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Effect of Ultrasonication Duration and Temperature on the Stability and Viscosity of MXene/Water Nanofluid

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Despite some encouraging results that nanofluids offer to the scientific community, several challenges remain before their widespread adoption in industry. One significant challenge is the stability of nanofluids, which can lead to nanoparticle aggregation and affect viscosity. Ultrasonication is a common method used to disperse nanoparticles in base fluids. Therefore, the main aim of this work is to investigate the effect of ultrasonication duration and temperature on the stability and viscosity of MXenes ($Ti_3C_2T_x$)/water nanofluids. A nanofluid containing 0.05 wt% MXenes ($Ti_3C_2T_x$)/water was formulated by adopting three different ultrasonication durations, namely 60, 90 and 120 minutes. The Zeta potential value was used as an indicator of their stability. In conjunction with visual inspections, the stability of the samples was examined on Day 1, 7 and 30 after the nanofluids' formulation. On Day 1, optimal stability was observed in nanofluids ultrasonicated for 90 minutes at the respective temperature, with moderate Zeta potential values exceeding -30 mV. However, stability decreased over time across all cases. Extending the ultrasonication duration to 120 minutes resulted in higher nanofluid's viscosity. The temperature variations from 20 to 60°C did not show similar trend of the stability for some cases, potentially indicating particle agglomeration with changing temperatures. Hence, more investigations were suggested to get more information of the nanofluids, such as characterization techniques using microscopy. The stability could also be improved via other methods, such as integrating surfactants, varying pH level and nanoparticles concentration, and modifying nanoparticle surfaces and base fluid.

Keywords: MXene nanofluids; ultrasonication duration; Zeta potential

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In recent years, researchers have explored the potential of replacing conventional heat transfer fluids such as water, glycols, and oils with nanofluids in various engineering applications due to their enhanced thermal conductivity and heat transfer performance [1]. However, there are several challenges to the implementation of nanofluids as heat transfer fluids, including their stability at high temperatures and over prolonged durations [2]. Stability in nanofluids refers to the ability of nanoparticles to resist aggregation at a significant rate [3]. Moreover, poor stability prevents further advancement and practical use of nanofluid in heat transfer applications [4]. Agglomeration, aggregation, and sedimentation of nanoparticles in nanofluids should be prevented, as they will also affect the viscosity of the nanofluids. Subsequently, nanofluids with high viscosity will lead to other issues such as high pressure drop and pumping power, especially in closed systems in heat transfer applications. Figure 1 shows three stability cases reported by Ali et al. [5], exhibiting distinct viscosity regions and sedimentation observations. From the figure, nanoparticle sedimentation in both unstable and semi-stable scenarios can clearly be observed. Hence, nanofluids' stability needs to be investigated, as the deposition of a part of the nanoparticles may affect the properties of nanofluids.

In previous studies, the stability of nanofluids has been improved via several techniques. These techniques include surface modification of nanoparticles, adjusting nanoparticle concentration, pH level manipulation, surfactant addition, and optimizing ultrasonication duration. Both qualitative and quantitative assessments of nanofluid stability have been conducted based on the literature [6-9], as illustrated in Figure 2.

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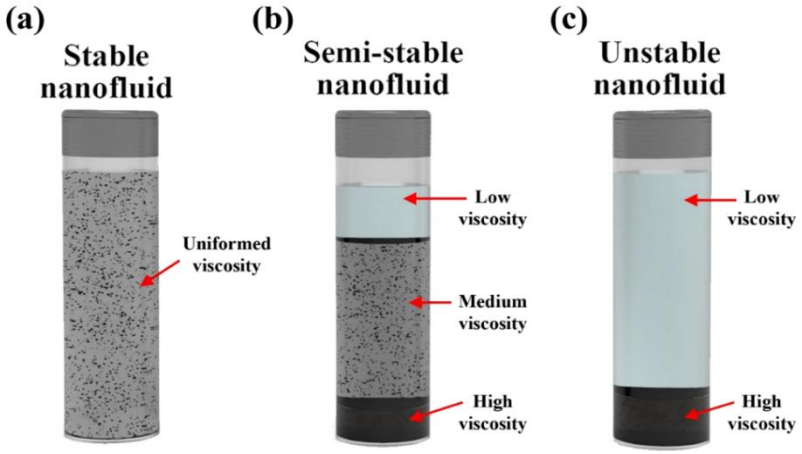

Figure 1. The viscosity classification of nanofluids for (a) stable, (b) semi-stable, and (c) unstable suspension cases. Reproduced under terms of the CC-BY license. 2021, Ali et al. [5], published by MDPI Open Access.

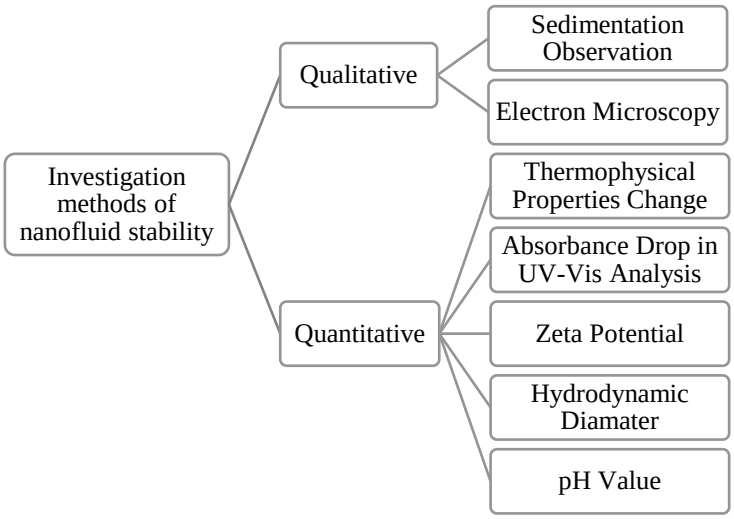

Figure 2. Investigation methods of nanofluid stability reported in the literatures [6]–[9].

Li et al. proposed surface modification of multi-walled carbon nanotubes (MWCNTs) by using β-cyclodextrin (β-CD) in deionized water [10]. Their study showcased the production of highly stable nanofluids, validated by Zeta potential and particle size measurements conducted via dynamic light scattering (DLS). With a relatively small increase in the viscosity, surface modification served to create resistance between carbon nanotubes, thereby reducing the formation of large agglomerates and the complicated entanglement of carbon nanotubes. This technique can also be utilized to enhance the stability of graphene in both aqueous and organic media through covalent and non-covalent functionalization. Sadri et al. employed covalent functionalization of graphene nanoplatelets (GNP) via free radical grafting of gallic acid in order to enhance the dispersion of GNP [11]. Their research also highlighted the increased thermal conductivity and reduced viscosity of the nanofluids, making them suitable to be used for various thermal and heat transfer applications. Naddaf et al. investigated the heat transfer performance of MWCNT and GNP dispersed in diesel oil at various nanoparticle concentrations and flow rates [12]. These nanoparticles were functionalized both covalently with hexylamine (HA) and non-covalently with oleic acid (OA). Nanofluids of OA-MWCNT, HA-MWCNT, OA-GNP, HA-GNP, and OA-MWCNT/GNP (1–1 Hybrid of each nanoparticle) were prepared in the concentration range of 0.05 – 0.5 wt%. UV-Vis analysis confirmed the good stability of all nanofluids even after 30 days. Moreover, the local heat transfer coefficient increased for all nanofluids compared to pure diesel oil [12]. Despite all these enhancements, the process of surface modification is complex and requires specialized equipment, which may not be readily accessible in the industry and incur more cost [13]. Therefore, this method needs to be carefully considered before its implementation.

It is also crucial to keep in mind that altering the pH level, the amount of surfactant, and the concentration of nanoparticles can have impacts not only on their stability, but also characteristics. Researchers have noted that a small quantity of surfactant can effectively preserve the dispersion of nanoparticles in the base fluid [14-20]. However, at higher temperatures, this may result in additional issues such as foam formation and degradation of the surfactants [5]. This occurs as the bonding between the nanoparticles and surfactants weakens, ultimately impacting the thermal and hydrodynamic properties of the nanofluids [5]. In addition to that, the presence of surfactants might restrict the maximum amount of nanoparticle that can be effectively dispersed in the base fluid. Another method to enhance nanofluid stability is by regulating the pH, as suggested by Said et al. [21]. In their study, aluminium oxide (Al_2O_3) nano powder was dispersed in distilled water, with hydrochloric acid used to adjust the pH of the base fluid. Interestingly, the highest stability was observed at pH 9, which was weakly alkaline. However, this finding contradicted those of Choudhary et al. [22] and Bhat et al. [23], who reported that nanofluids with acidic properties exhibited greater stability.

Apparently, the agglomeration of the nanoparticles can also be reduced by the ultrasonic agitation during the preparation of the nanofluids [24-27]. Ultrasonication is a process where intense ultrasound waves are applied to liquids, thus dispersing and separating the nanoparticle aggregates and improving stability [28]. Different ultrasonication durations result in varying cluster sizes of nanoparticles in the base fluid. This variation is not uniform across different nanofluids, as it depends on factors such as nanoparticle concentration, shape, and size, as well as the type of sonicator used (probe or bath) [29-31]. For instance, Shah et al. found an optimal sonication time of 80 minutes for copper oxide (CuO)/water/ethylene glycol (EG) nanofluids [32], while Mukherjee et al. suggested an optimum of 150 minutes to achieve stable silicon oxide (SiO_2)/water nanofluids [30]. Barai et al. investigated the impact of ultrasonication duration on the thermal conductivity of iron oxide (Fe_3O_4)/water nanofluids [33]. They found that the optimum ultrasonication duration was 40 minutes, and this remained consistent across different nanofluid concentrations. However, beyond 40 minutes, the thermal conductivity of the nanofluids decreased. Asadi et al. found that the optimum ultrasonication duration for MWCNT/water nanofluids was 60 minutes based on their Zeta potential value and thermal conductivity [25]. A significant result was presented by Al-Waeli et al., as no separation was observed in the silicon carbide (SiC)/water nanofluid for more than ten months and the reduction in the thermal conductivity was insignificant [34]. However, the results were only obtained when the nanofluid was added with Cetyltrimethylammonium Bromide (CTAB) surfactant and sonicated for 5 hours. Al-Waeli et al. also reported that stability decreased as the nanoparticle concentration increased [35]. Sardarabadi and Passandideh-Fard observed slight sedimentation of aluminium oxide (Al_2O_3)/water, titanium oxide (TiO_2)/water, and zinc oxide (ZnO)/water after 2 days after sonicating the nanofluids using an ultrasonic vibrator for 2 hours (with a 20 minutes interval) at 60°C [36]. Anushree and Philip examined the stability of three water-based metal oxide (α-Al_2O_3, TiO_2, and γ-Al_2O_3) nanofluids with varying particle concentrations using UV–Vis spectroscopy, dynamic light scattering (DLS), Zeta potential analysis, and visual observation [37]. DLS measurements tracked changes in the hydrodynamic diameter of the nanoparticles over several days. It was found that the γ-Al_2O_3 nanofluid exhibited superior stability compared to the other nanofluids tested, as it showed similar size of the nanoparticles up to 5 days, even though the sonication was performed for only 8 minutes using a sonicator with a power of 130 W. Nevertheless, Zheng et al. reported that nanofluid stability was more dependent on ultrasonication duration than sonicator power [38]. The homogeneity, uniformity, and average size of the nanoparticles in the nanofluid can also be measured by using electron microscopy. Aberoumand et al. presented the Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) images of silver (Ag)/water nanofluid [39]. Even though they obtained stable nanofluids for many months, the use of a one-step method for preparing the nanofluids in their work was limited to small amounts of production. This could be a barrier to its industrial manufacturing.

To understand the phenomenon in nanofluid stability, the Derjaguin-Landau-Verwey-Overbeek (DLVO) theory can be used [40]. According to theory, the stability of nanofluids is governed primarily by two forces; van der Waals forces and electrostatic repulsion, which influence the stability of nanofluids [40]. These forces are closely linked to the Zeta potential value, providing valuable insights into the stability and interactions of nanoparticles in a fluid medium [41]. Van der Waals Forces, for instance, arise due to temporary fluctuations in the electron distribution around nanoparticles, creating fluctuating electric dipole moments. These attractive forces tend to draw particles closer together, promoting particle agglomeration and aggregation. When these forces are particularly strong, nanoparticles may separate from the base fluid and the agglomerated nanoparticles are sedimented under the influence of gravity [40]. Meanwhile, nanoparticles with the same charges experience electrostatic repulsion that counteracts the Van der Waals forces, hence preventing agglomeration. Strong repulsive interactions between the nanoparticles keep them stable in the base fluid and they can be indicated by a high Zeta potential value [40]. An absolute 30 mV is frequently selected as a threshold indicating moderate stability, since nanoparticles typically tend to aggregate below this value [42]. More stable nanofluids are indicated by a greater range of absolute Zeta potential values, namely between 40 mV and 60 mV [43]. In a study by Choudhary et al., the behavior of zinc oxide (ZnO)/ethylene glycol/deionized water nanofluid was investigated over a

period of 25 days, evaluating its impact on the thermal characteristics of a flat plate solar collector under various parametric conditions [41]. On the 25th day, the Zeta potential value decreased by 51.16%, indicating reduced stability of the nanofluid over time.

MXenes are two-dimensional nanomaterials that are composed of thin layers that contain transition metal carbides, nitrides, or carbonitrides [7]. Therefore, MXenes have many stoichiometric formulations. One of the commonly studied MXenes is titanium carbide ($Ti_3C_2T_x$), which can be synthesized from a bulk crystal called MAX by a few synthesis methods [44-45]. In $Ti_3C_2T_x$, the titanium (Ti) atoms are arranged in a hexagonal lattice structure, and carbon (C) atoms occupy the octahedral interstitial sites between the titanium layers, while "T_x" stands for the hydroxyl, oxygen, fluorine, and/or chlorine terminations derived from the synthesis process [46]. Tan et al. presented the Field Emission Scanning Electron Microscopy (FESEM) image of the synthesized multilayered and delaminated pure MXenes with $Ti_3C_2T_x$ formulation [47], which can be viewed in Figure 3. MXene-based nanofluids have emerged as a promising new class of fluids, offering enhanced properties for various engineering applications, including energy conversion, storage, and thermal management [48-55]. Samylingam et al. reported that even a small amount of MXene could enhance the properties of MXene-based nanofluids [51]. Despite these enhancements, their stability remains relatively less explored in the field.

Thus, this research aims to investigate the stability of MXenes ($Ti_3C_2T_x$)/water nanofluids under varying parameters. One of the studied parameters is the ultrasonication duration, which is known to significantly influence nanofluid stability and is unique to each nanofluid type. To the authors' knowledge, this kind of study has not been reported for MXenes ($Ti_3C_2T_x$)/water nanofluids. Additionally, temperature and time are two other parameters that are considered in this research. Previously, Mao et al. performed 30-minute ultrasonication when preparing MXenes ($Ti_3C_2T_x$)/water nanofluids and obtained a poor Zeta potential value, ranging from -18.9 to -26 mV, and obvious sedimentation was observed after 1 hour of its preparation [56]. Furthermore, with an increase in $Ti_3C_2T_x$ concentration from 0.1 to 0.5 wt%, the Zeta potential value declined accordingly. Abdelrazik et al. formulated MXenes ($Ti_3C_2T_x$)/water nanofluids of less than 0.1 wt% and added surfactant to improve the nanofluids' stability [54]. The ultrasonication duration was fixed at 60 minutes. As a result, a high absolute Zeta potential value was obtained (greater than 50 mV). This might be due to the low concentration of $Ti_3C_2T_x$, which ranged from 0.0005 to 0.05 wt%, and the addition of surfactants to it. Neither study investigated the impact of temperature on the stability of MXenes ($Ti_3C_2T_x$)/ water nanofluids. In the current research, MXenes with a $Ti_3C_2T_x$ formulation were synthesized and dispersed in the deionized water. No surfactant was used to simplify the methods, and the results could serve as the basis for MXenes ($Ti_3C_2T_x$)/ water nanofluids.

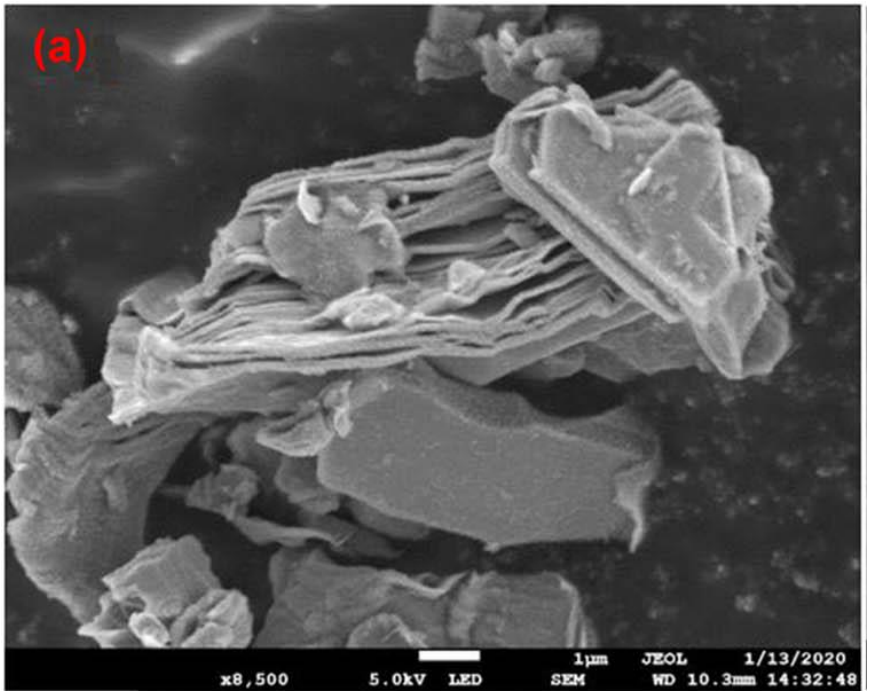

Figure 3. The Field Emission Scanning Electron Microscopy (FESEM) image of the synthesized multilayered and delaminated pure MXenes – Reproduced under terms of the CC-BY license. 2022, Tan et al. [47], published by De Gruyter Open Access.

The ultrasonication duration, temperature, and time of investigation were varied. Zeta potential values were employed to assess the stability of the resulting MXene-based nanofluids, as it offers a quantitative measure without requiring complex procedures or equipment. Additionally, visual observations were conducted to qualitatively analyze the stability of MXene ($Ti_3C_2T_x$)/water nanofluids. Subsequently, the viscosity of the nanofluids was measured to assess the impact of parameter changes on them. The findings of this study can provide valuable insights for scholars interested in further investigating MXene-based nanofluids, shedding light on the factors influencing nanofluid stability.

MATERIALS AND METHODOLOGY

Synthesis of MXene Nanoparticles

In the present research work, MXene nanoparticles with the formulation of titanium carbide ($Ti_3C_2T_x$) were synthesized using a wet chemistry method using research facilities at the Advanced Nano-Materials and Energy Research laboratory, situated within the Research Centre for Nano-Materials and Energy Technology, Sunway University. The materials employed included MAX Phase material (Ti_3AlC_2 from Y-Carbon Ltd.), hydrochloric acid (HCl, 37% wt. from Fisher Chemicals), lithium fluoride (LiF, 325 mesh powder, 98.5% purity from Alfa Aesar), sodium hydroxide (NaOH, 97% purity, pellets from Sigma Aldrich), and dimethyl sulfoxide (DMSO, analytical reagent grade from Fisher Chemicals). The first step involved the preparation of a hydrochloric acid solution by mixing 5 ml of deionized water with 15 ml of hydrochloric acid in a 30 ml volume beaker. Following this, 1 g of lithium fluoride was introduced into the diluted hydrochloric acid solution and stirred at 300 rpm for 30 minutes. Subsequently, 1 g of MAX phase material, Ti_3AlC_2, was weighed using a microbalance (Explorer series, EX224, Ohaus) and added gradually to the solution over a 15-minute period to prevent overheating due to exothermic reactions. The stirring process continued for 48 hours at room temperature to facilitate the etching of aluminum from the MAX phase, resulting in the production of layered MXene with a titanium carbide formulation, $Ti_3C_2T_x$ [57].

Once the etching process was done, a dilute solution of sodium hydroxide was slowly added to the solution until pH 7 was attained. Then, the solution was filtered and rinsed with deionized water four times, with each rinse lasting 5 minutes and carried out at 4200 rpm using an ultrahigh centrifuge (Sorvall LYNX 6000, Thermo Scientific). This sequence of steps resulted in the formation of the as-prepared MXenes. The delamination process was performed to obtain multi-layered sheets of $Ti_3C_2T_x$ by magnetically stirring the as-prepared MXenes in dimethyl sulfoxide for 12 hours at room temperature [58]. The ratio of the as-prepared MXenes to the dimethyl sulfoxide was 1 g to 15 ml. Finally, the MXene colloidal solution was produced and subjected to vacuum drying in an oven (VO 500, MEMMERT Germany) at 100 mbar and 65°C for 12 hours to yield the MXene nanosheets.

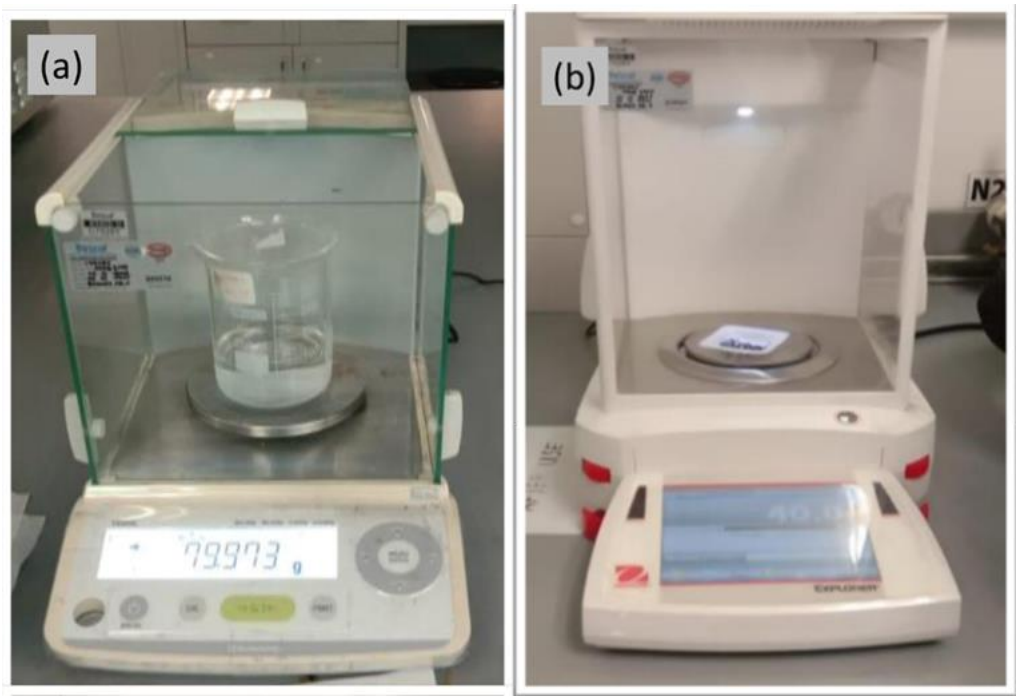

Figure 4. (a) Measurement of the weight of water and, (b) the required MXene ($Ti_3C_2T_x$) nanoparticles, for each sample in the first part of the investigation.

Preparation and Analysis of MXene ($Ti_3C_2T_x$)/ Water Nanofluid

The MXene ($Ti_3C_2T_x$)/water nanofluids were prepared using a two-step method, which involves producing the nanoparticles separately before dispersing them in the base fluid [59]. This method, commonly employed in previous nanofluid research [60]–[63], offers advantages for bulk manufacturing. The current study divided the experiments into three distinct parts. In the first part, three MXene ($Ti_3C_2T_x$)/water samples containing 0.05 wt% of MXene ($Ti_3C_2T_x$) were prepared. Each sample had a total volume of 80 ml, comprising 40 mg of MXene ($Ti_3C_2T_x$) and the remainder was deionized water. The weight of water for each sample was measured using a microbalance (TX323L, UNIBLOC), while the weight of the required MXene ($Ti_3C_2T_x$) nanoparticles was measured using microbalance (EX224, OHAUS), as depicted in Figure 4 (a) and (b).

Based on Abdelrazik et al.'s findings [54], MXenes ($Ti_3C_2T_x$) concentrations ranging from 0.0005 to 0.05 wt% were explored in the production of MXenes ($Ti_3C_2T_x$)/water nanofluids, revealing minimal visual presence of MXene nanoparticles below 0.05 wt%. Hence, a fixed loading of 0.05 wt% MXenes ($Ti_3C_2T_x$) was selected for current investigation to facilitate visual observations. Following the addition of the required MXene ($Ti_3C_2T_x$) amount to deionized water, ultrasonication was conducted using an ultrasonic probe sonicator (FS-1200N) operating at 70% power with on/off time settings of 7/3 s. The ultrasonication duration was varied starting from 60 minutes, 90 minutes, and 120 minutes, while an initial 30-minute ultrasonication attempt resulted in incomplete dissolution of the nanoparticles in the base fluids. The viscosity and stability of the samples were assessed, with Zeta potential serving as the stability indicator. Zeta potential values were measured using a particle analyzer (LITESIZER 500, Anton Paar) with ±10% accuracy and analyzed with Kalliope software. Testing involved transferring 5 ml of each sample to an omega cuvette container, as shown in Figure 5. On the same day of the formulation of the nanofluids, the Zeta potential measurement for each sample was performed three times to obtain accurate data. Results were averaged, and standard error, SE was calculated by using Eq. 1 [64], with a confidence level of 95%, (i.e., 1.96 times SE).

$$SE = \frac{\sigma}{\sqrt{N}} \quad \text{(Eq. 1)}$$

σ is the sample standard deviation, which is measured using Eq. 2, and N is the sample size.

$$\sigma = \sqrt{\frac{\sum(x_i-\mu)^2}{N-1}} \quad \text{(Eq. 2)}$$

x_i is each value of the measurements and μ is the mean value of all the measurement.

Each sample was prepared and analyzed on separate days, allowing one day per sample. The influence of ultrasonication duration on the dynamic viscosity of the MXene ($Ti_3C_2T_x$)/water nanofluids was examined using a rheometer (MCR92, Anton Paar), with a 10 mL volume of each sample used for testing. Furthermore, residual nanofluid samples were employed for visual observations, facilitating the observation of nanoparticle sedimentation over time. Visual observation offers a straightforward approach to assess nanofluid stability based on liquid color and sedimentation at the bottom of the container.

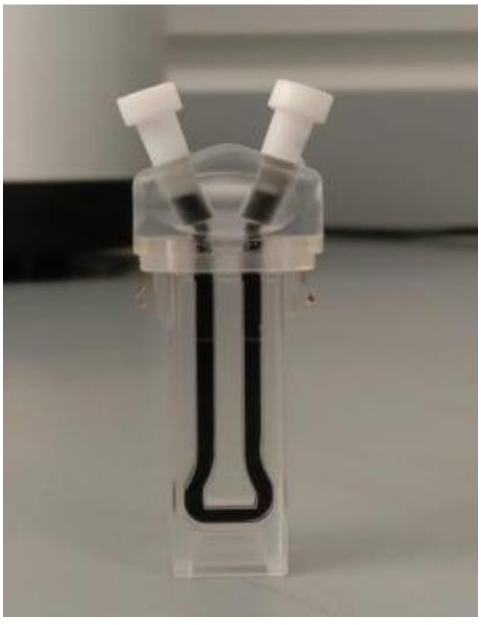

Figure 5. The sample of MXene/water nanofluid in omega cuvette.

Table 1. The samples testing conditions.

MXenes ($Ti_3C_2T_x$) Concentration (wt%)	Sample Number	Sonication Duration (minutes)	Measurement Time	Temperature (°C)	Testing
0.05	1	60	Day 1, Day 7, Day 30	20, 30, 40, 50, 60	(a) Zeta potential values (b) Viscosity measurement (c) Visual observation at room temperature (d) Chemical structure and molecular groups using FT-IR at room temperature
	2	90	Day 1, Day 7, Day 30		
	3	120	Day 1, Day 7, Day 30		

In the second part of the investigation, the effect of temperature on the viscosity and Zeta potential value of each sample from the first part was assessed. For all cases, the temperature variations were performed at 20, 30, 40, 50, and 60°C, which were common for low-temperature applications such as electronic cooling, heat exchangers, solar collectors, automobile radiators, thermal storage, and refrigeration [4]. For the third part of the investigation, all the tests were repeated on Day 7, and Day 30 after the preparation of the samples. Additionally, the chemical structure and molecular groups of these three samples were also presented and obtained from the FTIR analysis using the Perkin Elmer Spectrum Two FT-IR Spectrometer and Spectrum IR Software. The sample testing conditions are further explained in Table 1.

RESULTS AND DISCUSSION

Chemical Structure and Molecular Groups of MXene ($Ti_3C_2T_x$)/Water Nanofluids

The chemical structure of all samples of MXene ($Ti_3C_2T_x$)/water nanofluids in the current work is studied using FTIR analysis, as illustrated in Figure 6. Since each sample displays the same peaks, the primary chemical components of the functional groups are constant throughout the samples, regardless of their ultrasonication duration. As suggested by Kotia et al. [65], Samylingam et al. [51], and Tan et al. [47], the absence of distinct peaks in the FTIR analysis suggests that the nanofluids were chemically stable since no further chemical interactions were observed.

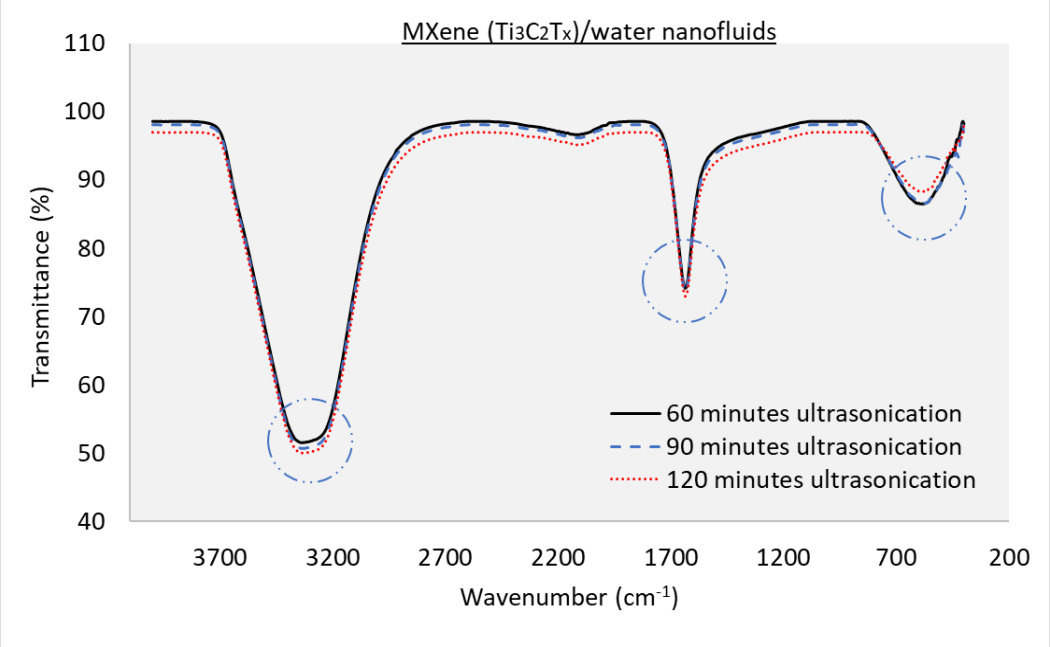

Figure 6. The FTIR spectra of the MXene ($Ti_3C_2T_x$)/water nanofluids in the current work from wavenumber range of 4000–500 cm^{-1}.

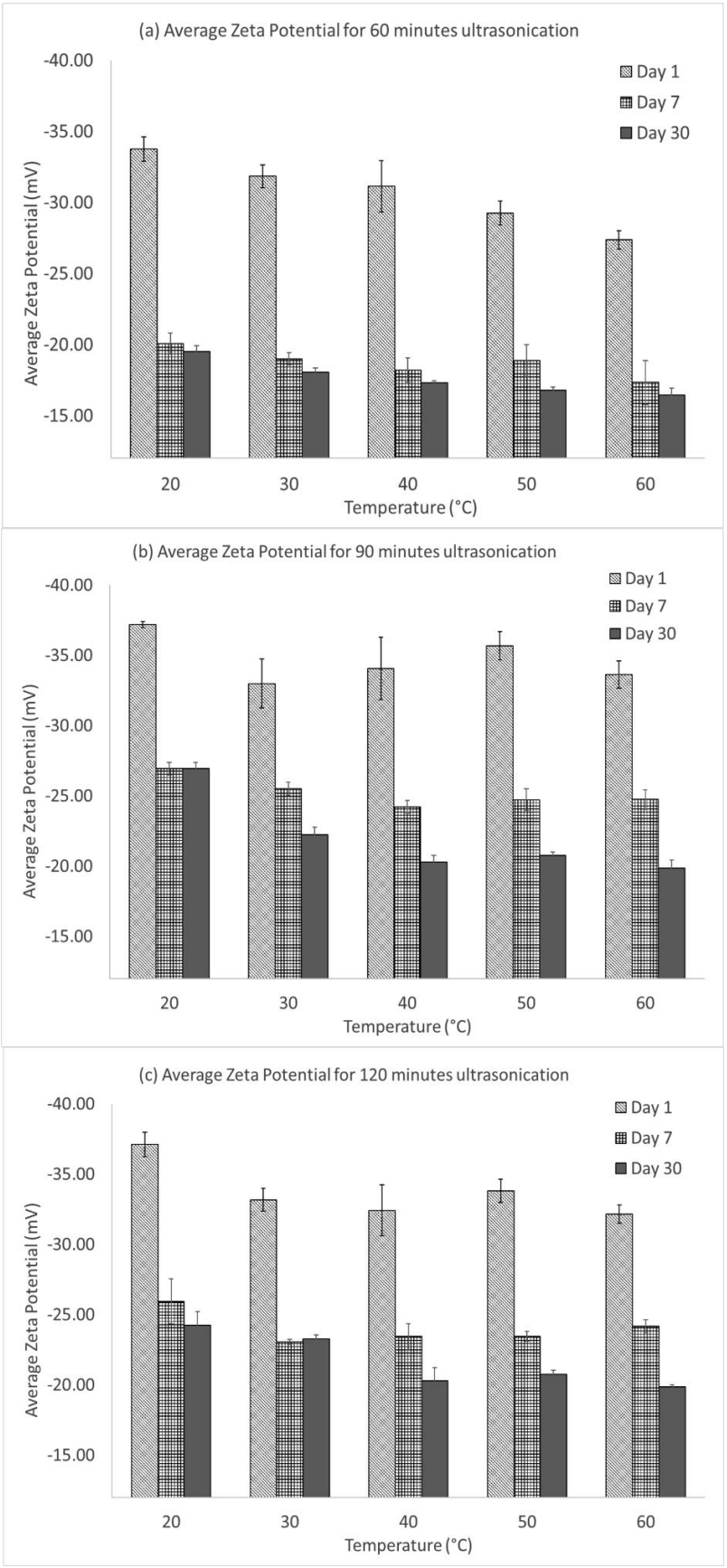

Figure 7. Average Zeta potential values of MXene ($Ti_3C_2T_x$)/water nanofluids for (a) 60 minutes of ultrasonication, (b) 90 minutes of ultrasonication, and (c) 120 minutes of ultrasonication at different temperature and measurement time.

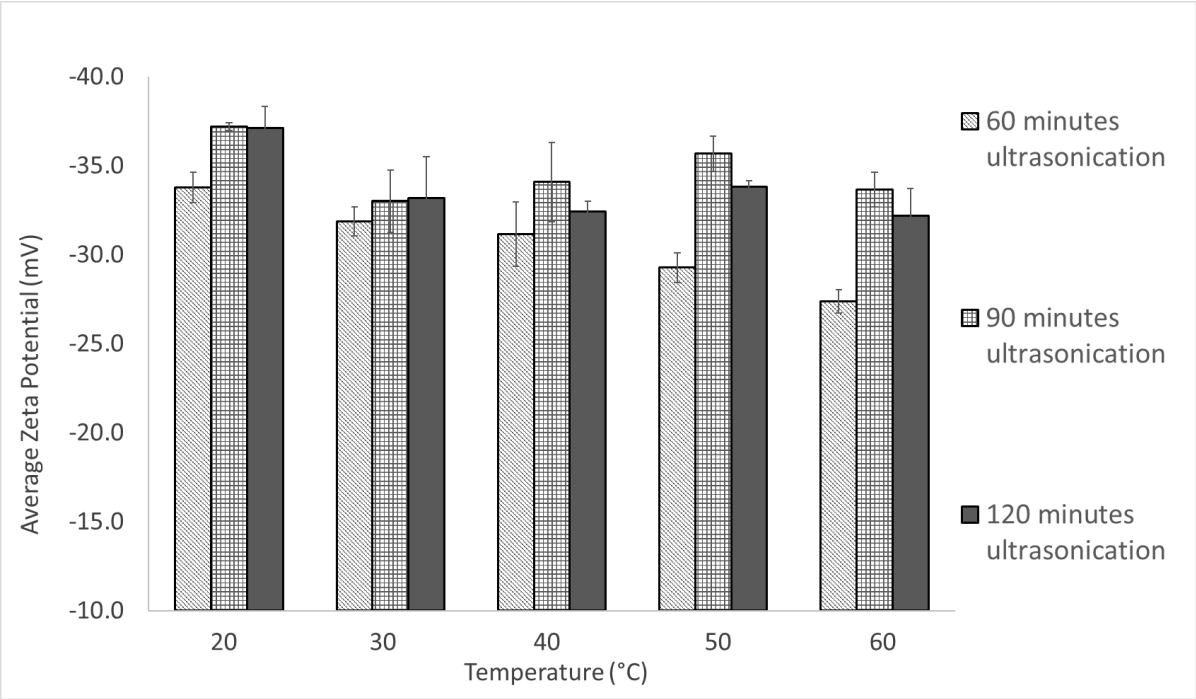

Figure 8. Average Zeta potential values of MXene ($Ti_3C_2T_x$)/water nanofluids on Day 1.

Table 2. Comparison between the Zeta potential values obtained in Day 1 of the current work and that of Abdelrazik et al. [54].

Reference	MXenes ($Ti_3C_2T_x$) Concentration (wt%)	Sonication Duration (minutes)	Surfactant	Temperature (°C)	Average Zeta Potential (mV)
Abdelrazik et al. [54]	0.05	60	Cetyltrimethylammonium Bromide (CTAB)	Not mentioned (most probably room temperature)	-58.01
	0.05	60	Sodium Dodecyl Benzene Sulfonate (SDBS),		-55.98
Current work	0.05	60	None	20	-33.8
	0.05	90	None	20	-37.2
	0.05	120	None	20	-37.1

The major peaks are presented at a wavenumber of approximately 3320 cm^{-1}, which could be the hydroxyl O–H stretch [66], [67]. The peak at the wavenumber of approximately 1640 cm^{-1} could be attributed to the carbonyl C=O stretch [50], [68] or hydroxyl O–H stretch existence [50], [67], while the peak at approximately 630 cm^{-1} could be alkane or alkene C–H stretch [50], [68].

Stability and Viscosity of MXene ($Ti_3C_2T_x$)/Water Nanofluids

The average Zeta potential values for Samples 1, 2, and 3 were plotted in Figure 7 (a), (b), and (c), respectively, corresponding to ultrasonication durations of 60, 90, and 120 minutes. The maximum standard error is 2.4% using a 95% confidence level. From the figures, it can be concluded that the stability of MXene ($Ti_3C_2T_x$)/ water nanofluids was moderate on Day 1, as the Zeta potential values were all above -30 mV. However, it declined with time, as was clearly revealed by the significant drop in the average Zeta potential values from Day 1 to Day 7 after the nanofluids' formulation. After 1 month, the value continued decreasing slightly. In fact, the values went below -20 mV in the sample that had been ultrasonicated for 60 minutes, indicating extremely poor stability. By looking closely at the average Zeta potential values of MXene ($Ti_3C_2T_x$)/

water nanofluids on Day 1 in Figure 8, the best stability achieved was by applying 90 minutes of ultrasonication. After that, extending the ultrasonication duration reduced the stability of the samples. A similar trend was observed at different temperatures.

Table 2 presented a comparison between the maximum Zeta potential values obtained on Day 1 of the current study (conducted at 20°C) and those obtained by Abdelrazik et al. [54], who utilized surfactants to improve the stability of the MXene ($Ti_3C_2T_x$)/water nanofluids. However, the temperature was unknown in their work and assumed to be at room temperature. From the table, it can be observed that the use of surfactants has enhanced the Zeta potential value by more than 50%. However, the effect of the surfactants on the thermophysical properties of the MXene ($Ti_3C_2T_x$)/water nanofluids was not investigated by Abdelrazik et al. [54]. Baek et al. further reported that while nanofluids with higher surfactant concentrations exhibited improved stability, they also experienced a reduction in thermal conductivity [20].

As reported by Gupta et al., numerous articles reported that viscosity increased as nanoparticle concentration increased but decreased at higher temperatures [69]. The theory by Masoumi et al. also suggested that nanofluid viscosity decreased with temperature for constant nanoparticle concentration [70]. In the present work, this behavior was true for MXene ($Ti_3C_2T_x$)/water nanofluids at certain range. As illustrated in Figure 9, the decreasing trend of viscosity with respect to temperature can be seen for both samples that had been ultrasonicated for 60 and 90 minutes, despite the sudden increment at certain points, especially between 35 to 45°C. However, for the sample that had undergone 120 minutes of ultrasonication, the increase in viscosity was more obvious, specifically beyond 45°C. It is true that longer ultrasonication durations improve stability by providing sufficient energy to overcome the attraction of the van der Waals forces between the nanoparticles, but excessive ultrasonication duration might also lead to undesired effects, such as the degradation of nanoparticles, over-dispersion, or agglomeration. As a result of these phenomena, the viscosity might also increase. To verify these hypotheses, characterization techniques using microscopy could help in providing a more detailed images of the samples.

Visual Observations of MXene ($Ti_3C_2T_x$)/Water Nanofluids

Figure 10 portrays the images of MXene ($Ti_3C_2T_x$)/water nanofluids for different ultrasonication duration and on different day. These visual observations showed a clear phase separation of MXene ($Ti_3C_2T_x$) nanoparticles and water on Day 30. However, not much different were observed for images on Day 1 and Day 7 for all cases. The suspension homogeneity could be achieved through additional methods, such as adding surfactant, altering the pH level and particle surface modification. However, optimum number and level of modifications should be investigated, so the process would not affect the characteristics of the nanofluids significantly.

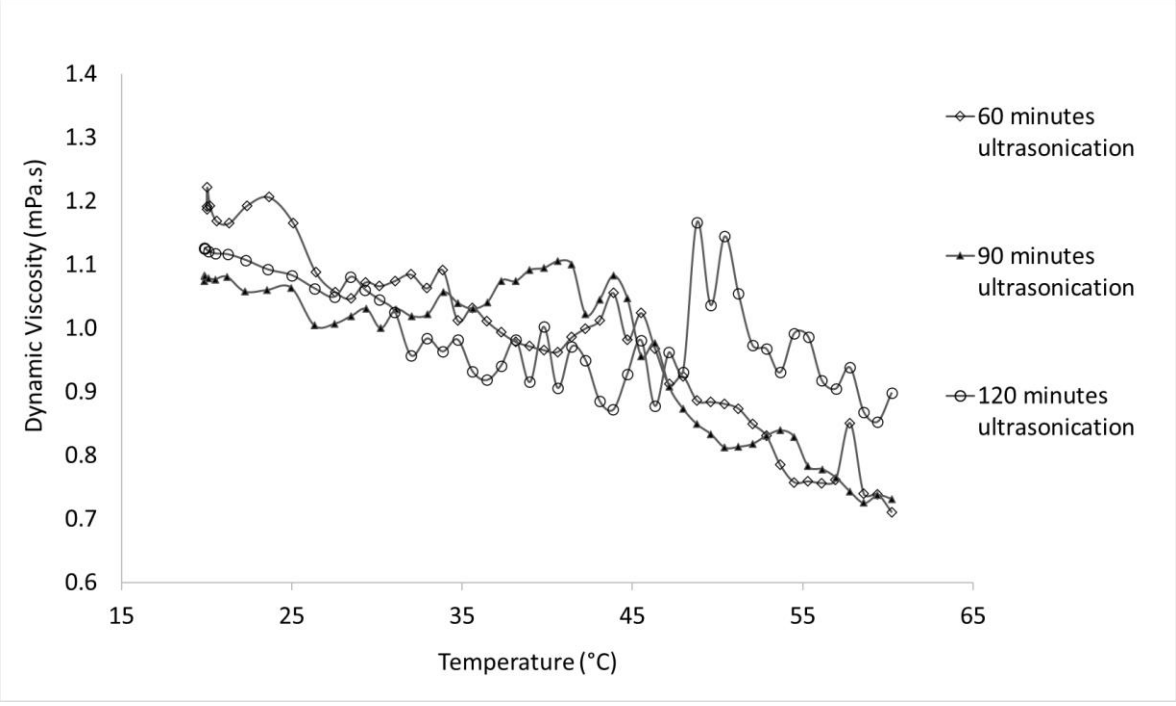

Figure 9. Dynamic viscosity of MXene ($Ti_3C_2T_x$)/water nanofluids on Day 1.

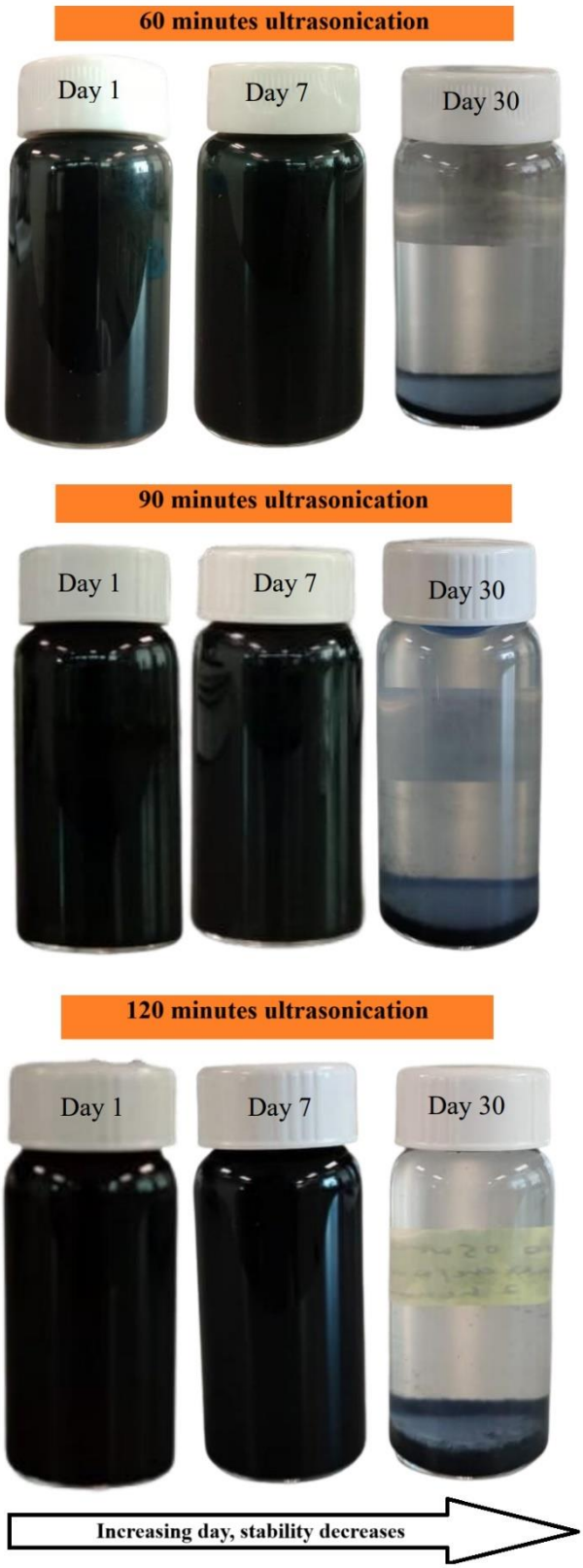

Figure 10. Visual observation of MXene ($Ti_3C_2T_x$)/water nanofluids for different ultrasonication duration and on different day.

CONCLUSION

Prior to their use in engineering applications, it is imperative to address the stability concerns associated with MXene-based nanofluids. Altering ultrasonication durations can impact both the stability and viscosity of MXene ($Ti_3C_2T_x$)/water nanofluids. The average Zeta potential values can be used to indicate the stability of nanofluids. Without adding any surfactant to MXene ($Ti_3C_2T_x$)/water nanofluids, the Zeta potential values are moderate and lie between -30 to -40 mV. The highest Zeta potential values were obtained when the duration was 90 minutes at almost all temperatures tested on Day 1. However, the values drop significantly after a week and continue dropping slightly after one month. Even though the higher ultrasonication durations helped in increasing the stability of MXene ($Ti_3C_2T_x$)/ water nanofluids, but too much increase in the duration might also cause other negative impacts, such as the increase in viscosity and reduction in the stability, especially for samples that undergo 120 minutes ultrasonication. It is important to note that the stability of nanofluids is a complex and dynamic process influenced by numerous factors. It can change over time and decrease under certain conditions, leading to particle agglomeration and sedimentation. Particle aggregation cannot be completely avoided but reducing particle aggregation requires additional treatments. Proper formulation and enhancement method, such as surface modification and concentration variation of the nanoparticles, addition of surfactants and pH level adjustment could aid in improving the stability of MXene ($Ti_3C_2T_x$)/water nanofluids over extended periods.

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