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Quantitative Recovery of Microplastics from Sediments Using an Integrated Foam Flotation Method with a Biodegradable Surfactant

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ABSTRACT

Sediments represent an important sink for microplastics, making efficient separation and recovery essential for their quantitative and qualitative analysis. In this study, an integrated froth-flotation method was developed for recovering microplastics from artificially prepared sediment samples using alkyl polyglucoside (APG) as a biodegradable surfactant. The effects of airflow rate, APG concentration, particle size, polymer type, and surfactant characteristics on flotation behavior were systematically evaluated. Under the selected operating conditions, including an airflow rate of 200 mL/min, the APG assisted flotation system achieved recovery efficiencies approaching 100% for the tested microplastics, including relatively high density polymers, and the separation process could be completed within approximately 2 min. The results further indicated that surfactant concentration and particle size influenced flotation behavior through changes in microplastic wettability and bubble particle interactions. Compared with conventional density and oil assisted separation approaches, the integrated flotation system provides rapid flotation and direct collection without requiring a high density salt solution or an additional oil phase. These findings demonstrate the potential of APG assisted froth flotation as a rapid approach for microplastic recovery from sediment matrices under controlled laboratory conditions.

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1. Introduction

Since the inception of plastic products, global plastic production has witnessed exponential growth. Since the 1950s, global plastic production has experienced a spectacular surge—rising from 1.5 million tons back then to an incredible 390.7 million tons by 2021 [1]. However, a concerning trend has emerged: studies reveal that roughly 80% of plastics ultimately find their way into landfills or the natural environment, many becoming ensnared in various sediment types. Microplastics, characterized by their diminutive size of less than 5 millimeters, are ubiquitously dispersed throughout all sediment varieties [2]. With their minute particle size, expansive specific surface area, and pronounced hydrophobic properties, microplastics exhibit a propensity to adsorb organic pollutants, heavy metals, and potentially pathogenic microorganisms, thereby escalating environmental and ecosystem apprehensions [3-7]. Organisms within the sediment and detritus food chain are susceptible to mistakenly ingesting microplastics, thereby amplifying the likelihood of microplastic accumulation within organisms and intensifying the bioconcentration effect within the food chain. This occurrence can potentially induce toxic effects in animals following ingestion, consequently culminating in indirect ramifications for humans [8]. Simultaneously, improper disposal of sludge, coupled with the infiltration of microplastics into soil ecosystems through land use practices, along with the erosion of shoreline microplastics by rivers and oceans, inevitably results in the deposition of these contaminants within sediments. With continued accumulation exacerbated by factors like rainwater infiltration, these contaminants pose a risk of contaminating groundwater reservoirs. These challenges have grown increasingly pronounced and harbor the potential to instigate broader environmental hazards [9-11].

In order to comprehensively and efficiently study microplastics in sediments, it is important to develop a uniform and standardized method for separating microplastics, as there is currently a lack of consistency in the means of separating and extracting microplastics [12-17]. Therefore, it is crucial to establish an efficient and clean method for separating microplastics in order to analyze the content, type and distribution of microplastics [18-22]. Currently, methods for separating microplastics in sediments can be broadly categorized into three groups: density separation, oil separation and air flotation [23-27]. Density separation is usually accomplished by adding saturated brine to the sediment sample, which after thorough mixing is allowed to stand, and then the upper solution is collected. Without considering microplastic attachment, the density of microplastics is usually in the range of 0.8-1.4 g/cm³, while the density of sediments is usually around 2.6 g/cm³. This method utilizes density differences in order to enable the extraction of microplastics from sediment samples [28-30]. However, since saturated sodium chloride has a density of 1.19 g/cm³, the separation is relatively ineffective for denser microplastic particles (e.g., PVC, with a density of 1.35-1.39 g/cm³) [30-32]. In addition, some studies have attempted to use saturated sodium iodide, zinc chloride and other salt solutions for density separation of microplastics. However, the insufficiently stable nature of these solutions, along with their high toxicity, has somewhat limited their application. In addition, issues such as the economic costs associated with these methods need to be considered [27, 33]. The oil separation method mainly utilizes the hydrophobicity and lipophilicity of microplastics by mixing sediment samples with oil and separating the microplastics by oil-water separation [34, 35]. However, this method requires further separation of the oil from the microplastics, which may affect the subsequent characterization of the microplastics and make the separation step relatively complex [36, 37]. The main principle of air flotation is to use air bubbles to suspend microplastics to the surface of the flotation solution [38, 39]. Microplastics have a special buoyancy due to their small density and hydrophobicity, and when the bubbles are introduced into the water, the hydrophobic interaction between the bubbles and the microplastics causes the microplastics to be carried to the surface of the solution. Subsequently, microplastics floating on the surface of the solution can be collected by overflows. Claessens produced flotation columns to separate microplastics from sediments in 2013, X. Zhu made improvements in the flotation column in 2015, but the results were not as good as expected, especially for the higher density microplastics, the recovery rate only reached about 52% or so [40, 41]. In these experiments, they used flotation columns made of PVC and added a salt solution of surfactant to the flotation solution, but did not reveal more specific details. The use of PVC flotation columns may be a key reason for the low recoveries, as we have found that microplastics are difficult to separate from the flotation column in solution due to hydrophobic interactions when using plastic flotation columns. Imhof also attempted to use froth flotation to separate microplastics from sediments, but the recovery rate was only about 55% or so for plastics 1-5 mm in size [42].

Despite these advances, existing sediment separation approaches still have several limitations, including incomplete recovery of relatively high density polymers, additional treatment steps associated with oil assisted extraction, and insufficient understanding of how surfactant properties influence microplastic flotation [37, 39, 43]. To address these limitations, an integrated froth-flotation device was developed in this study using a hydrophilic glass flotation column and an arched glass overflow tube to reduce microplastic adhesion and enable simultaneous flotation and collection. We hypothesized that effective microplastic flotation requires a balance between sufficient foam generation and preservation of microplastic hydrophobicity: while surfactants promote foam formation, excessive surfactant adsorption and wetting may weaken bubble microplastic attachment and inhibit flotation. APG was selected as the principal surfactant because of its biodegradability, foaming capability, and hydrophilic-lipophilic characteristics. Therefore, this study aimed to (1) develop an integrated froth-flotation system for microplastic recovery from sediment matrices; (2) evaluate the effects of airflow rate, APG concentration, particle size, and surfactant type on flotation behavior; and (3) explore possible surfactant-microplastic interaction mechanisms based on the observed flotation behavior and wettability-related parameters.

2. Materials and Methods

2.1. Experimental Materials

The experimental samples were prepared as shown in Table 1. After the sandy soil was washed repeatedly, 100 microplastics of 500 μm , 3 mm and 5 mm were mixed with 5 g of sandy soil to prepare sediment samples. Artificially prepared sandy sediment was intentionally used to provide a controlled experimental matrix and to minimize variability associated with natural organic matter, mineral composition, background microplastic contamination, and heterogeneous particle size distributions.

Table 1: Grain size, color, density and raw materials of self-made microplastics in the recovery rate experiment of different plastic types.

Polymer	Particle Size	Color	Materials	Density
PET	500 μm 3 mm 5 mm	Colourless	Drinking water bottle	1.36-1.40 g/cm ³
PVC	500 μm 3 mm 5 mm	Blue	PVC sheet	1.35-1.39 g/cm ³
PS	500 μm 3 mm 5 mm	Pink	Spoon	1.14-1.15 g/cm ³

PET, PVC, and PS were selected for the detailed flotation experiments because they represent polymers with different densities and surface properties. In particular, PET and PVC are relatively high density polymers that are difficult to recover using conventional saturated NaCl density separation, thereby providing suitable model materials for evaluating whether bubble-assisted flotation could overcome the density limitation of conventional separation. In the previous experiments, we compared the effects of density separation, oil separation and foam flotation on the separation of microplastics in sediments, and the results of the experiments showed that a small amount of separation of microplastics could be achieved by using a high density solution in the density separation process (Fig. S1). Subsequent optimization experiments also indicate that density separation can be applied to extract and separate low-density microplastics in the laboratory, but is not suitable for large-scale separation of microplastics (Fig. S2). The oil separation experiments showed that the separation efficiency was increased by the addition of oil (Fig. S3), but the efficiency was increased to about 99.5% after the introduction of air flotation separation in this system (Fig. S4), so this method can be used to investigate the abundance of microplastics, and it is not suitable for the qualitative study of microplastics in the environment. Under the tested laboratory conditions, the froth-flotation method achieved recovery efficiencies approaching 100% for the tested high density microplastics (Fig. S5), and the separation step was completed within approximately 2 min. Alkyl polyglucoside (APG), as a kind of green and completely biodegradable surfactant, guarantees the recovery rate in

the flotation process without pollution and with high efficiency, which can satisfy the quantitative analysis without affecting the qualitative analysis (Fig. S6). Therefore, the froth flotation separation method shows obvious advantages for the separation of microplastics in sediments. The following is the specific experimental procedure:

The prepared sediment samples were placed in the air-float column and then 500 mL of APG solution of different concentrations were added. Air was passed through the air pump for aeration, and with the help of hydrophobic interactions between microplastics and air bubbles, the air bubbles carried the microplastics to float up to the surface of the solution and formed bubbles. The overflowed foam was collected through a 0.45 μm filter membrane, after which the recovered microplastic particles were visually counted. Because a known initial number of relatively large and visually distinguishable microplastic particles was introduced into each experiment, direct particle counting was used to determine recovery efficiency (Fig. 1).

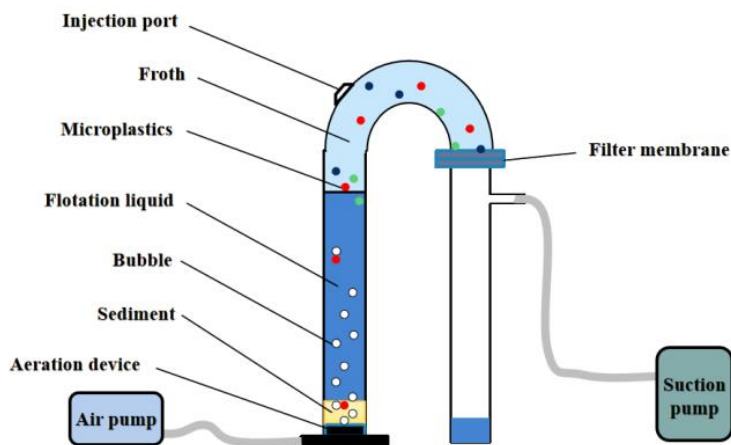


Figure 1: Foam flotation device.

2.2. Experimental Methods

The experimental conditions used in this study were established progressively through preliminary screening and sequential optimization experiments. Conventional density separation and oil assisted separation were first evaluated to identify their limitations, particularly for relatively high density microplastics. Air-assisted flotation was subsequently introduced, followed by optimization of airflow rate and surfactant concentration. The operating conditions used in subsequent experiments were selected based on the flotation performance observed during these preliminary tests.

2.2.1. Exploratory Experiments on the Effect of Air Flow Rate on the Flotation Effect of Microplastics

The prepared sediment samples were placed in the air flotation column at room temperature, and 500 mL of 0.05 g/L APG 0810 solution was added. The value of the aeration flow rate was changed to study the effect on the flotation effect of microplastics, and the completion of the flotation of microplastics within 5 s was used as the evaluation standard. Based on the preliminary airflow screening, 200 mL/min was selected for the subsequent experiments because it provided effective flotation while avoiding unnecessarily high airflow and excessive turbulence.

2.2.2. Effect of Different Types of APG Concentration on the Flotation Effect of Microplastics

In order to better assess the wetting effect between APG and microplastics, the time required for microplastics to rise to the upper layer of the liquid surface in the liquid was used as an evaluation index. When the required time exceeded 5 s, the APG concentration was considered to inhibit microplastic flotation, i.e., wetting. One hundred each of 500 μm , 3 mm, and 5 mm PVC, PET, and PS plastics were added to the separation device, respectively, and aeration was performed by passing 200 mL/min of air. The APG concentration was varied until the foam no longer overflowed. When the number of microplastics present in the liquid was 0, it was recorded as all the microplastics floated, and the time required for the microplastics to float was counted.

2.2.3. Effect of Different Types of Surfactants on the Flotation Effect of Microplastics

In order to better assess the wetting effect between APG and microplastics, the time required for microplastics to rise in the liquid to the upper level of the liquid surface was used as an evaluation index. When the time required for uplift exceeded 5 s, the APG concentration was considered to inhibit microplastic flotation as wetting. One hundred each of 5 mm PVC, PET and PS plastics were added to the separation unit and aeration was performed by passing 200 mL/min of air. The concentration of APG0814 was varied until the foam no longer overflowed. When the number of microplastics present in the liquid was 0, it was recorded as all the microplastics floated, and the time taken for the microplastics to float was counted.

2.2.4 Recovery Evaluation and Data Interpretation

Recovery efficiency was determined from the proportion of recovered microplastic particles relative to the known initial number of particles introduced into the system. The experiments were primarily designed for method development and operational screening rather than as a systematic independently replicated statistical study for all experimental conditions. Therefore, inferential statistical significance testing was not applied to the recovery data, and the reported near-quantitative recovery values represent the observed recovery efficiencies under the tested conditions.

3. Results and Discussion

3.1. Microplastic Contact Angle Test

To characterize the surface wettability of the selected polymer materials and provide descriptive information for interpreting their flotation behavior, contact-angle measurements were performed using a KRUSS DSA255 contact-angle meter. The measured contact angles are shown in Table 2 and Fig. (2).

Table 2: Contact angle size of different plastic types. The measured contact angles followed the order PET (99.1°) > PVC (95.1°) > PS (89.8°). These values are used here as descriptive indicators of surface wettability. Variability estimates were not available for the present contact-angle dataset; therefore, no statistical significance is inferred from the observed differences among the three polymers.

Polymer	PET	PVC	PS
Contact Angle/°	99.1	95.1	89.8

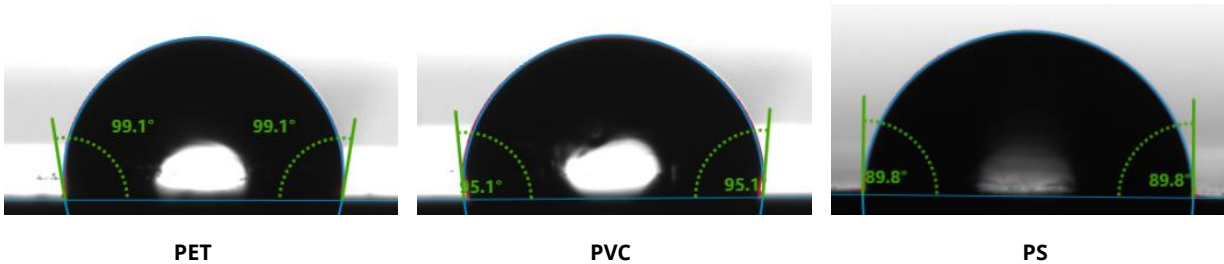


Figure 2: Contact angle test chart for different types of microplastics.

3.2. Influence of Air Flow Rate on Flotation Effect

From Fig. (3), it can be seen that the air flow rate has a certain effect on the flotation effect, with the increase of air flow rate, the uplift of microplastics in 5 s is the first to rise and then fall. The size of air flow affects the volume of bubbles in the flotation column, the distribution density and the degree of plastic tumbling [44]. When the air flow rate is small, the air bubbles in the flotation column are more stable, the distribution density is small, the turbulence degree is small, and the degree of plastic tumbling is small, which will lead to the microplastics not

being able to float in time. When the air flow increases, the more bubbles, the greater the distribution density, the greater the degree of turbulence, the greater the degree of plastic tumbling. This will lead to the plastic that has been floated and perhaps washed down by the tumbling bubbles, resulting in a decrease in the floating rate; and in the aeration flow rate of 150–800 mL/min, the floating rate of microplastics is the highest. In order to facilitate the follow-up test, it was decided to choose 200 mL/min ventilation flow rate as the experimental gas flow rate.

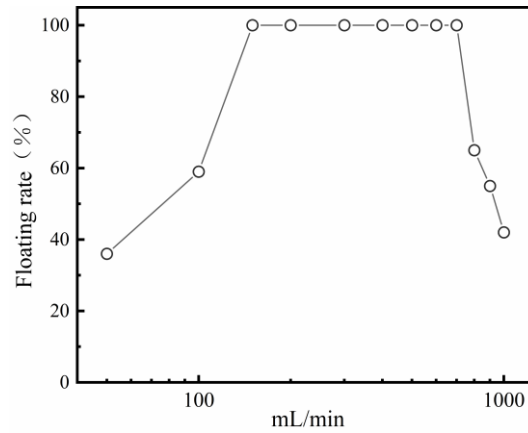


Figure 3: Influence of gas flow rate on flotation effect.

3.3. Effect of APG Concentration on the Flotation Effect of Microplastics

The flotation behavior of PET, PVC, and PS was evaluated separately at particle sizes of 500 μm , 3 mm, and 5 mm. Compared with previously reported sediment-flotation approaches, the present integrated system showed improved recovery under the tested conditions. Earlier flotation devices reported recoveries of approximately 52–55% for some microplastic fractions, particularly relatively high density particles, whereas the APG assisted system used in the present study achieved nearly quantitative recovery under the selected laboratory conditions. In addition, the integrated glass flotation configuration enables flotation and collection to occur within the same system, thereby reducing particle adhesion to plastic components and simplifying the recovery procedure.

During froth flotation, APG concentration influences the amount of froth and thus the recovery rate of microplastics separation. In order to investigate the minimum concentration of various types of APG surfactants for flotation of microplastics, 200 mL/min air was passed through for aeration.

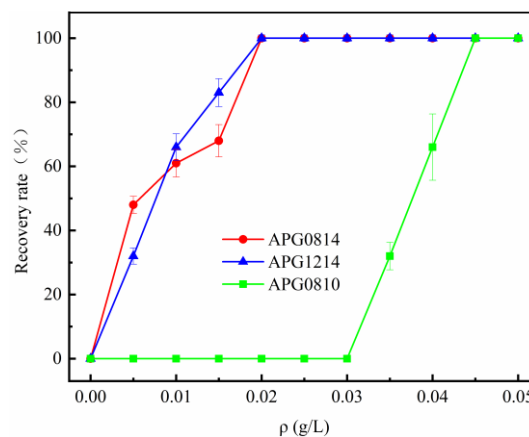
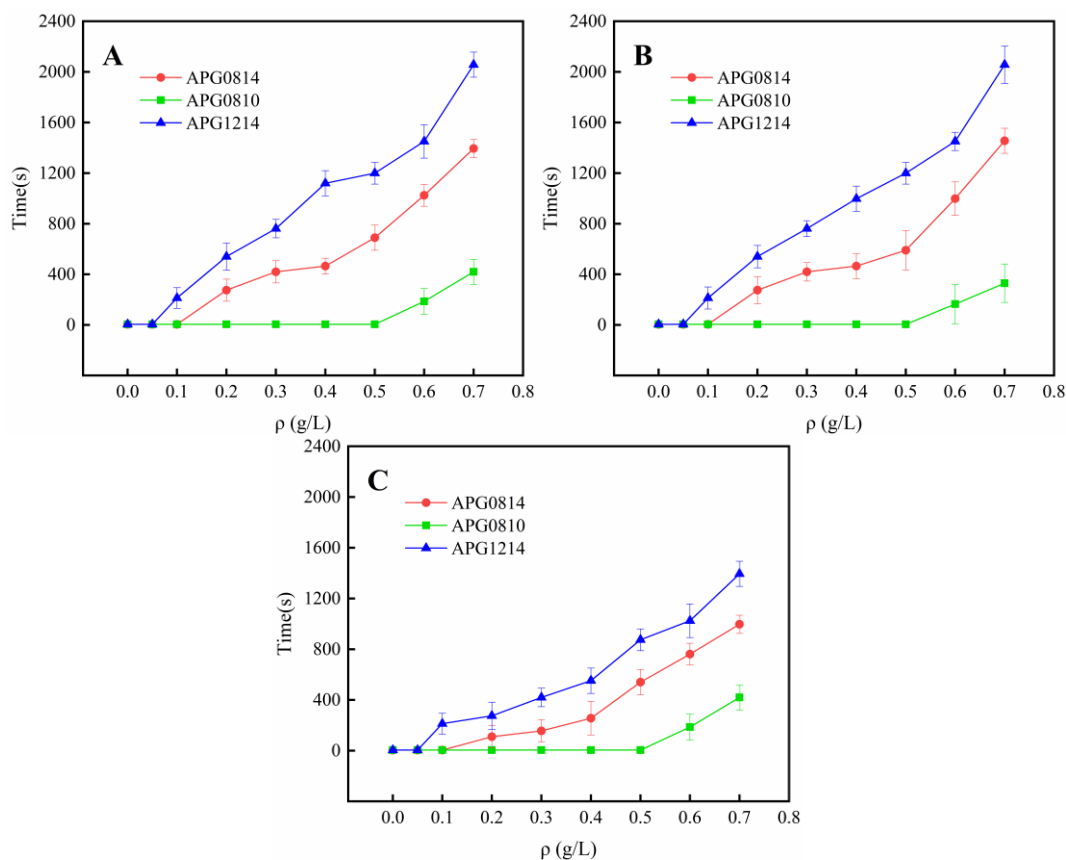


Figure 4: Relationship between concentration of different types of APG and recovery rate of microplastics.

One hundred 5 mm plastics of each type were added to the separation device and aeration was carried out by passing 200 mL/min of air. During this process, the air bubbles attached to microplastics floated up to the upper

layer of the solution and overflowed with the foam. With the increasing concentration, the ability of bubbles to carry microplastics gradually decreased. As can be seen from Fig. (4), before the concentrations of 0.05 g/L, 0.1 g/L and 0.5 g/L for APG1214, APG0814 and APG0810, respectively, the floating process of 5 mm microplastics could be completed within 5 s. In other words, its ability to float 5 mm microplastics could be completed in the same time. That is to say, its inhibition ability of 5 mm microplastic flotation recovery is: APG1214 > APG0814 > APG0810, and no difference was found between the inhibition points of APG solution on the flotation of three types of microplastics: PVC, PET and PS. However, the time for PS to complete upflotation was lower than that of PET and PVC, which may be due to the lower density of PS.

Plastic flotation methods can be roughly categorized into the following three types: chemically regulated flotation, physically regulated flotation and γ flotation. Theoretically, when the flotation system in the liquid surface tension value is located in the two different plastic materials between the wetting critical surface tension value, the flotation effect is optimal. The plastic with large surface tension will be wetted by the liquid or inhibited from floating, while the plastic with small surface tension value will not be wetted or not inhibited from floating, thus realizing plastic flotation separation, which is γ flotation separation. However, in the course of this experiment, no clear difference was observed in the flotation inhibition behavior of PVC, PET, and PS under the tested conditions. This may be due to the fact that the contact angles of the selected microplastic particles are similar and have not reached a point where a difference in wetting can be produced.

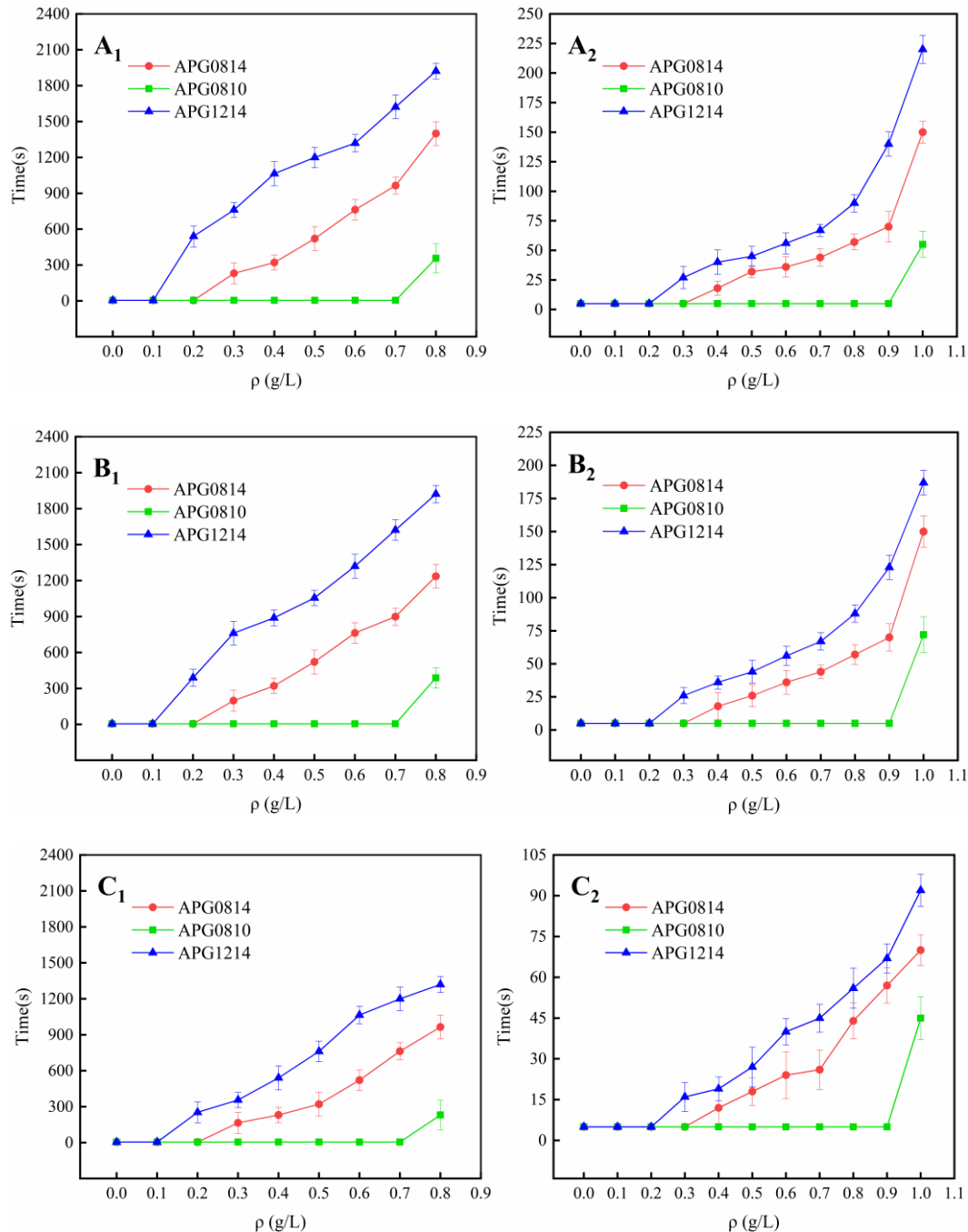


(A: 5 mm PVC; B: 5 mm PET; C: 5 mm PS).

Figure 5: Relationship between APG concentration and floating time of 5 mm microplastics.

One hundred 500 μm , 3 mm plastics of each type were added to the separation device and aeration was performed by passing 200 mL/min air. During this process, according to the results in Fig. (5), it can be observed that the flotation effect is similarly suppressed for smaller particle size microplastics as the APG concentration increases. Compared to the 5 mm plastic particles, in all three types of APG solutions, the flotation inhibition for 500 μm and 3 mm plastic particles occurs only after a certain concentration is reached. Specifically, flotation

inhibition of 500 μm microplastics occurred only after APG concentrations reached 0.2 g/L, 0.3 g/L, and 0.9 g/L, respectively, whereas inhibition of 3 mm microplastics occurred only after concentrations reached 0.1 g/L, 0.2 g/L, and 0.7 g/L, respectively. This suggests that there is a difference in the effect of microplastic particle size on APG concentration, with smaller particle size microplastics being more susceptible to inhibition by APG solutions with lower concentrations.



(A₁: 3 mm PVC; A₂: 500 μm PVC; B₁: 3 mm PET; B₂: 500 μm PET; C₁: 3 mm PS; C₂: 500 μm PS).

Figure 6: Relationship between APG concentration and floating time of 3 mm and 500 μm microplastics.

For the inhibition of microplastic flotation, we suspect that it is related to the critical micelle concentration (CMC) of the surfactant. Typically, conventional surfactants have a special molecular structure in which hydrophilic and hydrophobic portions are interconnected when their concentration reaches a certain level, resulting in the formation of a self-assembled micelle structure. The minimum concentration of this self-assembled structure is

known as the critical micelle concentration, i.e., the CMC value of the surfactant. The presence of this micellar structure may lead to complete wetting of the microplastics, thus affecting their flotation performance. The commonly used methods for the determination of CMC are: conductivity method and surface tension method [45, 46]. The surface tension method was used in this procedure to test the CMC values of different surfactants. The critical micellar concentration of the surfactant was determined to have been reached when its surface tension no longer decreased as the surfactant concentration increased. Subsequently, the surface tension of the three APG surfactants was tested and plotted in Fig. (6). It can be seen from the figure that the critical micelle concentrations of APG1214, APG0814 and APG0810 were near 0.04 g/L, 0.2 g/L and 1.4 g/L, respectively. In terms of the inhibited concentration of microplastic flotation, the inhibition of flotation of 500 μm microplastics occurred only after the APG concentration reached 0.2 g/L, 0.3 g/L and 0.9 g/L, respectively. Based on these results. Comparison of experimentally estimated CMC values with the observed flotation inhibition concentrations showed no consistent correspondence. These observations suggest that CMC alone may not determine the inhibition of microplastic flotation.

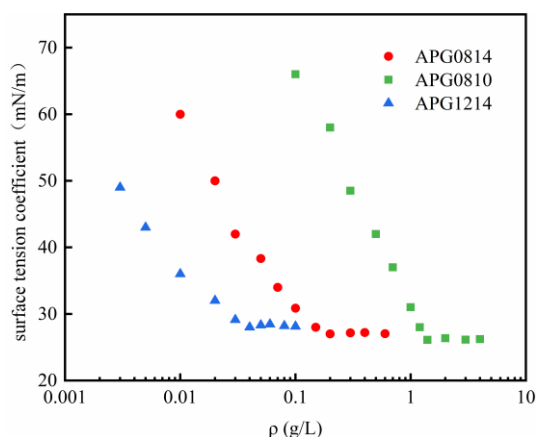


Figure 7: Surface tension coefficient of different APG concentrations.

In order to analyze the mechanism of surfactant flotation for microplastic wetting, the indicators of the three APG surfactants were plotted, as shown in Table 3. Among them, HLB value represents the hydrophilic-hydrophobic balance of the surfactant, which is used to measure the balance of size and strength between the polar and nonpolar groups of the surfactant, thus determining the degree of lipophilicity or hydrophilicity of the surfactant [47]. A larger HLB value represents more hydrophilicity, and a smaller HLB value represents more lipophilicity. In order to minimize the experimental error, three APG surfactants were selected for comparison. In the flotation process of microplastics interacting with APG, plastics possessing different groups showed relatively similar wetting behavior under the tested conditions. This may indicate that certain groups between different microplastic surfaces and APG surfactant molecules do not differ much in terms of hydrogen bonding and dispersion forces. On the contrary, the HLB value of APG largely influences the wettability of microplastics. Therefore, we can conclude that the main interaction between microplastics and APG surfactants is the hydrophobic interaction force. Without considering factors such as electrostatic forces, the smaller the HLB value, the stronger the lipophilicity and the stronger the wettability of microplastics.

Table 3: Performance indexes of different APG solutions.

Index	APG1214	APG0814	APG0810
Exterior	Light yellow paste	Light yellow liquid	Light yellow liquid
pH (50% aqueous solution)	11.5-12.5	11.5-12.5	11.5-12.5
CMC	0.04	0.2	1.4
HLB	10-12	13-15	15-17
structural formula	$\text{C}_{18}\text{H}_{36}\text{O}_6$	$(\text{C}_6\text{H}_{11}\text{O}_5)_n\text{OR}$	$\text{C}_{16}\text{H}_{32}\text{O}_6$

However, higher wettability of APG-type surfactants was observed for larger microplastic particles than for smaller particles under the tested conditions, which may be related to differences in the specific surface area of the microplastics. The specific surface area of microplastics increases as the particle size decreases, and a larger specific surface area indicates a stronger adsorption capacity, which also means that microplastics with smaller particle sizes are more difficult to be wetted. In addition, smaller microplastics require less time in the upwelling process, which may be related to the mass of the microplastics. At the same level of turbulence, smaller mass microplastics are more susceptible to turbulence and thus tumble to the upper layers of the liquid to achieve separation. These factors together influence the effectiveness of microplastic flotation, such that microplastics with different particle sizes show different responses to the wetting of APG surfactants (Fig. 7).

3.4. Effect of Different Types of Surfactants on the Flotation Effect of Microplastics

Having established that the HLB value of the surfactant was inversely related to the wettability of the microplastics, the effect of other types of surfactants on the flotation of 5 mm PVC was further tested. These surfactants included the biodegradable sophorolipid, the cationic surfactant cetyltrimethylammonium bromide (CTAB), and the anionic surfactants sodium dodecyl sulfate (SDS) and sodium dodecyl sulfate (SDBS). This study did not aim to exhaustively screen all commercially available nonionic surfactants. Instead, three APG formulations (APG1214, APG0814, and APG0810) were evaluated and further compared with a biodegradable biosurfactant, as well as typical cationic and anionic surfactants with varied physicochemical and ionic properties [48-50].

The experimental results are shown in Fig. (8) and Table 4 below. From the experimental results, it can be seen that different types of surfactants affected the flotation effect of microplastics to different degrees. This further verifies our previous conclusion that the wettability of surfactants is inversely related to their HLB values. The biodegradable acacia glycolipids showed strong wettability, similar to APG surfactants, which was favorable to the flotation effect of microplastics. On the other hand, the cationic surfactant CTAB and the anionic surfactants SDS and SDBS showed poor wettability and inhibited the flotation effect of microplastics.

Table 4: Different surfactants HLB and their inhibitory flotation concentration on 5 mm microplastics.

Index	Sophora Glycolipid	SDBS	APG1214	APG0814	APG0810	CTAB	SDS
HLB	9-12	10.638	10-12	13-15	15-17	15.8	40
Inhibition concentration (g/L)	0.05	0.8	0.05	0.1	0.5	0.1	1.0
Inhibition concentration (mol/L)	7.26×10^{-5}	2.29×10^{-3}	7.17×10^{-5}	1.43×10^{-4}	6.48×10^{-4}	2.74×10^{-4}	3.67×10^{-3}

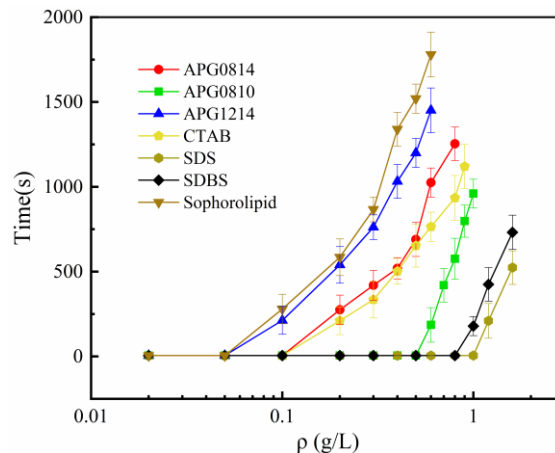


Figure 8: Effect of different surfactant concentrations on the floating time of 5 mm PVC.

As can be seen in Table 4, the HLB values of sophorolipid and APG1214 are similar. However, although the inhibited microplastic flotation concentration of sophorolipid was low (7.26×10^{-5} mol/L), the amount of foam generated by sophorolipid was not sufficient to support the upward flotation of microplastics before the inhibited flotation concentration was reached. This suggests that not all surfactants are suitable for the flotation of microplastics, and that the generation of sufficient foam volume and stability to support microplastic flotation also needs to be considered. Therefore, the acacia glycolipid solution cannot be used as a froth flotation agent for microplastics. Foam performance in this study was assessed operationally by its capacity to promote particle transport and overflow, without quantitative determination of foam height, drainage or lifetime. For this reason, foam stability is treated herein as an operational factor instead of a quantitatively validated mechanism.

On the other hand, the cationic surfactant cetyltrimethylammonium bromide (CTAB) had an HLB value of 15.8, and its inhibition of microplastic flotation concentration ranged from 2.74×10^{-4} mol/L. This indicates that CTAB has certain wettability in microplastic flotation, but requires a higher inhibition flotation concentration. The anionic surfactant sodium dodecyl sulfate (SDS) has a lower HLB value, but its inhibited flotation concentration is between 2.29×10^{-3} mol/L. This suggests that the wettability is not only related to the HLB value, but may also be affected by the chemical and charge properties of the surfactant. CTAB is a cationic surfactant, which exists mainly in the cationic form in solution. Microplastics are usually negatively charged and may be electrostatically charged in solution, enhancing wettability. On the contrary, SDS is an anionic surfactant, which exists mainly in anionic form in solution and may lead to electrostatic repulsion, reducing the wettability. Previous studies have reported that both microplastics and air bubbles may exhibit negative surface charge under aqueous conditions. Adsorption of ionic surfactants at the interfaces of bubbles and microplastics may thus help explain the observed flotation behavior (Fig. 9). Cationic surfactants may achieve favorable adsorption on negatively charged interfaces via electrostatic attraction, while electrostatic repulsion may hinder the adsorption of anionic surfactants. Such differences may affect attachment between bubbles and microplastics.

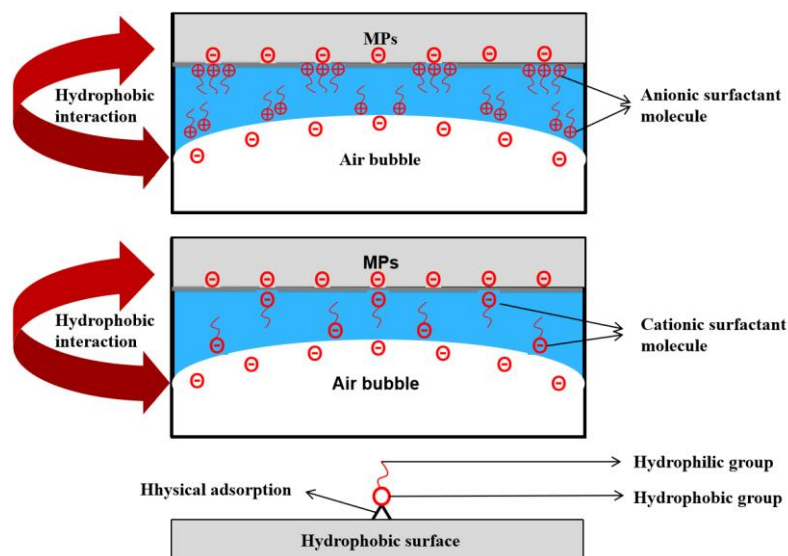


Figure 9: Proposed schematic representation of possible surfactant-mediated interactions between microplastics and air bubbles.

4. Conclusion

In this study, an integrated APG assisted froth-flotation system was developed for the rapid recovery of microplastics from artificially prepared sediment matrices. Under the selected laboratory conditions, the system achieved recovery efficiencies approaching 100% for the tested microplastics, including relatively high density polymers, while the separation process could be completed within approximately 2 min. The results demonstrate that airflow rate, APG concentration, particle size, and surfactant characteristics influence microplastic flotation behavior.

Increasing APG concentration altered microplastic wettability and, at sufficiently high concentrations, inhibited flotation. Particle size also influenced flotation behavior, with different inhibition thresholds observed for 500 μm , 3 mm, and 5 mm particles. Comparison among different surfactants further indicated that successful microplastic flotation requires both sufficient foam generation and favorable interfacial conditions for bubble particle attachment. HLB and surfactant ionic characteristics may contribute to these differences. The interfacial electrostatic interaction mechanism proposed in this work provides a reasonable theoretical interpretation for the observed surfactant-dependent flotation behavior.

In summary, the integrated APG-assisted froth-flotation strategy exhibits prominent advantages in terms of rapidity and recovery performance for microplastic remediation under controlled experimental conditions, demonstrating great application potential for sediment microplastic purification. This work focuses on methodological exploration and parametric optimization using artificially prepared sediment samples to eliminate the interference of complex environmental factors and clarify the core flotation mechanism. On the basis of the present findings, future research will focus on further verifying the applicability of the method in natural sediment environments, quantitatively characterizing foam performance, refining interfacial interaction mechanisms, and supplementing systematic statistical analysis, so as to further improve the stability and practical applicability of the proposed microplastic recovery technology.

Conflict of Interest

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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Availability of Data and Materials

All data generated or analyzed during this study are included in this published article.

Author's Contributions

Jinghui Wu: Investigation, Formal analysis, Resources, Writing - Original Draft.

Yidi Gao and Guanqiao Li: Investigation, Formal analysis.

Xinyuan Li and Yiming Wang: Investigation.

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