Research Article

Effects of Impeller Shape and Rotational Speed in a Stirred Tank on the Microplastic Capture Efficiency using Oil-Based Ferrofluid

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Abstract

Microplastics in aquatic environments pose serious threats to ecosystems and human health due to their persistence and ability to adsorb toxic substances. This research focuses on developing an application method for oil-based ferrofluid to capture microplastics. Experiments were conducted in a stirred tank designed to enhance contact between microplastics and ferrofluid. Three impeller types were tested: a 4-blade EMI Rotofoil, a 4-blade propeller, and a 4-blade 45° pitched blade turbine, each operated at rotational speeds of 100, 150, 200, 250, 300, and 350 rpm. The efficiency of microplastic capture was evaluated by comparing the Number of microplastic particles in water samples before and after mixing, using microscopic analysis. Results showed that the 4-blade EMI Rotofoil at 350 rpm achieved the highest capture performance, while the 4-blade propeller at 100 rpm yielded the lowest. These findings highlight the potential of integrating ferrofluid with mechanical mixing in a stirred tank as an effective approach for microplastic removal from water systems.

Keywords: Oil-Based Ferrofluid, Microplastic, Shear, Axial flow

1. Introduction

Microplastics are one of the causes of water pollution. This is because microplastics, which are plastics that become smaller due to exposure to sunlight and the force of water currents, cannot be degraded in a short period of time, can spread easily, and also serve as a medium for the accumulation of other pollutants in the environment, such as toxic chemicals and heavy metals. When humans and animals consume water contaminated with accumulated toxins, carried by microplastics, it leads to some health problems, such as neurotoxicity and endocrine disruption, as well as causing harm to the reproductive system and reducing aquatic biodiversity (1). Ferrofluid is a suspension that can respond to magnetic fields and can be

divided into several types according to its structure and properties. It has therefore been applied in various ways, such as in medicine, where it is used to enhance the efficiency of tumor destruction through hyperthermia, and in space technology, which is used as satellite fuel. One of the types of ferrofluids, called oil-based ferrofluid, is regarded as a new approach for capturing microplastics in water in an environmentally friendly and cost-effective manner (2).

The invention and development by Ferreira (3) of the removal of microplastics from water using oil-based ferrofluid. Experiments were conducted with several types of microplastics, including HDPE, LDPE, PVC, PP, PE, and PET, as well as microbeads from a

washing machine. The results showed that the ferrofluid was able to capture fibers and microbeads with an efficiency of up to 93 ± 1.9 %. Ibrahim (4) compared the efficiency of microplastic removal from water using ferrofluids with different carrier oils, namely lubricating oil and cooking oil, as well as between ferrofluids prepared with used and unused oils. The results showed that ferrofluids with lubricating oil as the carrier achieved up to 99.5% microplastic capture efficiency, which was higher than that of ferrofluids with cooking oil as the carrier. Moreover, ferrofluids prepared with unused oil exhibited greater microplastic capture efficiency compared to those with used oil, due to their lower viscosity, which allows the oil to penetrate the pores of microplastics more easily and thereby enhances capture performance. Hamzah (5) investigated how different carrier oils, oil volumes, and magnetite dosages affect the removal efficiency of 2-mm PET microplastics. A ferrofluid prepared with an oil-to-magnetite ratio of 1:2.5, using lubricating oil as the carrier, achieved a 99% removal efficiency.

Recent research studies on identifying appropriate oils for oil-based ferrofluids and determining the mixing ratios that provide the highest efficiency in microplastic capture. However, investigations applying this ferrofluid-based technique to larger-scale treatment systems, as well as studies examining additional factors beyond mixing ratios that may influence removal efficiency, are still relatively scarce. The oil-based ferrofluid captures microplastics through direct contact, resulting from its unique property. Moreover, this type of ferrofluid still has limitations, as it can disintegrate and lose its properties easily when subjected to high shear rates, thereby reducing its efficiency in capturing microplastics.

This work proposes a novel microplastic capture system integrated within a stirred tank, designed to increase the frequency of contact between the ferrofluid and microplastics. Due to its higher density relative to water, the ferrofluid naturally settles at the bottom of the tank, forming a designated capture zone. The experimental approach leverages the flow behavior inside the stirred tank—particularly the axial flow generated by the impeller—which facilitates the downward transport of microplastics toward the capture zone. Within this configuration, the effects of impeller shape and rotational speed on

microplastic capture efficiency using oil-based ferrofluid can be systematically evaluated. These operating parameters directly influence shear forces, ferrofluid stability, and overall capture performance. The outcomes of this study are expected to support the advancement of ferrofluid-based microplastic removal systems for future water treatment applications.

2. Materials and Experiment
2.1 Fabrication of Impellers and Baffles and Creating a Microplastic Capture System Simulation Model

Figure 1 shows a 4-blade EMI Rotofoil impeller, a 4-blade propeller, and a 4-blade 45° pitched turbine blade with a diameter of 6 cm, along with a rectangular baffle measuring 1.8 cm in width, 8 cm in length, and 5 mm in thickness, all designed using Tinkercad. The design files were exported in .STL format and imported into FlashPrint 5 software to be converted into .gx files for 3D printing. After cooling, all fabricated parts were removed from the printing base. shaft and a control circuit for stirring operation.

4-blade EMI Rotofoil impeller   4-blade 45° pitched turbine blade

4-blade propeller
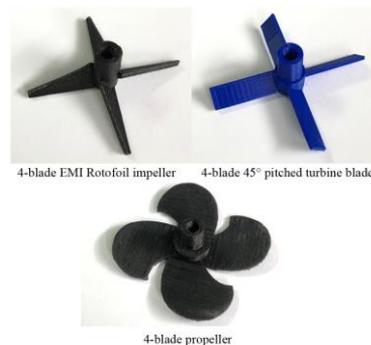
Figure 1 Simulation model of the microplastic capture system

2.2 Experimental Design for Microplastics Removal System

The system was designed with the following features: a cylindrical stirred tank with a diameter of 18 cm and a height of 21 cm, equipped with four flow baffles on the side wall to reduce vortex formation; and a stirring tank lid with a motor support base, assembled from five acrylic sheets in the shape of a box, with a hole on top for inserting the motor shaft and a circuit for controlling the stirring process, as shown in

Figure 2. An impeller was installed in the tank, which was filled with microplastic-contaminated water up to 18 cm. Lubricating oil (40.3 ml) and magnetite powder (100.75 g) were added, based on the previously reported mixing ratio that yielded the highest microplastic-removal efficiency (5). The motor was set to 100 rpm via an Arduino microcontroller. The mixture was stirred for 1 minute, and water samples were collected from depths of 1, 9, and 17 cm, with three samples per depth, to determine the quantity of microplastics before capture. The procedure was repeated at 150, 200, 250, 300, and 350 rpm, and experiments were conducted with three different impeller shapes.
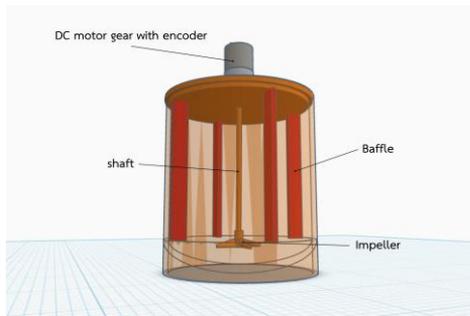
Figure 2 Simulation model of the microplastic capture system

2.3 Determining the quantity of microplastics before capture.

Deionized water was first cooled to 20 °C to improve microplastic dispersion, after which PVC microplastic powder, one of the five most frequently detected types in aquatic environments (6), was added at a concentration of 0.1 g/L. Water samples containing these microplastics were collected by pipette from depths of 1, 9, and 17 cm in the stirred tank. Three drops from each sample were placed on a microscope slide, covered with a coverslip, and examined under a light microscope (4× magnification), as shown in Figure 3(a). Images were captured using a mobile phone, and the Number of microplastic particles was quantified with ImageJ, as shown in Figure 3(b). This process was repeated to obtain three samples from each depth.
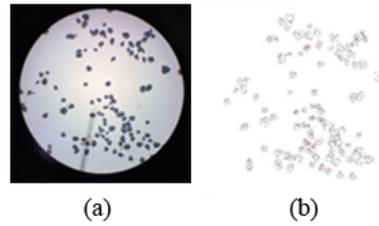
Figure 3 (a) Microplastics in a contaminated water sample before capture, under a microscope (b) Image of microplastics analyzed using ImageJ software

2.4 Measuring the Efficiency of Microplastic Capture

Three drops of microplastic-contaminated water from section 2.5 were placed on a microscope slide and covered with a coverslip. The slide was examined under a light microscope at 4×10 magnification, and images were captured using a mobile phone. The Number of microplastic particles in each image was counted using ImageJ software, and the average quantity was calculated to determine the efficiency of microplastic capture using the following formula:

$$\bar{p} = \frac{\Sigma p}{n} \qquad (1)$$

and the Percentage of microplastic capture

$$R = \left[\frac{p_0 - \bar{p}}{p_0}\right] \times 100 \qquad (2)$$

Where: p_0 = Number of microplastics before capture (pieces), $\bar{p}$ = Average Number of microplastics (pieces), Σp = Sum of the Number of microplastic pieces remaining after trapping (pieces), n = Number of repetitions (times)

3. Results and Discussion

3.1 Effect of Impeller Shape and Rotational Speed on the Microplastic Capture Efficiency

The 4-blade EMI Rotofoil impeller tends to capture more microplastics as the rotational speed increases. Moreover, this impeller design exhibits high microplastic capture efficiency in the 98-98.7% range, as shown in Figure 4. This is because the 4-blade EMI Rotofoil generates lower shear forces compared to the other designs (6-8), resulting in less ferrofluid deformation and thereby enabling greater microplastic capture.
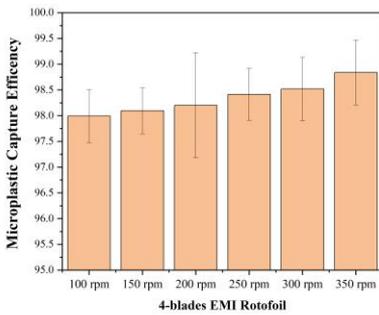
Figure 4 Microplastic capture efficiency of oil-based ferrofluid when stirred with a 4-blade EMI Rotofoil impeller at different rotational speeds

Figure 5 shows that the 4-blade 45° pitched blade turbine impeller demonstrates an increasing trend in microplastic capture within the rotational speed range of 100–150 rpm. However, when the rotational speed exceeds 200 rpm, the capture efficiency tends to decrease as the speed increases. This is because the 45° pitched blade turbine generates higher shear forces compared to the other two impeller types (6-8), leading to ferrofluid deformation starting at 200 rpm, which consequently reduces its ability to capture microplastics.
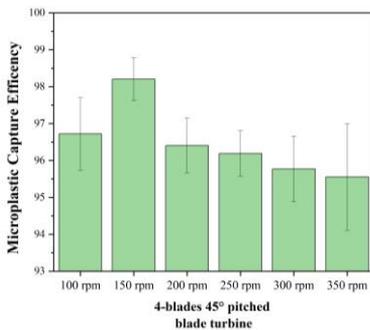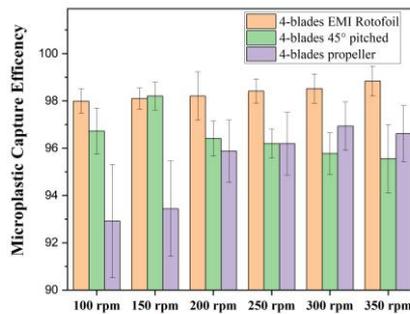

Figure 5 Microplastic capture efficiency of oil-based ferrofluid when stirred with a 4-blade 45° pitched blade turbine at different rotational speeds

The 4-blade propeller demonstrated the lowest efficiency in capturing microplastics at 100 rpm. The increase in efficiency with higher speeds up to 300 rpm, with the highest efficiency at 97%, as shown in Figure 6. The propeller impeller provides high mixing efficiency only at higher stirring speeds than

those investigated in this study. As a result, microplastics were less able to come into contact with the ferrofluid than the other impeller types (6-8).
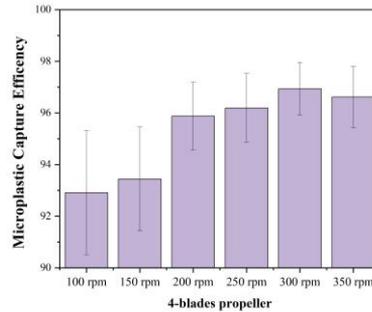
Figure 6 Microplastic capture efficiency of oil-based ferrofluid when stirred with a 4-blade propeller at different rotational speeds

Figure 7 Comparison of the microplastic capture efficiency of oil-based ferrofluid under agitation with different impeller shapes at different rotational speeds

3.2 Discussion

Rotational speed and impeller shape are key variables governing the circulating capacity (Q), which reflects mixing efficiency within a stirred tank. This relationship is expressed by:

$$Q = (N_q)ND^3$$

Where N_q is the pumping number determined by the impeller shape, N is the rotational speed, and D is the impeller diameter, which was held constant in this study

According to the equation, when the impeller shape is fixed, increasing the rotational

speed directly enhances the circulating capacity. Conversely, when rotational speed is constant, different impeller geometries yield markedly different pumping capacities. Among the three impellers tested, the 4-blade pitched blade turbine (PBT) exhibits the highest circulating capacity due to its high pumping number, while the 4-blade propeller yields the lowest circulating capacity because of its comparatively low N_q (7).

Table 1 Pumping Number, N_q, under Turbulent Conditions for Various Impellers (7).

Impeller Type	N_Q
Propeller	0.4-0.6
Pitched-blade turbine	0.79
Hydrofoil impellers (Rotofoil)	0.55-0.73
Retreat curve blade	0.3
Flat-blade turbine	0.7
Disk flat-blade turbine (Rushton)	0.72
Hollow-blade turbine (Smith)	0.76

The attachment between ferrofluid and microplastic particles constitutes a heteroagglomeration process, governed by interpartide forces such as van der Waals attraction, hydrophobic interactions, and magnetic dipole interactions when applicable (8). These heteroaggregates can undergo structural degradation when exposed to sufficiently high shear stresses, which disrupts the interparticle bonds stabilizing the aggregates (9). Therefore, shear must be considered alongside circulating capacity when evaluating the microplastic-capture efficiency of the system.

In highly agitated systems, when the Reynolds number reaches the fully turbulent regime (Re$\geq 10^7$), momentum transfer is dominated not by viscosity but by turbulent energy dissipation rate (ε). Impelliers with higher power numbers (N_p) generate higher ε, which in turn increases the characteristic turbulent shear rate according to the scaling:

$$\dot{\gamma} \propto \sqrt{\frac{N_p N^3 D^5}{V v}}$$

Where $\dot{\gamma}$ is the shear rate, N_p is the power number determined by impeller shape (9),

V is the liquid volume within the tank, and v is the kinetic viscosity of the fluid.

Consequently, although higher rotational speed improves circulating capacity, it simultaneously increases shear intensity, which, beyond a threshold, can induce deformation or breakup of heteroaggregates. At a fixed rotational speed, the pitched blade turbine, having the highest N_p, produces the greatest shear, whereas the 4-blade propeller and 4-blade EMI rotofoil, which possess lower N_p, generate proportionally lower shear levels (7).

Consequently, the 4-blade EMI rotofoil demonstrated the highest overall efficiency in removing microplastics. This performance can be attributed to its comparatively lower shear rate relative to the other two impellers, while still providing the second-highest circulating capacity. The 4-blade 45° pitched-blade turbine exhibited high removal efficiency at lower rotational speeds due to its highest circulating capacity among the tested impellers. However, at higher rotational speeds, its efficiency tended to decrease, suggesting that excessive shear rate exerts a more pronounced negative effect on heteroaggregate stability than the positive contribution gained from improved circulation. Finally, the 4-blade propeller showed the lowest removal efficiency at low rotational speeds, primarily because it produced the lowest circulating capacity.

4. Conclusions

This work successfully designs a microplastic capture system integrated within a stirred tank, designed to increase the frequency of contact between the ferrofluid and microplastics. Experiments conducted in a stirred tank revealed that both impeller geometry and rotational speed significantly influence capture efficiency through their effects on shear forces and ferrofluid stability. Among the tested impellers, the 4-blade EMI Rotofoil exhibited the highest efficiency, achieving optimal performance at 350 rpm, while the 4-blade propeller showed the lowest capture efficiency within the studied speed range. The results indicate that excessive shear stress can cause ferrofluid deformation, thereby reducing its ability to bind with microplastics, whereas moderate shear conditions promote efficient capture. These findings highlight the importance of optimizing hydrodynamic conditions in

designing ferrofluid-based microplastic capture systems. In particular, the 4-blade EMI Rotofoil impeller provides a promising balance between sufficient mixing and minimal ferrofluid degradation, suggesting its suitability for further development of practical microplastic treatment technologies.

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Declaration of Conflicting Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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