SILICONE-COATED ALUMINA HOLLOW FIBER MEMBRANES FOR SUSTAINABLE MICROPLASTIC SEPERATION IN WATER SYSTEM

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Abstract. Microplastic (MP) pollution represents a new wave of some of the most devastating environmental stressors, with such an impact on aquatic environment degradation, food chain contamination, and human health. Conventional filtration techniques are ineffective toward smaller MPs; hence there is a dire need for advanced methods of filtration. The present study fabricates and evaluates silicone-coated alumina hollow fiber membranes (AHFMs) by curing temperature variation, membrane configuration variation, and flow rate conditions variation. Contact angle analyses found that the curing at 60°C optimized rapid water interaction and at 70°C gave stable hydrophilicity which can be used for long-term applications. Multi-membrane configurations greatly improve water throughput validating surface area expansion that does not compromise MP separation. Flow rate variations influenced how much volume was collected but did not influence separation efficiency since all tested modules demonstrated complete removal of MPs. This puts a seal on the noticeable increase in durability and antifouling performance of AHFMs with silicone coatings, hence their ability to work perfectly well under diverse hydraulic conditions. The results prove that productivity is actually a function of operative conditions while selectivity lies within the material property as engineered. That places silicone-coated AHFMs as an accessible technology toward community-based purification systems up to industrial wastewater treatment plants. Apart from bringing membrane science one step closer, this study also plays its share in the Sustainable Development Goal 6 by offering an upbeat, resilient, and sustainable technology for mitigating global water contamination by microplastics.

Keywords: *microplastics, hollow fiber membranes, silicone coating, hydrophilicity, water treatment*

Introduction

Microplastic pollution of water represents an important global ecological crisis in consideration of its effects on the aquatic environment and the health hazards it imposes on humans. Microplastics can be defined as plastic particles less than 5mm in size that are found in water bodies like rivers, lakes, or seas. These mainly originate from larger plastic debris breaking down, synthetic fibers shed during washing clothes, and microbeads used in personal care products (Brooks et al., 2023). What is more frightening is the scale of water contamination by microplastic; research has found these plastics not only in drinking water but also in seafood and even table salt (Koelmans et al., 2019). The current filtration systems cannot extract smaller-sized microplastics due to their size. There is a strong need for an efficient and sustainable separation technology. Ceramic-based, especially those made of alumina, membrane filtration technologies are effective when applied to wastewater because they possess good strength, are less attacked by chemicals, and give high separation efficiency. The

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introduction of alumina hollow fiber membranes coated with silicone is highly hopeful toward the solution for problems associated with water microplastic pollution. The major problem identified in this study is that water treatment systems are not very efficient at removing plastics, especially those smaller than 5mm. Plastics of different sizes and from various sources, including urban runoff and wastewater treatment plants, cannot be filtered out because proper filtration has yet to be conducted and the steps being used presently do not support traditional filtration (Hasni et al., 2023). Though several filtration techniques have been used, Plastic of the smallest size is not adequately trapped by most of the existing systems. Thus, water still gets contaminated. The problem is double since plastic accumulation in aquatic environments keeps increasing. It is hazardous to both the environment and human health. So, the problem is to come up with a good filter that can take out microplastics of all sizes and densities from water. This study tries to solve this problem by making alumina hollow fiber membranes better with silicone coating which should make them work faster.

The hypothesis of this study is that a silicone-coated hollow fiber membrane made from alumina will provide an efficient and durable separation of wastewater and microplastics. It is assumed that by coating the surface with silicone components, hydrophilic properties will be generated, thus enhancing the capability for efficient separation of microplastics while keeping durability against fouling. Variables that will be used in testing this hypothesis are curing temperatures, membrane configurations-single, double, and triple membranes-and flow rates. The hypothesis can best be described as the expectations that, upon optimization of all variables under study in this research, a highly effective yet scalable method to remove microplastics from water sources would be obtained. This study shall be guided by the following objectives: (1) To synthesize alumina hollow fiber membranes coated with silicone by varying drying temperatures as a way of optimizing hydrophilicity and performance of membranes in the separation of microplastics; (2) To determine the effect that the number of alumina hollow fiber membranes has on the efficiency, on which microplastic/water separation can be performed; i.e., how the filtration capacity is impacted; (3) To study how well microplastic/water separation works by changing the flow rate in the alumina hollow fiber membrane module, with the goal to find the best flow rates for good separation. These goals seek to beat the weaknesses of present filtration ways and boost the efficiency of alumina hollow fiber filters in taking microplastics out of water. The study will give useful clues about how membrane setup and working factors help improve filtering systems.

Literature review

Microplastic contamination and its environmental impact

One of the most critical environmental issues that have developed in recent years is pollution by microplastics, and it is an issue most prevalent within aquatic environments. Microplastics are generally defined as plastic particles less than 5 mm in size and pose threats to both environmental and human health. They are known to be significantly dangerous pollutants with diverse origins that include the degradation of large plastic wastes, primary microbeads from personal care products, and synthetic fibers from clothes (Brooks et al., 2023). The abundance of such microplastic water pollutants in river bodies, lakes, and the oceans all over the world raises concern for marine biology as well as food chains. Scientific findings already showed evidence where microplastics had accumulated inside the alimentary canal of aquatic organisms causing them physical harm directly lowering their reproductive ability as well as providing a pathway for chemicals contained within plastics to enter the human food chain via seafood (Koelmans et al., 2019). Studies on microplastics in drinking water have also indicated shocking levels, since in bottled water and tap water microplastics were found, showing how pervasive this problem is. Because of the environmental and health hazards that microplastics pose, it leads to a call for immediate research about effective removal methods particularly in wastewater treatment systems where current filtration technologies are inadequate. It is from the literature that existing traditional methods focus more on larger particle capture; however, microplastics evade the normal filtration due to their small size and as well as their varying densities.

Advancements in membrane filtration for microplastic removal

Filtration is one of the promising technologies as it attracts a great deal of attention in removing microplastics since it ensures high efficiency in separation. Ceramic-based membranes are particularly applicable for water treatment as they possess some advantageous features such as strength, chemical resistance, and providing the facility to separate different types of pollutants; microplastics included (Lee et al., 2015). Alumina hollow fiber membranes have brought great hope in microplastic filtration due to their fouling resistance compared to other available membranes, which is one of the problems related to membrane filtration (Hakami et al., 2020). The ceramic membranes have also delivered improved performance under aggressive conditions versus polymeric membranes that had shown more vulnerability towards decomposition. Membranes based on alumina with their strong structure serve significant importance in wastewater applications specifically desalination and oil-water separation industries for removing microplastics from wastewaters (Robert et al., 2023). However, challenges exist with using hollow fiber alumina membranes for microplastic removal. They do very well in getting rid of suspended solids but smaller microplastics can foul them reducing the efficiency of filtration and making it less effective over time (Yin et al., 2023). Scientists have so far taken steps toward the direction of optimally designing these membranes by modifying their surface properties to increase hydrophilicity and decrease fouling as well as improving capacity to filter microplastics effectively (Lee et al., 2015). However, more studies are required concerning optimization of these membranes for large-scale applications in wastewater treatment plants that always contain a high concentration of microplastics.

The role of silicone coatings in enhancing membrane performance

Silicone coatings have proven to be one of the most viable alternatives in increasing the performance efficiency of alumina hollow fiber membranes when applied on hydrophobic and fouling resistance efficient membranes. It provides enhanced membrane efficiency as well as durability during an application involving microplastic separation. Chemical degradation, mechanical wear, and inorganic fouling resistance were increased by silicone coating in a membrane making it applicable for long-term uses (Alessandro and Macedonio, 2025). More hydrophilic surfaces were achieved by some recent researches which tried different silicone coating techniques to optimize surface properties of alumina hollow fiber membranes targeting higher water permeability and consequent better efficiency regarding microplastics removal (Sun et al., 2021). The interaction between the water molecules themselves and the coated surface is here considered important because filtration efficacy is mostly based on contact angle wettability, where faster water reaction promotes filtration being desirable for high filtration efficiency (Acarer, 2023). Silicone coatings will particularly enhance in the aspect concerning the fouling problem since it is mainly contamination that sticks on the surface, which will include microplastics and all other contaminants. Challenges that have been raised by literature regarding applying silicone coatings are curing temperatures that need to be optimized and might change the structure of the membrane. Therefore, notwithstanding these challenges, the development constitutes a great leap forward in membrane technology for microplastic filtration with generalization potential over a wide range of applications from industry to municipalities.

Materials and Methods

In the methodology, materials play an important role in achieving efficiency as well as the sustainability of the microplastic separation system. Alumina hollow fiber membranes, being the main filtration medium, were selected because they possessed high mechanical strength and chemical resistance coupled with their ability to work well under extreme conditions (Lee et al., 2015). Filtration applications generally respect Alumina membranes for their robustness specifically towards fine particle separations which normally are quite difficult to attain through ordinary means of filtration (Hakami et al., 2020). Silicone is selected as a coating material on alumina membranes in order to increase hydrophobicity so that fouling resistance can be increased. The silicone coating shall be applied to the membrane so that surface properties can be enhanced together with ensuring durability and efficiency of the membrane during application for water treatment (Sun et al., 2021). The equipment used in this work, namely the water pump, acrylic tube, and analytical balance strongly support accuracy with consistency during fabrication and testing. The water pump allows for a steady flow of water going through the filtration setup; the acrylic tube acts as housing for alumina hollow fiber membranes providing proper sealing that leads to function very well. An analytical balance provides exact weighting of microplastic solutions used in the tests so that test reliability may be maintained and repeatability ensured. *Table 1* details the key supplies and tools that were applied in all steps of the experiment. The broad variety of supplies guarantees the accurate making of the membrane unit and helps in the managed test of microplastic splitting.

***Table 1**. Materials and apparatus used in the study.*

No.	Materils and apparatus	Quantity
1	Alumina hollow fiber membrane	6
2	Silicone	20 ml
3	Brush	1
4	Microplastics solution	1 L
5	Clear hose pipe (small, medium, large)	2 meters
6	Water pump	1
7	Acrylic tube (25mm diameter)	21 cm
8	Glue	10 ml
9	Filter paper and filter funnel	1
10	Acrylic board	1
11	Cutter	1

12	Analytical balance	1
13	Mini grinder	1
14	Beaker	1

Preparation of alumina hollow fiber membranes coated with silicone

The process of making alumina hollow fiber membranes covered with silicone is key to this work since the cover greatly boosts the hydrophilic traits of the membranes. Cleaning the membranes with acetone, as seen in *Figure 1*, takes away dirt and makes sure the cover sticks well. This step is very important because dirt on the membrane can ruin the quality of the silicone layer which has a direct effect on filtration performance (Alessandro and Macedonio, 2025). After cleaning, the membranes get a coat using a brush, making sure there is an even spread of silicone. The curing steps shown in Figure 2 are also very important for getting the right membrane features. By changing the curing heat (50°C, 60°C, and 70°C) they test what effect heat has on membrane work from hydrophilicity and filtering ability. *Figure 1* is the cleaning process is very important for removing any kind of contamination and readying the membrane surface for coating with silicone. This process occurs in the same place where the picture has been drawn. *Figure 2* is the silicone coating also takes place at that particular location and after this curing at different temperatures, this material would provide us with maximum hydrophobic properties as well as mechanical strength that it can render.

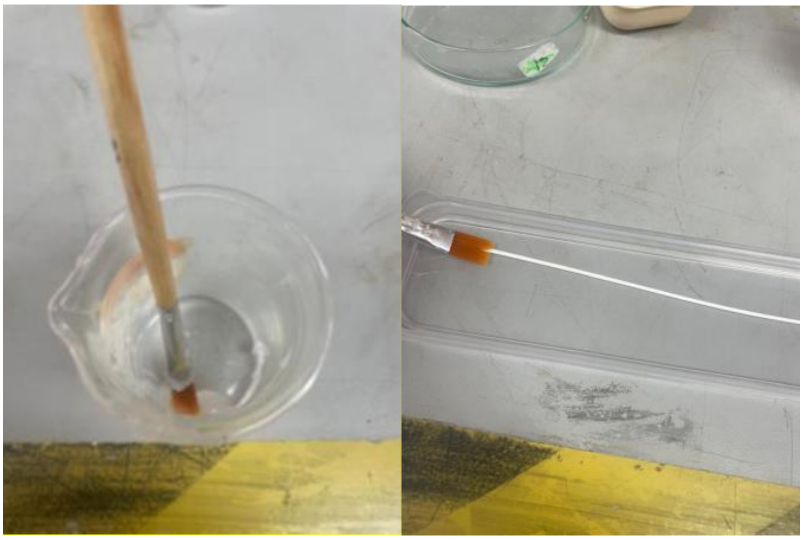


Figure 1. *The process of cleaning alumina hollow fiber membrane with acetone.*

Figure 2. *The process of applying alumina hollow fiber membrane with silicone and curing process using oven.*

Membrane characterization

The efficiency of the silicone layering can be determined by contact angle analysis, and this study refers to how hydrophilic those membranes are. A pictorial representation of contact angle measurement is shown in *Figure 3* such that it describes a change in angle between the surface of the membrane and a water droplet with time. That contact angle gives an exact criterion for how easily water can interact with the membrane and a lower angle usually means more hydrophilicity which is required for efficient microplastic filtration (Domergue et al., 2023). The testing involved membranes cured at different temperatures, hence offering to describe which curing temperature might be termed best to reach optimal filtration performance. These measurements would be very instrumental in choosing that particular membrane that offers interaction with water best toward enhancing general efficiency in microplastic removal. Figure 3 gives an idea of how the contact angle measurement is carried out because hydrophilicity and the efficiency of the coated membranes depend on it.

Figure 3. *The process of contact angle analysis.*

Preparation of membrane module

The next step is very critical. It involves putting together the membrane module with an acrylic tube of 25mm diameter as shown in *Figure 4*, resulting in three setups: single, double, and triple membrane arrangements. The number of membranes is varied to see its effect on the system's separation performance. RTV silicone is used for making a watertight seal; therefore, no leakage occurs during filtration. After assembling the module, leave it to cure for about 24 to 48 hours since curing is a prerequisite for testing so that the integrity of the module can be maintained during testing (Yin et al., 2023). At this stage also here one should test his/her module for leakage by ensuring that under experimental conditions it works optimally. The illustration of the module membrane made up of alumina hollow fiber in Figure 4 makes sure how important securing them is because if they are not well secured, leakage will occur and filtration will never take place.

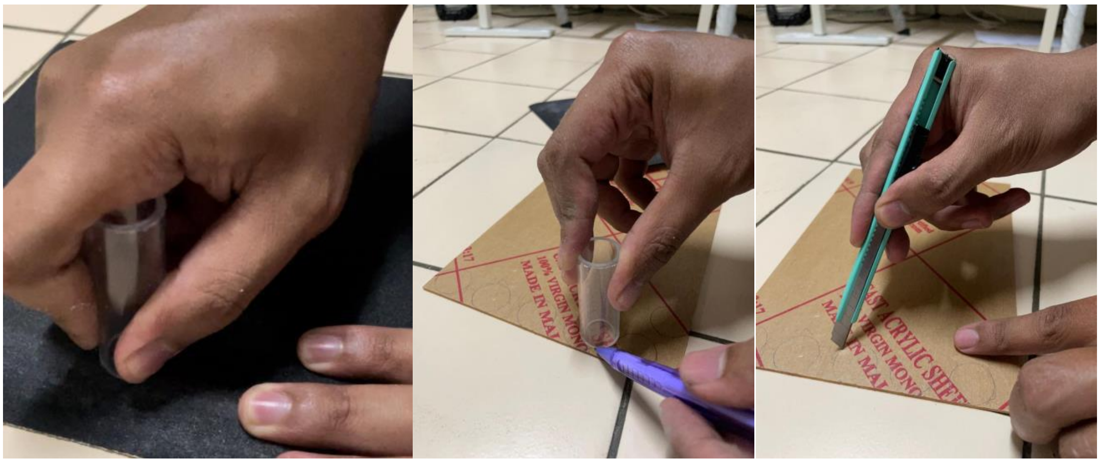


Figure 4. *The process of preparation of the membrane module.*

Preparation of microplastic solution

To simulate real-world water pollution, a microplastic solution is prepared by grinding plastic bottle caps and then sieving the particles until microplastics less than 5mm are obtained as illustrated in *Figure 5*. This solution is mixed with distilled water so that a concentration of 10g/L is attained and used to test the membrane's capability in filtering microplastics. The preparation of the microplastic solution is an important step toward ensuring filtration tests are relevant because this has to be similar to those found in wastewaters (Brooks et al., 2023). *Figure 5* shows the process of preparing the microplastic solution by grinding and sieving plastic particles. This comes closer to a real-world scenario where water gets contaminated with microplastics.

Figure 5. *The preparation of microplastics.*

Performance testing of alumina hollow fiber membrane for microplastic separation

Performance is tested by the amount of water collected after running for five hours straight. In this experiment, tubes with different sizes are used to help adjust the flow rate as shown in Figure 6. It can be seen that there exists a direct relationship between the quantity of membranes and volumes of water collected wherein maximum throughput is achieved using a three-membrane configuration. The study evaluates how well microplastics can be separated by checking for any leftover microplastics in the collected water which proves that alumina hollow fiber membranes do work when it comes to removing microplastics. *Figure 6* shows three different membrane configurations in order to analyze the effect that the number of membranes may have on the performance of the filtration system.

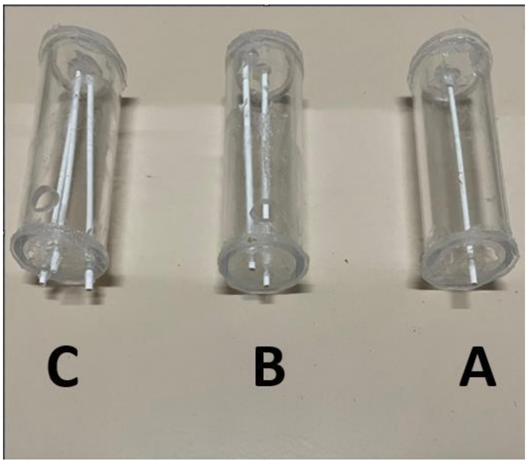


Figure 6. *Three Types of Alumina Hollow Fiber Membrane Modules A, B, And C.*

Results and Discussion

This study discussed the fabrication and performance evaluation of alumina hollow fiber membranes (AHFMs) which were extracted in the process of rejecting MPs from water with silicone coating, under curing temperature optimization, a number of membranes in a module, and flow rate influence on the overall separation performance. It is thus through these three factors, curing conditions, membrane configuration, and hydraulic operation: that an understanding can be based on how efficiency can not only be brought about but also how it can practically be applied when using AHFMs for water purification. The making focused on putting silicone coatings for better strength, fouling resistance, and chemical stability. Though AHFMs are naturally hydrophilic, coating with silicone gave improved wear resistance and running life. The study also looked at the effects of changing curing temperature on surface hydrophilicity, scaling the number of membranes on throughput as well as varying flow rates on both water volume and MPs separation. The hydrophilicity of the silicone-coated AHFMs cured at 50°C, 60°C, and 70°C for 2.5 hours was determined by contact angle (CA) measurements. The wetting of the membrane material by water is crucial in discussing its permeability to water as well as its fouling resistance and efficiency in retaining MPs (*Table 2* and *Figure 7*). The results show a much defined trend: (1) 50°C curing initiates with moderate hydrophilicity and so on and so forth; (2) 60°C gives the fastest improvement in hydrophilicity, therefore suitable for application within short periods and at high intensities; (3) 70°C gives the lowest final CA-meaning stable hydrophilicity, that is desired for long-term applications. Recent reports indicate that intermediate curing develops reactive surface while higher curing temperatures stabilize hydrophilic behavior due to stronger cross-linking validate these findings (Liu et al., 2023; Yuan et al., 2023).

***Table 2**. The result and analysis of sample A, B and C by using contact angle.*

Sample Name	Trial	A	B	C	D	E	F	G	H	I
Sample A (50°C)	1	101.02	104.97	97.60	100.86	3.415	4.119	1.138	0.632	1.373
	2	112.37	108.64	3.733	1.244					
	3	104.49	100.00	4.490	1.497					
	4	112.66	108.71	3.950	1.317					
	5	94.33	89.33	5.007	1.669					
Sample B (60°C)	1	112.54	109.01	109.20	103.50	3.353	5.507	1.118	3.650	1.835
	2	111.34	104.45	6.895	2.298					
	3	109.71	107.32	2.398	0.799					
	4	107.28	95.99	11.287	3.762					
	5	104.15	100.55	3.600	1.200					
Sample C (70°C)	1	94.16	100.39	90.61	96.27	3.550	4.143	1.183	0.399	1.381
	2	98.48	94.21	4.269	1.423					
	3	103.72	99.79	3.938	1.313					
	4	106.89	102.37	4.519	1.506					
	5	98.70	94.26	4.438	1.479					

Note: A=Initial CA (°); B=Initial Average CA (°); C=Final CA (After 3 min) (°); D=Final Average CA (°); E=Change in CA (°); F=Mean Change in CA (°); G=Rate of Change per Minute (°/min); H=Standard Deviation (CA Change); I=Rate of Change per Minute (°/min).

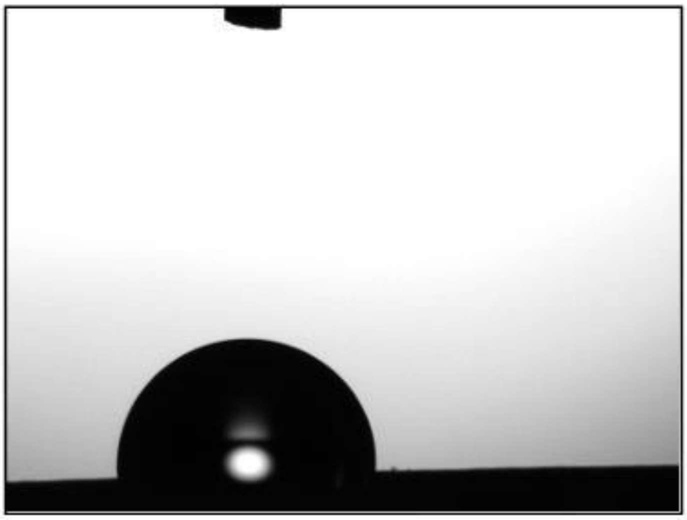
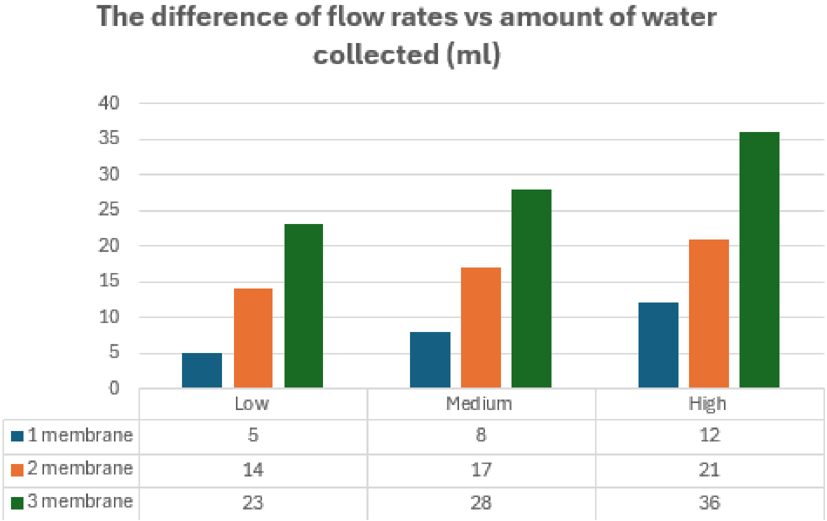


Figure 7. *The contact between water and alumina hollow fiber membrane test.*

Evaluation of flow rate and water retention

Flow rate, and module setup were done with 1, 2, and 3 membranes at low, medium, and high flow rates. It is quite apparent that increasing the number of membranes and increasing the flow rate increases throughput. Maximum yield was obtained at high flow for a three-membrane module which was 36 mL whereas it gave only 5 mL for a single membrane at low flow. This scaling effect surfaces area expansion imperative for productivity improvement as found in other studies related to hollow fiber configuration (Zhang et al., 2022; Gao et al., 2019). However, the experiment's dependence on tube size to simulate flow rates introduces a variance compared to the pressure-driven pumps normally used in industry. As noted by Rocamora et al. (2022), controlled hydraulic pressure is what is needed for a proper assessment of flux dynamics and fouling behaviors. Even with this limitation, the trend that has been observed goes on to prove how plausible multi-membrane modules are when applied particularly in an upscaling system, capacity of water treatment systems (*Figure 8*).



	Low	Medium	High
🟦 1 membrane	5	8	12
🟧 2 membrane	14	17	21
🟩 3 membrane	23	28	36

Figure 8. *Relationship of flow rates and number of membrane vs amount of water collected (ml) graph.*

Microplastic separation performance

The main result in all experiments was that no MPs could be found in the filtered water at any curing temperature, number of membranes used, or flow rate applied. This already speaks much for high selectivity maintained by silicone-coated AHFMs since it allows passage of water molecules while effectively retaining MPs. This result implies that the hydrophilicity of the membranes has been maintained by coating them with silicone, allowing water flux to be accompanied by the rejection of MPs. It is in line with recent works on polymer-coated ceramic membranes which assert increased anti-fouling resistance without any compromise on selectivity (Kumar et al., 2023; Zhang et al., 2021). Lab conditions made it work very well. Real wastewater has much more complex organic matter, oils, and even smaller plastic pieces that may challenge long-term stability. So yes, it is promising but let’s run those membranes through some real-world effluents before we start thinking about scale-up and robustness (Acarer, 2023).

The combination of findings proves that: (1) Curing temperatures have a strong hydrophilicity and durability relation; (2) Throughput scales directly with the number of membranes proving the need for multi-membrane configurations to show efficiency; and, (3) Yield is a function of flow rate but not separation therefore proving the robustness of the system since it would be yield and not quality that varies. This makes silicone-coated AHFMs a possible practical adjustable solution for MPs removal, changeable from low resource settings by simple pumps up to industrial applications requiring pressure-driven systems. At a broader level, results attest to the interlink between all three objectives. Hydrophilicity improvement through optimization of curing temperature (Objective 1) comes together with the strength of durability, which in turn would support upscaling the number of membranes in a module (Objective 2). For example, since membranes cured at 70°C and hydrophilicity remain stable are more applicable for multi-membrane configuration where long-term durability under increased hydraulic loads is required. On the other hand, membranes cured at 60°C show more rapid water interaction will be very effective when coupled with higher flow rates (Objective 3), allowing even faster throughput without compromising selectivity. In this manner, current work places emphasis on aligning fabrication conditions with operational requirements as recently principled in membrane engineering literature (Omar et al., 2024; Ebrahimi et al., 2022).

Another key takeaway between the objectives is the throughput-selectivity relation. Increased recovered water volume with more membranes at higher fluxes is clearly an efficiency gain, whereby the fact that MPs removal stays high for all conditions tested proves that it is material and surface chemistry which are optimized under Objective 1 that are responsible for defining separation efficiency. This implies that once membranes are engineered to attain hydrophilicity as well as stability on optimum levels, productivity becomes a function of flow rate and module size, thereafter leaving selectivity to be determined by these two operational variables. Practically speaking, this finding means that Silicone-coated AHFMs can be designed benevolently for both small-scale community water filters and large-scale industrial wastewater plants by only changing module size and flow configurations without having to change the membrane chemistry itself (Rocamora et al., 2022; Zhang et al., 2022). In overall, the results reinforce the scalability and sustainability potential of this technology. Since it has been demonstrated that MPs removal is not a function of any particular mode of operation, it speaks volumes about the robustness of the membranes when applied in real-life situations where ideal conditions may never be obtained. For instance, there are always variations in flow rates in community-based water purification systems since pumps seldom operate at their rated capacities or water is drawn at different rates. Industrial effluent can also vary both in volume and particle load. From an SDG 6 perspective, Clean Water and Sanitation, having AHFMs consistently rejecting MPs under all forms of operational stress would speak more to resilience. The three objectives taken together say as much about scientific progress in optimizing materials as they do about social or environmental relevance when applied to what is arguably one of the most urgent global problems, plastic pollution of water bodies.

Conclusion

This study finds that silicone-coated alumina hollow fiber membranes (AHFMs) can present a radically new approach to the stubborn problem of microplastic (MP) contamination in aqueous systems. The findings provide information on the relationship between material science, system design, and operational conditions defining performance by curing temperature optimization, multi-membrane module configuration, and flow rate effect assessment. More specifically, the result found out that curing temperatures largely define hydrophilicity and membrane robustness: at 60°C curing condition that allows quick interaction with water; 70°C curing condition creates stable hydrophilicity which is known as needed for use in the long run. Directly advancing Objective 1 results show that fabrication conditions have to be optimized for the application intended, either short-term high-intensity operation or long-term industrial setup. Likewise, the effect of increasing the number of membranes (Objective 2) validated that surface area extension permits very great enhancement of throughput without any compromise on separation efficiency, which is a finding standing in line with global trends when scaling membrane technologies. Flow rate adjustments (Objective 3) disclosed further that while throughput can be altered, selectivity of the membranes for MPs stays the same, hence emphasizing robustness plus reliability of this particular system under different hydraulic conditions. These results validate the assumption that silicone coating makes AHFMs more effective plus durable and at the same time proves its scalability across all applications in water purification contexts.

More crucial is the fact that the broader implications of this research would play above laboratory validation in the very pressing environmental and societal conversations relating to water security and pollution control. All test conditions consistently result in getting filtered water free from MPs, pointing toward the possibility of these membranes coming into accommodation under a viable, resilient pathway towards attaining elements of Sustainable Development Goal 6: Clean Water and Sanitation. The interlink between those three objectives describes how once membranes are engineered to optimal hydrophilicity versus stability, productivity becomes an issue based on operational flexibility rather than the need for any form of chemical redesign. This thus situates silicone-coated AHFMs as highly flexible material suitable from low-resource community-level purification systems dependent on simple pumps up to high-capacity, pressure-driven industrial-scale wastewater treatment plants. The scale and strength we prove here is not for purely academic material optimization but rather shares some insight into the very real, very pressing world problems of microplastic pollution. This work insists, however, that scientific novelty be coupled with environmental sustainability and public health interests; consequently, it opens a pathway for membrane technology to move forward beyond laboratory curiosity toward becoming an integral part of an international strategy for cleaning water.

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Conflict of interest

The authors confirm that there is no conflict of interest involve with any parties in this research study.

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