ORIGINAL ARTICLE

Dispersion and Stability Study of Functionalised Multiwalled Carbon Nanotubes and Zinc Oxide Nanoparticles in Various Dispersion Solvents

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ABSTRACT

Introduction: : Functionalised multiwalled carbon nanotubes (fMWCNTs) and zinc oxide (ZnO) nanoparticles exhibit exceptional mechanical, electrical, and optical properties, making them highly suitable for applications in biosensors, polymer composites, and electronics. However, their strong tendency to agglomerate due to van der Waals interactions and high aspect ratios presents a major challenge. Achieving uniform and stable dispersions is therefore essential to fully exploit their functional properties. Selecting an appropriate solvent is a key factor in overcoming aggregation and enhancing nanoparticle performance. Materials and **Methods:** This study examined the dispersion and stability of fMWCNTs and ZnO nanoparticles in four solvents: N,N-dimethylformamide (DMF), dimethyl sulfoxide (DMSO), ethanol, and deionized water. The nanoparticles were dispersed using magnetic stirring followed by ultrasonication. Electrostatic stability was evaluated through zeta potential (ζ) measurements, where higher absolute ζ values indicate better dispersion stability. **Results:** DMF produced excellent dispersion for fMWCNTs, with a zeta potential of +50.4 mV, signifying strong electrostatic repulsion. In contrast, deionized water resulted in poor dispersion due to low charge stabilization. For ZnO nanoparticles, DMSO achieved the highest stability with a zeta potential of –37.7 mV, attributed to strong solvent–particle interactions, while ethanol showed low stability with –1.89 mV. **Conclusion:** Effective nanoparticle dispersion is crucial for maintaining consistent mechanical, electrical, and thermal properties, particularly in biosensor fabrication. This study concludes that DMF and DMSO are the most suitable solvents for achieving stable dispersions of fMWCNTs and ZnO nanoparticles, respectively.
Malaysian Journal of Medicine and Health Sciences (2025) 21(SUPP11): 82-87.doi:10.47836/mjmhs.21.s11.12

Keywords: Functionalized multiwalled carbon nanotubes (fMWCNTs), Zinco oxide, Dispersion, Zeta potential, Dispersion stability

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INTRODUCTION

Functionalised multiwalled carbon nanotubes (fMWCNTs) and zinc oxide (ZnO) nanoparticles are at the forefront of nanotechnology due to their exceptional mechanical, electrical, and optical properties. fMWCNTs, known for their high tensile strength, excellent electrical conductivity, and thermal stability, are widely used in the production of polymer composites, semiconductor and biosensor devices (1). Similarly, ZnO nanoparticles offer unique optical, electronic, and antibacterial properties, making them ideal for applications in sensors, photocatalysis, and biomedical devices. Many electrochemical sensors can be modified with fMWCNTs to promote electron-transfer reactions and sensitivity (2). The incorporation of these nanomaterials into various matrices can significantly enhance the performance and functionality of the resulting composites. Recent studies also show that a novel molecularly imprinted polymer based on functionalized multiwalled carbon nanotubes was found to be more effective for selective extraction of a target analyte (3).

Despite their remarkable properties, the practical use of fMWCNTs and ZnO nanoparticles faces significant challenges due to their strong tendency to agglomerate (4). The high aspect ratio and strong van der Waals interactions between fMWCNTs result in entangled and bundled structures, which hinder uniform dispersion in solvents. This agglomeration leads to the formation of thick bundles, compromising the mechanical, electrical, and thermal properties of the composites. Similarly, ZnO nanoparticles tend to aggregate due to their high surface energy, leading to poor dispersion stability. Achieving a stable and uniform dispersion of these nanoparticles is therefore a critically important characteristic, since only well-dispersed nanomaterials can fully exploit their high surface area, maximize interfacial contact with the host matrix, and maintain the intrinsic electrical, thermal or optical pathways. Poor dispersion (i.e., clustering) not only reduces effective surface area and increases scattering/voids but also accelerates sedimentation, heterogeneity and loss of function over time. For example, recent work emphasizes that nanoparticle dispersion stability governs the translation of nanoscale properties into bulk composites and long-term performance (5). Moreover, zeta-potential measurements (e.g., > |30 mV|) are increasingly used to quantify electrostatic repulsion and infer long-term stability of colloidal nanoparticle dispersions (6).

To address these dispersion challenges, various methods have been employed. Mechanical stirring and ultrasonication are commonly used techniques to break down large agglomerates and enhance nanoparticle dispersion. Magnetic stirring is initially used to disperse the nanoparticles in solvents (7), followed by ultrasonication to further improve dispersion stability. The choice of solvent is a key factor influencing the ultimate dispersion state, because solvent properties (polarity, dielectric constant, surface tension, viscosity) determine nanoparticle–solvent and nanoparticle–nanoparticle interactions (wettability, steric/solvation layers, effective charge screening). Solvents such as N,N-dimethylformamide (DMF), ethanol, and deionized water have been studied for their ability to disperse fMWCNTs and ZnO nanoparticles. DMF, being a polar aprotic solvent with relatively high dielectric constant and good ability to solvate functional groups (such as carboxyl, hydroxyl) on fMWCNTs, tends to promote individual nanotube separation and stable dispersions. Ethanol, while less polar than DMF, offers moderate solvation and is often used for post-dispersion transfers or as a mixed solvent; it can reduce agglomeration by reducing surface tension and promoting wetting of both inorganic (ZnO) and organic (CNT) surfaces. Deionized water, though highly polar, often faces challenges with hydrophobic nanotubes unless functionalised or surfactant-aided; nevertheless, for ZnO nanoparticles (which often have hydrophilic surfaces) water is a convenient medium and allows strong electrostatic repulsion and high zeta potentials if properly stabilised. Moreover, solvent choice affects downstream processing (e.g., composite casting, sensor fabrication). Recent reports show, for example, that use of water/ethanol mixtures improved nanoparticle dispersion compared to single-component solvents (8).

Zeta potential measurements are used to assess the electrostatic stability of the dispersions, providing insight into the effectiveness of the solvent-nanoparticle interactions. High absolute zeta potential values indicate strong electrostatic repulsion between particles, which is essential for preventing agglomeration and ensuring a stable dispersion. Through these methods of solvent selection and ultrasonication researchers aim to identify optimal dispersion conditions that maximize the functional properties of fMWCNTs and ZnO nanoparticles for their effective use in advanced composite materials and devices.

MATERIALS AND METHODS

Materials

The starting materials, fMWCNTs (Nanochemazone, India), zinc oxide (<100nm) (Sigma-Aldrich), dimethyl sulfoxide (DMSO) (Merck), ethanol, N,N-dimethylformamide (DMF) (Sigma-Aldrich), deionised water.

fMWCNT and ZnO dispersion in different solvents

To prepare well-dispersed fMWCNTs, 5 mg of multiwalled carbon nanotubes was weighted using a precision weighing balance. These measured fMWCNTs were then meticulously transferred to clean, dry glass vials or containers. For each selected solvent (DMF, ethanol and deionised water), separate vials were prepared, each containing 5 mL of the chosen solvent. To facilitate the dispersion process, magnetic stir bars or magnetic beads were carefully placed within each vial containing the solvent. The accurately weighed fMWCNTs were then introduced into the respective solvent vials, ensuring a consistent ratio of 5 mg fMWCNTs to 5 mL solvent.
With the vials securely capped to prevent evaporation or contamination, an initial stirring phase was initiated. These vials, housing the fMWCNTs and solvents, were placed on a magnetic bead stirrer, set to a moderate speed, and allowed to stir for 5 minutes. This initial stirring step served to break down larger fMWCNTs agglomerates within the solvent, laying the foundation for further dispersion.

Following the initial stirring, the vials were then transferred to an ultrasonic bath or sonicator. The vials, now submerged in the sonicator bath (Fig. 1), underwent a continuous sonication process lasting 30 minutes at room temperature, typically around 25°C (9).

This sonication step played a pivotal role in achieving uniform fMWCNTs dispersion by effectively breaking down smaller agglomerates and promoting even distribution of fMWCNTs throughout the solvent.

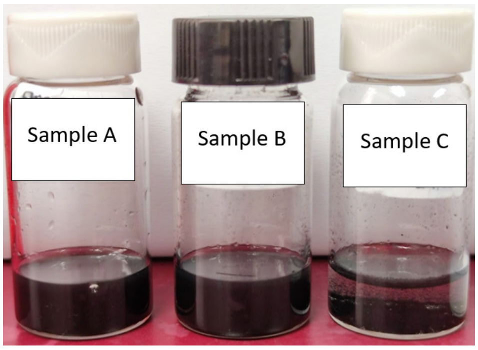
Fig 1: Sonication of fMWCNTs nanoparticles in various solvents

Throughout the 30-minute sonication period, dispersion progress was periodically monitored. Visual inspection of the vials ensured that fMWCNTs were dispersing evenly within the solvent. If necessary, gentle swirling of the vials was employed to facilitate dispersion further. Upon the completion of the 30-minute sonication period, the vials were carefully removed from the sonicator. The samples were observed immediately after the dispersion and 24 hours later. Each sample was also sent for zeta potential analysis to assess the surface charge of the fMWCNTs suspension in solution. As for dispersion of zinc oxide nanoparticles, the similar process was conducted by using a different set of dispersion solvents including ethanol, DMSO and DMF.

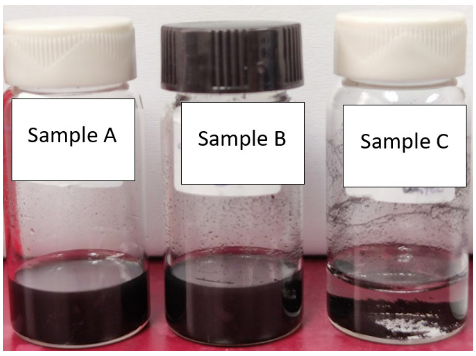
RESULTS

Dispersion Quality of fMWCNTs and ZnO Nanoparticles

The dispersion behavior of functionalized multi-walled carbon nanotubes (fMWCNTs) was evaluated in N,N-Dimethylformamide (Sample A), ethanol (Sample B), and deionized water (Sample C). All samples underwent 30 minutes of bath ultrasonication, then were visually examined immediately and after 24 hours (Fig. 2). Sample A (DMF) exhibited a uniformly dark, opaque suspension with no settling over 24 hours, indicating minimal flocculation. Sample B (Ethanol) showed slightly lower turbidity than DMF but remained homogeneously dispersed, with negligible sediment formation even after prolonged standing. Sample C (Water) displayed large visible aggregates immediately, which grew into a dense sediment layer by 24 hours, confirming rapid coagulation. These observations underscore the importance of solvent polarity and solvation interactions in maintaining fMWCNT dispersion.



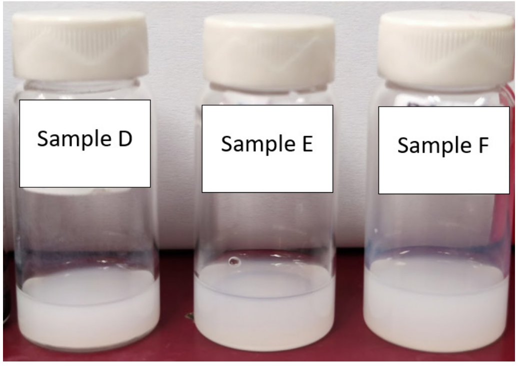
(a)



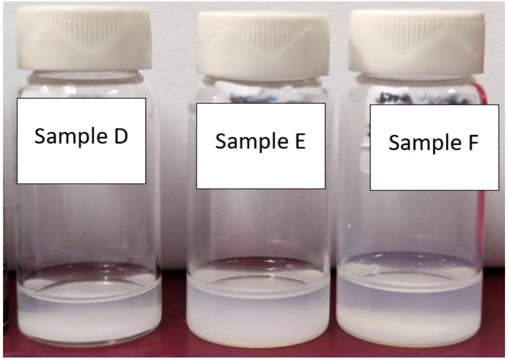
(b)

Fig 2: Physical characteristics of fMWCNTs suspensions in different dispersion solvents. (a) Suspension state immediately after sonication b) suspension state after 24 hours

Furthermore, the dispersion of zinc oxide nanoparticles was also observed and shown in Fig. 3. ZnO were suspended in ethanol (Sample D), DMSO (Sample E), and DMF (Sample F). All samples were sonicated for 30 minutes. Based on Fig. 3, sample E shows better dispersity immediately and after 24 hours of sonication. The turbidity of the solution was the highest after 24 hours and no visible sedimentation and agglomeration observed. Although sample F also shows good dispersion immediately after sonication, sedimentation appeared after 24 hours. Sample D has the poorest dispersion as the turbidity of the solution reduces significantly with presence of sedimentation after 24 hours. To further examine the dispersion stability, zeta potential analysis was performed next.



(a)



(b)

Fig 3: Physical characterisation of zinc oxide nanoparticles suspension in different dispersion solvents. (a) Suspension state immediately after sonication (b) Suspension state after 24 hours

Electrostatic Stability of Dispersion Via Zeta Potential
To further investigate the dispersion characteristics of the solution, the zeta potential of the fMWCNTs and ZnO solution were measured using a zeta potential analyzer. These measurements are critical for assessing the stability of the fMWCNTs and ZnO dispersions within various solvents, as they quantify the electrical potential difference between the bulk of the dispersion medium and the stationary layer of fluid that is adsorbed onto the surface of the dispersed particles.

The zeta potential values obtained provide insight into the electrostatic stability of the nanoparticle dispersions in different solvents. Specifically, Table 1 details the zeta potential values for fMWCNTs dispersions in DMF, ethanol, and deionized water, which are 50.4 mV, 32.3 mV, and -1.84 mV, respectively. These values are indicative of the dispersion stability, where higher magnitudes of zeta potential (positive or negative) suggest that the electrostatic repulsion between particles is strong enough to overcome the attractive van der Waals forces, leading to a well-dispersed system (10). Conversely, lower zeta potential values suggest that the attractive forces dominate, increasing the risk of particle aggregation or flocculation due to insufficient electrostatic repulsion to keep the particles separate.
The high zeta potential value of 50.4 mV in DMF indicates excellent stability of fMWCNTs dispersions in this solvent. In ethanol, the zeta potential value of 32.3 mV indicates moderate stability. Ethanol, being less polar than DMF, offers a different solvent environment that interacts with the functional groups on fMWCNTs but with slightly less efficiency. Deionized water showed a very low zeta potential value of -1.84 mV, indicating poor stability and a high likelihood of aggregation.

Furthermore, the zeta potential values for ZnO nanoparticle dispersions in different solvents (ethanol, DMSO, and DMF) are also provided, with values of -1.89 mV, -37.7 mV, and 30.5 mV, respectively as shown table 2. The high zeta potential value of -37.7 mV in DMSO indicates good stability of ZnO nanoparticle dispersions in this solvent. In contrast, ethanol and DMF show lower stability for ZnO dispersions. Ethanol, with a zeta potential of -1.89 mV, indicates poor stability, similar to its effect on fMWCNTs.

Table I : Zeta potential value of fMWCNT dispersion in different solvent

Sample	Solvent	Zeta Potential Value (mV)
A	N,N-Dimethylformamide (DMF)	50.4
B	Ethanol	32.3
C	Deionized water	-1.84

Table II : Zeta potential value of ZnO nanoparticles dispersion in different solvent

Sample	Solvent	Zeta Potential Value (mV)
D	Ethanol	-1.89
E	DMSO	-37.7
F	N,N-Dimethylformamide	30.5

Table 3 indicates the relationship between the zeta potential and the stability characteristic reported by Kamble (11). It has been demonstrated that at low potential, the attractive force can exceed the repulsion and the dispersion coagulate and flocculate, while high zeta potential (negative or positive) is electrically stabilized (11). Therefore, based on our analysis, the DMF and DMSO provide the best dispersion for fMWCNTs and ZnO respectively. The results obtained are in line with our previous observation of the suspended nanoparticles.

Table III : Zeta potential reference value and corresponding stability assessment

Assessment stability	Zeta-potential (mV)
Flocculation of coagulation	0 to ±5
Incipient instability	±10 to ±30
Moderate stability	±30 to ±40
Good stability	±40 to ±60
Excellent stability	Greater than ±60

DISCUSSION

To understand how solvents interact with functionalized MWCNTs at the molecular level, DMF's high dielectric constant (ε ≈ 36.7) efficiently screens attractive van der Waals forces between nanotubes, while its polar nature provides strong dipole–dipole interactions with oxygen-containing functional groups on the fMWCNT surface (–COOH, –OH, –C=O), resulting in the highest measured zeta potential +50.4mV and retention of over 85 % turbidity after 24 hours. In ethanol, the zeta potential value of 32.3 mV indicates moderate stability. Ethanol (ε ≈ 24.5), being less polar than DMF, offers a different solvent environment that interacts with the functional groups on fMWCNTs but with slightly less efficiency. The solvent molecules of ethanol can still form hydrogen bonds and interact with the functional groups on the fMWCNTs, contributing to a relatively stable dispersion, although not as effective as DMF. The primary interactions in ethanol are hydrogen bonding and dipole interactions with hydroxyl groups on the fMWCNTs (12). In contrast, deionied water's high surface tension and inability to solvate hydrophobic CNT sidewalls lead to rapid bundle re-formation –1.84 mV and visible aggregation within minutes (13). These findings are consistent with previous studies, where the authors reported that dispersions of single-walled carbon nanotubes (SWCNTs) in DMF produced much finer bundle networks with smaller pore sizes compared to those prepared in ethanol or water (14). It should be noted, however, that dispersion quality can also depend on sonication parameters such as power density and probe versus bath setup. Therefore, optimizing these variables may shift the relative performance of each solvent and warrant additional experiments to identify true industrial scale conditions.

When considering ZnO nanoparticles, the choice of solvent similarly dictates colloidal stability. DMSO (ε ≈ 47.2) binds tightly to surface oxygens, forming a solvation shell that sterically hinders particle approach and generates a substantial negative –37.7 mV (15), while DMF, lacking sulfur–oxygen coordination, yields only moderate electrostatic repulsion +30.5 mV and slow sedimentation. Ethanol, unable to show sufficient surface charge –1.89 mV, leaves ZnO vulnerable to aggregation driven by intrinsic oxide surface energies.

These results demonstrate that solvent choice is critical for maintaining particle dispersion, which in turn is essential for producing uniform films via drop-casting in biosensor fabrication. Future studies should emphasize a deeper understanding of solvent nanomaterial interactions and the mechanisms governing long term dispersion stability of functionalized multiwalled carbon nanotubes (fMWCNTs) and zinc oxide (ZnO) nanoparticles. Both experimental and computational investigations are necessary to reveal how solvent polarity, dielectric constant, and hydrogen bonding collectively influence interfacial interactions and solvation behavior. Zhou et al. demonstrated that solvent dielectric environments critically determine the degree of CNT dispersion and interfacial electron transfer, directly affecting the functional performance of CNT-based nanocomposites (16). Similarly, Nikolaev et al. showed that assessing colloidal stability through accelerated aging, sedimentation, and dynamic light scattering (DLS) is vital to ensure nanoparticle reliability over time (17). Therefore, future research should also focus on systematic optimization of ultrasonication parameters (time, power, and temperature) and long-term monitoring of particle stability under realistic environmental and operational conditions. Such integrated approaches will enable the development of durable, high-performance nanocomposite materials and biosensing platforms with enhanced reproducibility and stability.

CONCLUSION

This study highlights the important role of solvent selection in achieving stable and uniform dispersions of functionalized multiwalled carbon nanotubes (fMWCNTs) and zinc oxide (ZnO) nanoparticles. By employing ultrasonication and analyzing zeta potential values, we found that N, N-dimethylformamide (DMF) provided the best stability for fMWCNTs, while dimethyl sulfoxide (DMSO) was most effective for ZnO nanoparticles. Ensuring stable dispersions is vital for maximizing the functional properties of these nanomaterials, which are key to their successful application in coatings, composites, and electronic devices. These findings offer practical insights into how we can better utilize fMWCNTs and ZnO nanoparticles in advanced materials science and technology.

ACKNOWLEDGEMENT

This work was financially supported by the Universiti Teknologi Malaysia under the Research University Grant and the Ministry of Higher Education Malaysia with reference number Q.J130000.3823.31J71. This paper is based on a dissertation submitted in partial fulfillment of the requirements for the PhD degree at Universiti Teknologi Malaysia.

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