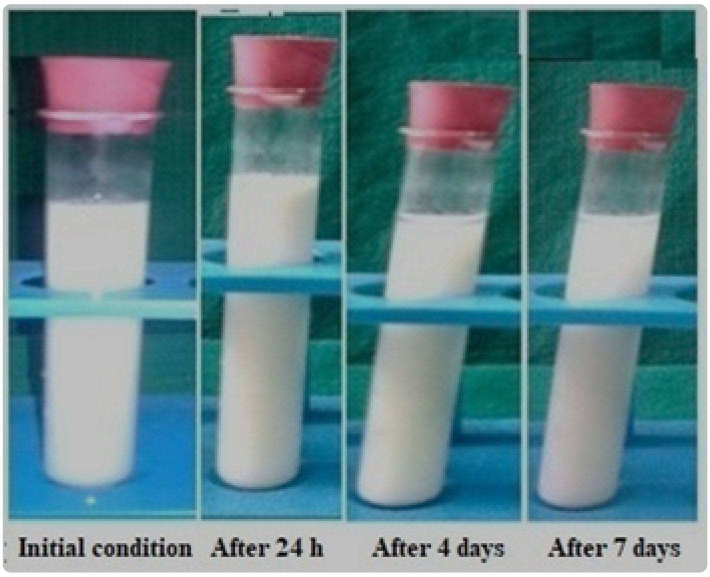


Figure 4. Stability analysis of a sample showing no sedimentation for 7 days.

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