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Magnetic Field Induced Changes in Surface Tension in Pure Water and Polystyrene Micro-Nanoparticle Dispersions

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ABSTRACT

The escalating presence of microplastics (MPs) in the aquatic, terrestrial, and atmospheric ecosystems has raised significant environmental concerns, driving the urgent need for the development of effective separation techniques. This study examines the fundamental mechanisms of a novel method for separating microplastics using magnetic force and investigates its effects on dynamic surface tension. The surface tension behavior of degassed DI water and water containing polystyrene (PS) micro-nanoparticles (MNPs) was studied under the influence of a relatively weak magnetic field. The results confirmed notable changes in the dynamic surface tension of both systems. In degassed water, the presence of a magnetic field induced fluctuations and increased surface tension. Conversely, in the PS-water system, the magnetic field led to a significant reduction in surface tension at the air interface. Further experiments using a magnetometer to analyze PS particles in the degassed DI water provided insights into the behavior of PS particles in aqueous environments. This study offers understanding of the fundamental mechanisms that govern dynamic surface tension and the interaction between PS-MNPs and magnetic forces. The findings have implications for understanding the fundamental physics of separation technologies, aimed at mitigating the environmental impact of microplastics.

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INTRODUCTION

In recent years, a growing concern over microplastic pollution has become a central point of environmental dialogue. This persistent issue results from the widespread dispersion of engineered microplastic particles and the gradual degradation of larger plastic fragments, which pollute soil, water and even atmosphere (Deswati et al., 2025; Kamani et al., 2024; de Souza Machado et al., 2018; Rezania et al., 2018). Microplastics (MPs) are polymers and particles of plastic origin that are less than 5 mm in size. They pose a significant threat to our ecosystems and require urgent attention due to their adverse effects. Implementing effective mitigation strategies, including efficient separation from polluted water sources and wastewater, is crucial in addressing this environmental challenge (Thompson et al., 2024; Nikpay and Toorchi, 2024; An at al., 2024; Rashed at al., 2023; Osman et al., 2023; Kiran et al., 2022; Kolmans et al., 2022; Gouin et al., 2022; Chia et al., 2021).

Conventional particle separation techniques, including filtration, centrifugation, and electrocoagulation, encounter challenges in terms of efficiency and scalability, particularly when confronted with microplastic pollutants (Maliwan and Hu, 2025; Senathirajah et al.,

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2023; Hildebrandt et al., 2019). Consequently, magnetic separation technology, which utilizes magnetic force, has emerged as a promising, environmentally friendly, and sustainable solution for the removal of MPs. Recent advancements have explored the use of engineered magnetic nanoparticles, which selectively bind to MPs. This binding allows for the efficient removal of MPs under an applied magnetic field which has been reviewed in various cases by Vohl et al., (2024). Nonetheless, there are still challenges to be addressed regarding the scalability, sustained effectiveness over time, and environmental impact of the relevant technologies. The ongoing research in this field focuses on the addition of cost-effective materials that maintain high separation efficiency and the functionalization of magnetic nanoparticles to enhance their selectivity for different types of plastics.

Additionally, the application of magnetic levitation techniques which utilize strong magnetic fields, has been shown to facilitate the manipulation of non-magnetic materials, including plastics, based on their diamagnetic properties (Zhao et al., 2018). However, this approach is also have accompanied by significant economic and technical challenges including the requirement for extremely strong magnetic fields, which can restrict the method’s effectiveness for heterogeneous microplastic mixtures, and the need for stable levitation in dynamic liquid environments.

In contrast, the application of magnetic force for the separation of micro-nanoplastics (MNPs), as outlined in the patent filed by Nikpay (2023), has effectively addressed critical challenges, including high energy consumption, economic viability, environmental sustainability, and scalability. Additionally, the method employs a non-invasive approach that eliminates the need for chemical additives, thereby minimizing the risk of secondary contamination. Compared to conventional separation methods, it enables continuous processing, making it highly suitable for large-scale industrial applications. Furthermore, its adaptability to diverse water matrices, including wastewater and marine environments, underscores its potential as a versatile and efficient solution for microplastic removal. Despite these advancements, the fundamental physical mechanisms behind this method remain a frontier of scientific research and defy full explanation within the current framework of physics. This knowledge gap highlights the need for further interdisciplinary studies integrating physics, chemistry, and materials science to develop a comprehensive understanding of these interactions.

In this context, our research aims to investigate the complex relationships between microplastics and external factors, with a particular focus on the effects of a steady magnetic field. We performed surface tension tests to investigate the phenomenon described by Nikpay (2023). Surface tension tests were conducted on deionized (DI) water containing polystyrene (PS) micro-nanoparticles (MNPs) and degassed DI water under the influence of a magnetic field. The changes in surface tension under this influence were measured using pendant drop tensiometry, a well-established method for determining surface and interfacial tension. Surface tension is a critical parameter in colloidal systems, including emulsions, foams, and wetting phenomena, and plays a crucial role in various applications, ranging from industrial processes to biological systems (Soncini and Klein, 2023; Berry et al., 2015; Karbowiak et al., 2006).

Previous studies have demonstrated that exposure to a magnetic field can influence the physical properties of water, including inducing abnormal changes in surface tension (Fujimura et al., 2009; Pang and Deng, 2008). Further research by Wang et al., (2018) and Hayakawa et al., (2019) confirmed alterations in heat, evaporation, and liquid-liquid interfacial tension when water exposed to a magnetic field. The effect of the magnetic field on water properties is attributed to various mechanisms, such as the binding of H2O molecules via low-energy intermolecular van der Waals forces, hydrogen bonding, and dipole-dipole interactions (Esmaeilnezhad et al., 2017). Despite these findings, a substantial gap persists in the existing literature regarding changes in surface tension, particularly in the presence of microparticles such as PS.

We also investigated the behavior of PS particles using magnetometry, employing direct current (DC) magnetic measurements. This technique enables the determination of the equilibrium magnetization of a sample when exposed to a constant magnetic field. By measuring the magnetic moment of the sample, we gained valuable insight into the sensitivity of PS particles in both aqueous and non-aqueous environments (Cullity and Graham, 2011; Fiorillo, 2010).

This research aims to investigate the influence of an external steady magnetic field on the surface tension of both pure degassed DI water and DI water containing PS microplastics. The study offers valuable insights into the complex interplay between magnetic fields and fluid properties, contributing to a broader understanding of these interactions.

MATERIAL AND METHODS

Dynamic Surface Tension Measurements

Dynamic surface tension measurements were performed with a PAT1 instrument (SINTERFACE technologies) using a pendant drop shape tensiometer. The experimental setup involved suspending a droplet from a capillary with an inner diameter of 1 mm, as shown in Fig. 1A. A neodymium magnet N42 with size 10 x 10 x 10 mm was placed 10 mm beneath the pendant drop. This placement was essential to study the effects of the magnetic field on the behavior of water molecules and PS-MNPs in the liquid. The measured flux density and gradient flux density of the magnet used in the test are shown in Fig. 1B. The flux density is indicative of the strength of the magnetic field in the experimental setup, while the gradient indicates the variation of field strength with distance. The graph also demonstrates that the N42 magnet utilized in the setup generates a robust and uniform field.

The magnet under the pendant drop creates a magnetic field gradient in the vicinity of the droplet, which affects the distribution and behavior of the substances in the liquid. By observing the dynamic surface tension of the droplet in the presence of the magnetic field, we can understand how magnetic forces affect the intermolecular interactions and structural organization of the liquid. Consequently, the addition of PS-MNPs to water allows the study of their dispersion and aggregation behavior when exposed to a magnetic field.

The camera, integrated with the PAT1 instrument, continuously monitored the surface tension by capturing and analyzing image data of the droplet over time. Prior to each experimental run, the PAT1 instrument was calibrated to ensure accurate and reliable surface tension measurements. Calibration involved validating the accuracy and sensitivity of the device using

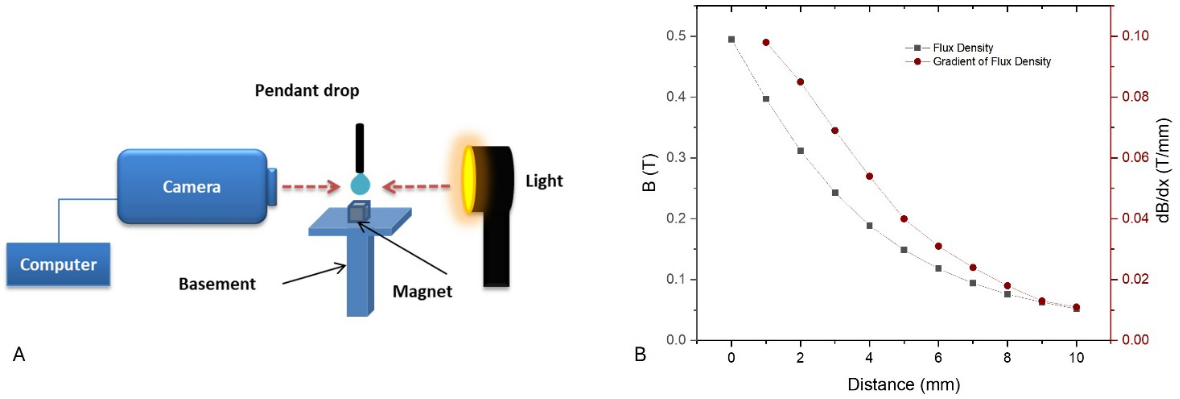

Fig. 1. A) The experimental setup illustrates a pendant drop configuration with a neodymium magnet, positioned 10 mmm beneath the generated droplet and B) the graph illustrating the measured flux density and gradient of flux density of the applied magnet of N42 in the setup

standard reference liquids.

DI Water and Particle Susceptibility Characterization

To study the effect of PS particles on the surface tension, pure fluorescent PS-MNPs with mean diameter of 5.03 µm were obtained from Micro Particles GmbH were diluted in DI water. The PS particles had a density of 1.05 g/cm³, were hydrophobic and non-porous, and exhibited a coefficient of variation (CV) of less than 5%. The particle size distribution of the applied PS was measured and is shown in Fig. 2. This figure provides information about the homogeneity and dispersion of the MNPs in the water matrix and confirms the particle specifications provided by the manufacturer.

The surface tension of the pure DI water was measured as 71.3±0.1 mN/m at 23°C and with a pH of 6.2. According to Jin et al., (2008), the magnetic susceptibility (χ) of polystyrene was reported to be -0.75×10^{-6}. The pure water used in the experiments exhibits diamagnetic properties with a magnetic susceptibility of approximately χwater= -9.05×10^{-6} ppm (Schenck, 1996). The experiments were also conducted using degassed DI water to establish a baseline for surface tension measurements. We used degassed DI water to reduce the effects of dissolved gases, especially oxygen and nitrogen, and to simplify the unknown reactions during the tests that could influence the results.

Degassed water provides more controlled and consistent experimental results, particularly when studying changes in surface tension. It increases the sensitivity of the experiment and reduces variations caused by dissolved gases. When gases are present in water, working on dynamic surface tension can lead to the formation of bubbles at the liquid-air interface, which interferes with measurements. Hence, degassed water reduces the likelihood of such interference.

To provide degassed water, dissolved gases were removed by vacuum pumping the DI water. It was then transferred to a tightly closed container and kept sealed during the experiments to minimize contact with air as much as possible. All experiments were conducted at a controlled temperature of 23°C to maintain consistency in the surface tension measurements.

Sampling and Measurement of Magnetic Susceptibility

Pure PS particles with size approximately 900 microns were obtained from Goodfellow Co. and tested in their dry state (without water) and when encapsulated in water. The samples

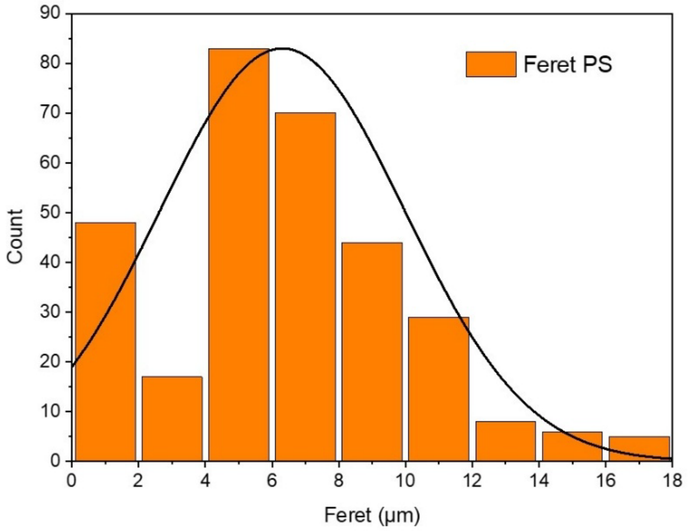

Fig. 2. The graph of PS-MNPs particle size distribution.

were then subjected to magnetic susceptibility measurements using an MPMS3 SQUID magnetometer from Quantum Design. The temperature during these measurements remained between 26.84°C and 26.85°C for both PS in water and PS without water.

Statistical Analysis

Data were analyzed using ImageJ software for particle counting. Origin software v.2018 was used for comprehensive data visualization, trend analysis, and statistical tests.

RESULTS AND DISCUSSION

Magnetic Field Effects on Degassed Water

Figure 3 shows the results of testing degassed DI water under two conditions: without the application of a magnetic field and with a steady magnetic field applied beneath the pendant drop. The surface tension of degassed water without the magnet exhibits a relatively consistent linear trend, ranging from 71.00 to 71.50 mN/m.

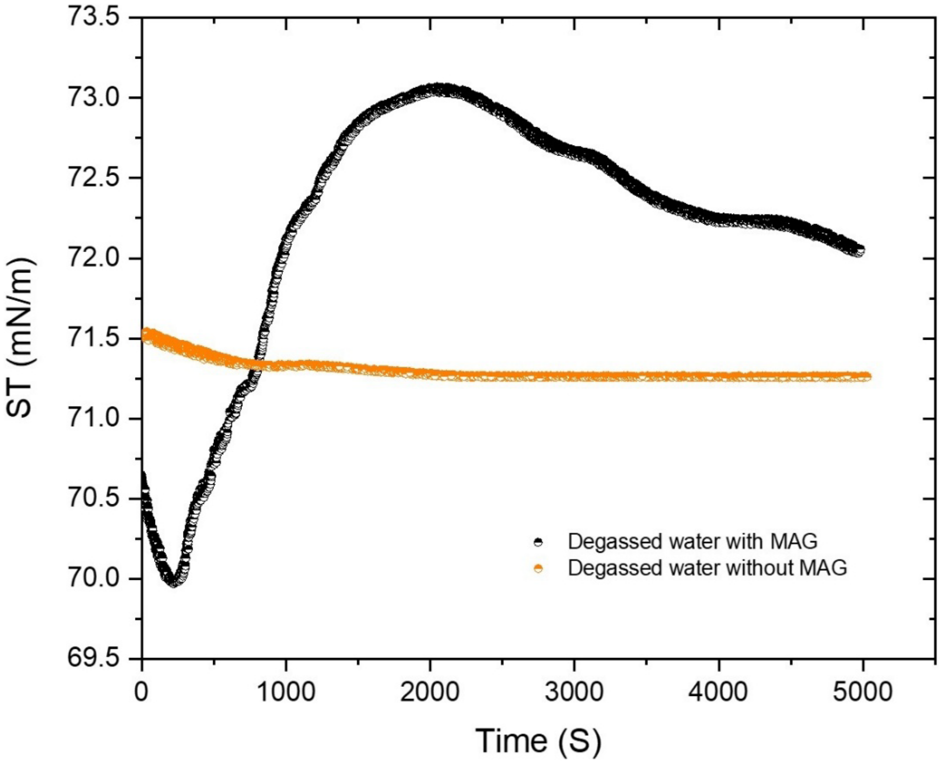

Fig. 3. The dynamic surface tension (ST) of degassed DI water in intraction with air under the influence of a magnetic field is compared with the condition without magnetic field exposure

In contrast, when a magnet is placed under the droplet, the surface tension profile shows notable fluctuations during the experiment. Initially, there is a sharp decrease in surface tension, with values dropping from 70.7 to 69.8 mN/m within the first 250 seconds. Subsequently, the surface tension increases to a peak value of about 73 mN/m at 2100 seconds. Following the peak, the surface tension gradually decreases and stabilizes at about 72 mN/m toward the end of the 5000-second experiment.

The observed changes in the surface tension of degassed DI water with and without the application of a magnetic field suggest that the presence of the magnetic field alters the behavior of water molecules at the liquid-air interface. The application of a magnetic field beneath the droplet resulted in the reduction of surface tension to 69.8 mN/m. This reduction can be attributed to the induced changes in the orientation and movement of water molecules at the liquid-air interface. These changes can initially decrease surface tension by weakening the cohesive forces between water molecules. Furthermore, the weakly bonded water molecules at interfaces are inherently susceptible to fluctuations in surface tension over time, which can be amplified by magnetic force, resulting in temporary disruptions of surface tension (Liu and Cao, 2021; Reed et al., 2020; Cai et al., 2009; Scatena et al., 2001).

The subsequent rapid increase in surface tension to about 73 mN/m could be attributed to the rearrangement of water molecules in response to the applied magnetic field. Hence, the magnetic field aligns the induced magnetic dipoles in water molecules, which increases the cohesive forces at the liquid-air interface and resulting in an increase in surface tension (Portuguez et al., 2017).

Towards the end of the experiment, the surface tension stabilized around 72 mN/m, which is slightly higher than the initial baseline. This observation indicates that the influence of the magnetic field on the water molecules has reached a steady state, with the surface tension settled into a new equilibrium level. This change could be due to alterations in the distribution of water molecules and the formation of transient structures at the interface in response to the applied magnetic field (Toledo et al., 2008). Additionally, the stabilized surface tension may also result from additional forces acting on the droplet, such as magnetic ponderomotive forces. These forces could alter the droplet's shape, potentially leading to misinterpretation of surface tension measurements if not properly considered.

Magnetic Energy and Experimental Outcomes

The magnetic energy resulting from the alignment of water molecules in a magnetic field can be described by Eq. 1 (Coey, 2010):

$$E = -m.B \tag{1}$$

where E is the magnetic energy, m is the magnetic moment of the water molecules, and B is the magnetic field. In a diamagnetic material like water, the magnetic moment is induced and aligns opposite to the applied magnetic field. Since water molecules do not possess a permanent magnetic dipole, the application of a magnetic field primarily influences the alignment of these induced moments. This alignment may alter the arrangement of water molecules at the liquid-air interface.

The response of water molecules to changes in surface tension can be described by following equation which represents the rate of change of the surface tension γ over time t as follows:

$$\frac{d\gamma}{dt} = f \tag{2}$$

where f represents the influence of different factors such as magnetic field, temperature, contamination, and other experimental parameters.

To account for the influence of the magnetic field in this context, it is essential to consider the relationship between the magnetic field and the surface tension in detail. First, we establish a clear functional form for the dependence of, f, on B:

$$f = f\left(B\right) \tag{3}$$

To include the influence of the magnetic field B in the Eq. 3, we integrate the magnetic energy equation over time:

$$\int \frac{d\gamma}{dt} dt = \int f\left(B\right) dt \tag{4}$$

This integration yields the following equation for surface tension γ over time:

$$\gamma = \int f\left(B\right) dt \tag{5}$$

The integral of Eq.5 represents the cumulative effect of the magnetic field over time on the surface tension, but the relationship between *f(B)* and *B* would need to be clearly defined or derived to simplify the integral further. According to the graph in Fig.3, there is a direct relationship between the change in surface tension γ and applied magnetic field *B*. This proportionality constant is represented by *k*. Hence, the surface tension of degassed water under the influence of a magnetic field can be described by a mathematical model as:

$$\gamma = k.B \tag{6}$$

where γ is the surface tension, *k* is a constant representing the sensitivity of the surface tension to the magnetic field, and *B* is the strength of the applied magnetic field. The constant *k* reflects the degree to which the surface tension changes in response to variations in the magnetic field strength.

Magnetic Field Influence on Surface Tension in PS-Water System

Figure 4 illustrates the results of the surface tension measurements of the PS-water system under two conditions: with and without the influence of a magnetic field. When the magnetic

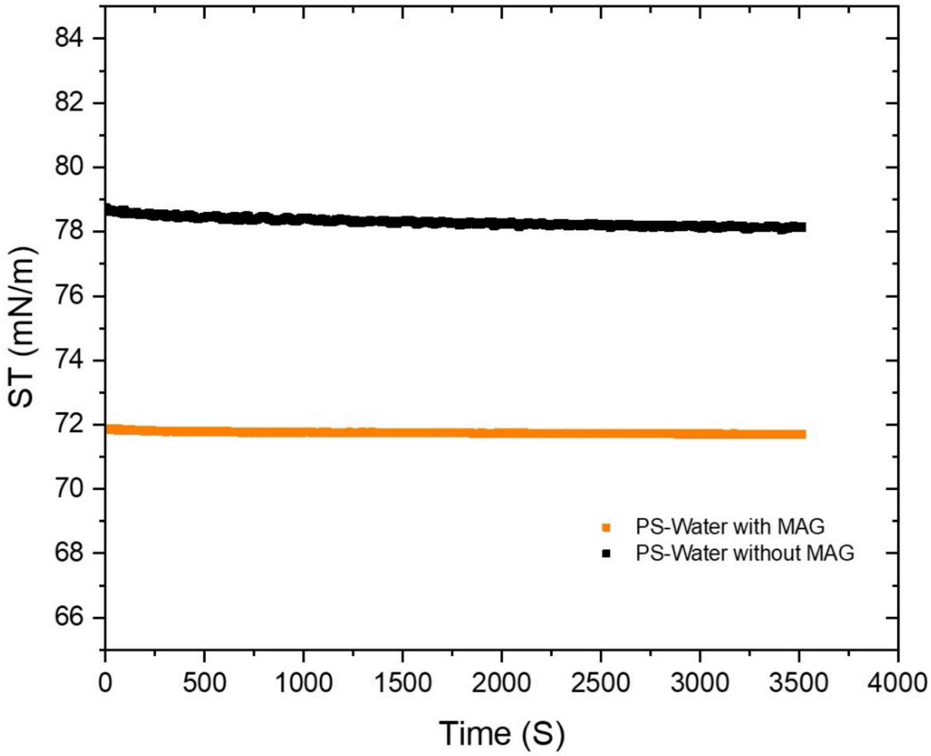

Fig. 4. Dynamic surface tension of PS-water in interaction with air under the influence of a magnetic field compared to conditions without magnetic field exposure

field is applied, the graph representing the surface tension of the PS-water droplet interacting with air exhibits an almost linear trend, starting at a value of 71.8 mN/m. In contrast, in the absence of a magnetic field, the surface tension of the same PS-water system is approximately 78.7 mN/m. Despite this difference, both scenarios display linear trend with a slight tendency towards lower values in the absence of the magnetic field, reaching approximately 78.1 mN/m. This variation in surface tension suggests that the magnetic field likely affects the distribution and arrangement of the PS particles dispersed in the water and contributes to the observed decrease in the surface tension.

Given the experimental setup, the interaction between a magnetic field and an aqueous solution containing PS particles is complex and likely occurs through indirect mechanisms. PS particles themselves are not inherently magnetic, but the diamagnetic surrounding water molecules, can be influenced by the magnetic field. Consequently, despite the lack of intrinsic magnetic properties in PS particles, the applied magnetic field may induce changes in the arrangement and dynamics of the water molecules, particularly at the interfaces. This structuring at the particle-water interface could impact the behavior of the particles in the solution, such as their tendency to aggregate or remain dispersed.

Magnetic Force on PS Particles in Non-Uniform Magnetic Fields

The force F experienced by a magnetic dipole m, in a non-uniform magnetic field B is mathematically described by Eq. 7:

$$F=(m\cdot\nabla)\,B \tag{7}$$

In this equation, m refers to the induced magnetic moment of the water molecules in the presence of the external magnetic field. The application of the magnetic field influences the orientation of these water molecules, aligning their induced magnetic moments with the field. The direction and magnitude of the force depend on the alignment of the magnetic moment relative to the field gradient, which can result in either attraction or repulsion of the particles along the field lines. If the PS particles are attracted, they may settle within the droplet, potentially leading to a sedimentation effect that reduces surface tension (Delahaije et al., 2022).

Furthermore, the movement of PS particles in water is affected by hydrodynamic forces, notably the drag forces applied by the surrounding water molecules. These forces are governed by Stokes' law (Stokes, 1851), expressed as:

$$F_d = 6\pi\mu R v \tag{8}$$

where F_d is the drag force experienced by the particle, μ is the dynamic viscosity of the fluid, R is the radius of the particle, and v is the velocity of the particle relative to the fluid.

Magnetic Field Influence on PS-Water Interaction and Surface Tension

In conjunction with the observed changes in surface tension described in Fig. 4, it is evident that the magnetic field predominantly influences the induced magnetic moments of the water molecules. This interaction causes the water molecules to align antiparallel to the field lines due to their diamagnetic nature. This alignment may affect the structure and organization of water molecules at the interface, potentially altering how they interact with PS particles and influence the overall behavior of the system.

Under the influence of the magnetic field, water molecules may form temporary and weakly ordered layers around the PS particles. The extent of this structuring is highly dependent on the strength of the magnetic field and could lead to an increase in viscosity or segregation of the PS particles from bulk water (Yu et al., 2019). Such weakly ordered structures may limit the interactions between water molecules and the hydrophobic PS particles, potentially reducing van der Waals interactions and contributing to the observed stability in the PS-water system. This stability is reflected by the linearity in the graph in Fig. 4 compared to pure water in Fig. 3.

PS particles suspended in water are also subject to Brownian motion caused by random collisions with water molecules. This motion results in irregular movement and dispersion of the PS particles in the water. The magnitude of this motion can be quantified using the Einstein-Smoluchowski equation:

$$D = \frac{k_B T}{6\pi\eta r} \tag{9}$$

where D is the diffusion coefficient, k_B is Boltzmann's constant, T is the temperature, η is the viscosity of the fluid, and r is the radius of the PS particle. The influence of the magnetic field can influence the Brownian motion of the particles, potentially leading to changes in their diffusion behavior. To account for this effect, we can define a modified diffusion coefficient D':

$$D' = D + \Delta D \tag{10}$$

Here, D is the standard diffusion coefficient without the influence of the magnetic field, and ΔD represents the change in diffusion coefficient resulting from the magnetic applied field. The relationship between the change in the diffusion coefficient ΔD and the force F experienced by the particles, can be determined using appropriate empirical or theoretical models.

PS particles can also experience van der Waals forces, depending on their surface charge and the presence of charged groups in the surrounding aqueous environment. These intermolecular forces can influence the aggregation behavior of the particles and contribute to changes in particle distribution (Yu et al., 2019). PS particles, composed of nonpolar hydrocarbon chains, are primarily subject to van der Waals forces. When these particles come into proximity, the attractive van der Waals forces between them lead to the formation of particle clusters or aggregates.

Pang and Deng (2008) documented that magnetic fields can enhance the hydrophobic interactions between water and certain materials, thereby affecting their behavior in aqueous environments. In such environments, hydrogen bonds play a crucial role for the cohesive and adhesive properties of water, forming between the partially positive hydrogen atom of one water molecule and the partially negative oxygen atom of another. However, the application of a magnetic field introduces a new dynamic that alters the arrangement and orientation of these water molecules, potentially impacting the overall interaction between PS particles and water.

Hence, PS particles which are typically held at the liquid-air interface by intermolecular forces, experience enhanced attraction towards water molecules under the influence of a magnetic field. This magnetic field exerts a directional force that drives the PS particles away from the interface and into the bulk of the liquid, aligning with the field's gradient.

The altered interaction between water molecules and PS particles in the presence of a magnetic field has significant implications for surface tension dynamics. As the magnetic field induces a rearrangement and reorganization of the water molecules, stronger interactions with hydrophobic PS particles disrupt the molecular arrangement at the liquid-air interface. This disruption leads to a decrease in surface tension, as the concentration of particles at the interface reduces.

Magnetic Susceptibility of PS Microparticles in the Presence and Absence of Water

Fig. 5 illustrates the magnetic susceptibility of PS microparticles, comparing measurements in the absence of water and in the degassed water. The graphs display the relationship between the applied magnetic field (in Oe) and the fixed DC moment (in emu), which explains the

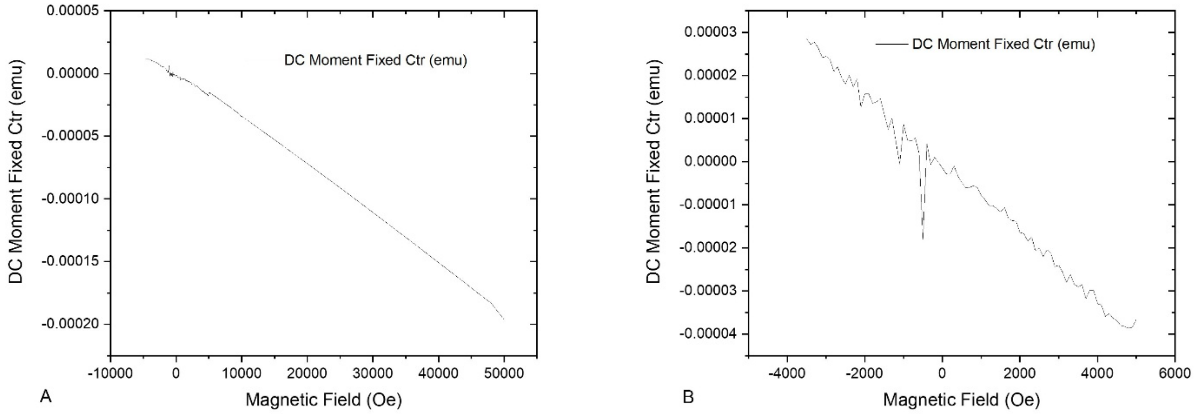

Fig. 5. The graphs illustrate the relationship between magnetic and DC moment field measurements for PS particles approximately 900 microns in size in (A) dry and (B) degassed water

degree of magnetization of the PS particles.

In Fig.5A for dry PS microparticles, a steady increase in the DC moment is observed as the magnetic field varies from negative to positive values. For instance, at a field strength of -2099.4 Oe, the DC moment measures 5.44E-06 emu, indicating a moderate alignment of the PS particles with the magnetic field. As the field strength reaches -2999.7 Oe, the DC moment rises to 8.40E-06 emu, indicating an increase in the magnetization. This trend suggests that PS particles exhibit greater magnetization as the magnetic field strength increases in the negative direction.

Fig.5B shows the magnetic susceptibility of PS particles in the presence of water, showing a more complex interaction between the magnetic field and the DC moment compared to the PS particles without water. As the magnetic field increases from negative to positive values, the DC moment initially remains relatively stable or exhibits a slight decrease. Notably, between approximately -500 Oe to -600 Oe, there is a significant decrease in the DC moment, reaching a minimum value of -1.79831E-05 emu and 2.00486E-06 emu, respectively. Following this decline, the DC moment starts to rise again as the magnetic field strength continues to increase.

This behavior indicates a non-linear relationship between the magnetic field and the DC moment for PS particles in water, suggesting that the interaction is influenced by additional factors, possibly related to the diamagnetic properties of water and its structuring around the particles under varying magnetic fields.

CONCLUSIONS

The impact of magnetic fields on degassed water and PS-water system was tested using pendant drop tensiometry. In degassed water, the application of a magnetic field primarily affects the structuring of water molecules, leading to an increase in surface tension. This increase is likely due to alterations in the arrangement of water molecules at the liquid-air interface, potentially driven by changes in hydrogen bonding patterns or altering the balance of intermolecular forces at the interface.

In the PS-water system, the magnetic field likely affects both the structuring of water and the interaction between water molecules and PS particles. The enhanced hydrophobicity of PS particles may result in more robust interactions with water molecules under the influence of the magnetic field, thereby leading to a more pronounced decrease in surface tension. This effect results in a more stable system with predictable behavior, demonstrated by the observed consistency and linearity in the experimental results. The interplay of van der Waals forces and changes in the distribution of water molecules around hydrophobic PS particles is likely to contribute to these observations.

While pendant drop tensiometry is an effective method for measuring surface tension, its sensitivity to interfacial changes and potential droplet shape deformations under a magnetic field can pose challenges for accurately capturing dynamic interactions in complex systems. Future studies should consider incorporating additional techniques, to provide a more comprehensive understanding of these interfacial phenomena.

In summary, our findings contribute valuable insights into the complex dynamics of colloidal systems under the influence of magnetic field. Further exploration of these mechanisms through comprehensive experimental investigations and theoretical modeling is crucial to improve our understanding of interfacial phenomena and to refine magnetic manipulation techniques in various applications.

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CONFLICT OF INTEREST

The authors declare that there is not any conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

REFERENCES

An, X., Wang, Y., Adnan, M., Li, W. & Zhang, Y. (2024). Natural factors of microplastics distribution and migration in water: A review. *Water*, 16(11), 1595.

Berry, J. D., Neeson, M. J., Dagastine, R. R., Chan, D. Y., & Tabor, R. F. (2015). Measurement of surface and interfacial tension using pendant drop tensiometry. Journal of Colloid and Interface Science, 454, 226–237.

Cai, R., Yang, H., He, J., & Zhu, W. (2009). The effects of magnetic fields on water molecular hydrogen bonds. Journal of Molecular Structure, 938(1–3), 15–19.

Chia, R. W., Lee, J. Y., Kim, H., & Jang, J. (2021). Microplastic pollution in soil and groundwater: A review. Environmental Chemistry Letters, 19(6), 4211–4224.

Coey, J. M. (2010). Magnetism and magnetic materials. Cambridge University Press.

Cullity, B. D., & Graham, C. D. (2011). Introduction to magnetic materials. John Wiley & Sons.

de Souza Machado, A. A., Kloas, W., Zarfl, C., Hempel, S., & Rillig, M. C. (2018). Microplastics as an emerging threat to terrestrial ecosystems. Global Change Biology, 24(4), 1405–1416.

Delahaije, R. J., Sagis, L. M., & Yang, J. (2022). Impact of particle sedimentation in pendant drop tensiometry. Langmuir, 38(33), 10183–10191.

Deswati, D., Yusuf, Y., Putra, Z. A., & Putra, A. (2025). Abundance and characteristics of microplastics in surface water of Lake Singkarak in Tanah Datar, West Sumatra, Indonesia. Pollution, 11(2), 464–476.

Esmaeilnezhad, E., Choi, H. J., Schaffie, M., Gholizadeh, M., & Ranjbar, M. (2017). Characteristics and applications of magnetized water as a green technology. Journal of Cleaner Production, 161, 908–921.

Fiorillo, F. (2010). Measurements of magnetic materials. Metrologia, 47(2), S114.

Fujimura, Y., & Iino, M. (2009). Magnetic field increases the surface tension of water. Journal of Physics: Conference Series, 156(1), 012028.

Gouin, T., Ellis-Hutchings, R., Thornton Hampton, L. M., Lemieux, C. L., & Wright, S. L. (2022). Screening and prioritization of nano- and microplastic particle toxicity studies for evaluating human health risks: Development and application of a toxicity study assessment tool. Microplastics and Nanoplastics, 2(1), 2.

Hayakawa, M., Vialetto, J., Anyfantakis, M., Takinoue, M., Rudiuk, S., Morel, M., & Baigl, D. (2019). Effect of moderate magnetic fields on the surface tension of aqueous liquids: A reliable assessment. RSC Advances, 9(18), 10030–10033.

Hildebrandt, L., Voigt, N., Zimmermann, T., Reese, A., & Proefrock, D. (2019). Evaluation of continuous flow centrifugation as an alternative technique to sample microplastic from water bodies. Marine Environmental Research, 151, 104768.

Jin, X., Zhao, Y., Richardson, A., Moore, L., Williams, P. S., Zborowski, M., & Chalmers, J. J. (2008). Differences in magnetically induced motion of diamagnetic, paramagnetic, and superparamagnetic microparticles detected by cell tracking velocimetry. Analyst, 133(12), 1767–1775.

Kamani, H., Ghayebzadeh, M., & Ganji, F. (2024). Characteristics of microplastics in the sludge of wastewater treatment plants. Pollution, 10(2), 653–663.

Karbowiak, T., Debeaufort, F., & Voilley, A. (2006). Importance of surface tension characterization for food, pharmaceutical and packaging products: A review. Critical Reviews in Food Science and Nutrition, 46(5), 391–407.

Kiran, B. R., Kopperi, H., & Venkata Mohan, S. (2022). Micro/nano-plastics occurrence, identification, risk analysis and mitigation: Challenges and perspectives. Reviews in Environmental Science and Bio/Technology, 21(1), 169–203.

Koelmans, A. A., Redondo-Hasselerharm, P. E., Nor, N. H. M., de Ruijter, V. N., Mintenig, S. M., & Kooi, M. (2022). Risk assessment of microplastic particles. Nature Reviews Materials, 7(2), 138–152.

Liu, J., & Cao, Y. (2021). Experimental study on the surface tension of magnetized water. International Communications in Heat and Mass Transfer, 121, 105091.

Maliwan, T., & Hu, J. (2025). Release of microplastics from polymeric ultrafiltration membrane system for drinking water treatment under different operating conditions. Water Research, 274, 123047.

Nikpay, M., & Toorchi Roodsari, S. (2024). Crafting a scientific framework to mitigate microplastic impact on ecosystems. Microplastics, 3(1), 165–183.

Nikpay, M. (2023). Method and device for separating plastic particles with a magnetic filter. Patent no. DE102022001154A1. Germany.

Osman, A. I., Hosny, M., Eltaweil, A. S., Omar, S., Elgarahy, A. M., Farghali, M., Yap, P. S., Wu, Y. S., Nagandran, S., Batumalaie, K., & Gopinath, S. C. (2023). Microplastic sources, formation, toxicity and remediation: A review. Environmental Chemistry Letters, 21(4), 2129–2169.

Pang, X. F., & Deng, B. (2008). The changes of macroscopic features and microscopic structures of water under the influence of a magnetic field. Physica B: Condensed Matter, 403(19–20), 3571–3577.

Portuguez, E., Alzina, A., Michaud, P., Oudjedi, M., & Smith, A. (2017). Evolution of a water pendant droplet: Effect of temperature and relative humidity. Natural Science, 9(1), 1–20.

Rashed, A. H., Yesilay, G., Hazeem, L., Rashdan, S., AlMealla, R., Kilinc, Z., Ali, F., Abdulrasool, F., & Kamel, A. H. (2023). Micro- and nano-plastics contaminants in the environment: Sources, fate, toxicity, detection, remediation, and sustainable perspectives. Water, 15(20), 3535.

Reed, D. M., Fortenberry, A., Wolfe, E. A., Stanhope, R. A., Daniel, C. I., Hern, C. M., Smith, A. E., & Scovazzo, P. (2020). Interfacial vs bulk phenomena effects on the surface tensions of aqueous magnetic surfactants in uniform magnetic fields. Langmuir, 36(34), 10074–10081.

Rezania, S., Park, J., Din, M. F. M., Taib, S. M., Talaiekhozani, A., Yadav, K. K., & Kamyab, H. (2018).

Microplastics pollution in different aquatic environments and biota: A review of recent studies. Marine Pollution Bulletin, 133, 191–208.

Scatena, L. F., Brown, M. G., & Richmond, G. L. (2001). Water at hydrophobic surfaces: Weak hydrogen bonding and strong orientation effects. Science, 292(5518), 908–912.

Schenck, J. F. (1996). The role of magnetic susceptibility in magnetic resonance imaging: MRI magnetic compatibility of the first and second kinds. Medical Physics, 23(6), 815–850.

Senathirajah, K., Kandaiah, R., Panneerselvan, L., Sathish, C. I., & Palanisami, T. (2023). Fate and transformation of microplastics due to electrocoagulation treatment: Impacts of polymer type and shape. Environmental Pollution, 334, 122159.

Soncini, R., & Klein, W. (2023). Surface tension in biological systems: A common problem with a variety of solutions. Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology, 111475.

Stokes, G. G. (1851). On the effect of the internal friction of fluids on the motion of pendulums. Transactions of the Cambridge Philosophical Society, 9, 8–106.

Thompson, R. C., Courtene-Jones, W., Boucher, J., Pahl, S., Raubenheimer, K., & Koelmans, A. A. (2024). Twenty years of microplastics pollution research—what have we learned? Science, eadl2746.

Toledo, E. J., Ramalho, T. C., & Magriotis, Z. M. (2008). Influence of magnetic field on physical–chemical properties of the liquid water: Insights from experimental and theoretical models. Journal of Molecular Structure, 888(1–3), 409–415.

Vohl, S., Kristl, M., & Stergar, J. (2024). Harnessing magnetic nanoparticles for the effective removal of micro-and nanoplastics: A critical review. Nanomaterials, 14(14), 1179.

Wang, Y., Wei, H., & Li, Z. (2018). Effect of magnetic field on the physical properties of water. Results in Physics, 8, 262–267.

Yu, S., Shen, M., Li, S., Fu, Y., Zhang, D., Liu, H., & Liu, J. (2019). Aggregation kinetics of different surface-modified polystyrene nanoparticles in monovalent and divalent electrolytes. Environmental Pollution, 255, 113302.

Zhao, P., Xie, J., Gu, F., Sharmin, N., Hall, P., & Fu, J. (2018). Separation of mixed waste plastics via magnetic levitation. Waste Management, 76, 46–54.