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Development Upcycled Styrofoam/Activated Carbon Composite Membranes for High-Efficiency Microplastic Retention

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Abstract. Styrofoam waste presents as a persistent environmental hazard due to its resistance to natural degradation and the toxic emissions associated with conventional incineration. Concurrently, microplastic contamination in freshwater ecosystems poses growing ecological and human health risks. In this study, waste Styrofoam was upcycled into flat sheet composite filtration membranes integrated with powdered activated carbon (74 μm) for water filtration and microplastic removal. Composite membranes were fabricated on a nonwoven fabric substrate by varying Styrofoam binder concentrations (5, 7, and 9 wt.%) and PAC filler loadings (0, 4, and 8 wt.%). The filtration performance was evaluated using synthetic wastewater containing microplastics (3 g/L, initial turbidity of 811.5 NTU). While the bare nonwoven substrate exhibited poor separation efficiency (1.04–1.22% rejection; permeate turbidity of 801.6–803.1 NTU), all Styrofoam/PAC composite membranes achieved complete turbidity clarification (0.0 NTU, 100% nominal turbidity rejection), satisfying national drinking water standards. Morphological characterization and gravimetric Total Suspended Solids (TSS) retention analyses demonstrated that increasing Styrofoam concentration progressively sealed the porous nonwoven network to establish a continuous polymer film. Meanwhile, the addition of PAC effectively filled microscopic voids within the polymer matrix, increasing surface density. Among the tested formulations, the 9 wt.% Styrofoam / 8 wt.% PAC composite demonstrated the highest microplastic retention capacity, removing an average of 391.10 mg/L (peaking at 463.3 mg/L), corresponding to 13.0% of the initial mass loading. Digital microscopic analysis confirmed that the composite membrane captured microplastics across a size spectrum ranging from fine particles of 1 μm to coarse fragments up to 4910 μm . These findings demonstrate a feasible method for up-cycling Styrofoam waste into functional filtration membranes for freshwater filtration.

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Keywords: Waste upcycling, Styrofoam, Powdered activated carbon, Composite membrane, Microplastic removal, clean water.

1 Introduction

Access to safe drinking water is a basic human rights, yet the world's freshwater systems are increasingly threatened by growing populations and industrialization [1-3]. As of 2022, approximately 2.2 billion people failed to manage their drinking water [4-5]. One of the key determinants of safe drinking water is the turbidity it represents, which represents clarity influenced by suspended clay, silt, and organic matter. In Indonesia, the national standard for drinking water turbidity is strictly regulated at a maximum of 3 Nephelometric Turbidity Units (NTU) [6]. Despite these regulations, surface water particularly rivers as the primary source of raw water often exceed permissible limits due to untreated industrial discharges [7].

Of the persistent water pollutants, plastic waste stands out as a critical environmental concern because of its durability and poor post-consumer management [8]. When physically and chemically weathered, bulk plastics degrade into microplastics (< 5 mm) that show non-uniform sizes, shapes, and plastic compositions [9]. While early literature focused mainly on marine environments, recent investigations have highlighted widespread microplastic contamination in freshwater ecosystems, dominated by polymers such as polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), and polyethylene (PE) [10, 11]. Consumed by aquatic biota, microplastics facilitate trophic transfer and present severe human health risks upon consumption [12, 13].

Membrane filtration provides a high-efficiency, scalable approach to intercepting these microplastic contaminants [14]. Additionally, using expanded polystyrene (EPS) waste as a polymer binder turns a persistent environmental pollutant into a filtration material [15, 16]. However, waste derived polymer membranes often suffer from irregular pore networks and mechanical instability during continuous filtration. The addition of powdered activated carbon (PAC) as a filler can alter surface density and porosity [17, 18]. Despite previous studies on waste upcycling, the synergistic between upcycled Styrofoam and powdered activated carbon (74 μm) in tailoring substrate adhesion, microscopic interstitial voids, and physical sieving mechanisms for microplastics is insufficiently quantified.

Therefore, this study aims to develop and optimize a composite filtration membrane fabricated from upcycled Styrofoam and 74 μm powdered activated carbon supported on a nonwoven substrate. The structural, morphological, and separation properties of the composite membranes were evaluated for microplastic retention and turbidity reduction. The outcomes of this work demonstrate a sustainable waste to value strategy for repurposing dangerous polymeric waste into functional filtration media for freshwater filtration.

2 Materials and Methods

2.1 Material

Expanded polystyrene (EPS) packaging waste was ground, cleaned of surface impurities, and dried properly. Powdered active carbon (PAC) with an average particle size of 74 μm was used as a functional filler to improve membrane adsorption and filtration properties. A 100 μm thick non-woven fabric was used as a support substrate for the composite membrane. N-Methyl-2-pyrrolidone (NMP), from Merck & Co., Inc. (USA), was used as a solvent. All chemical reagents were analytical grade and were used as received without additional purification, and pure water was used for all experiments.

2.2 Preparation of the Membrane Dope Solution

Recycled expanded polystyrene (Styrofoam) was shredded and dissolved in NMP in a sealed glass flask. The solution was heated to 80 $^{\circ}\text{C}$ and stirred until a clear solution was obtained by complete dissolution. PAC was added to the resulting solution at different concentrations as indicated in Table 1. To homogenize the dope solution and obtain uniform dispersion of PAC particles, the solution was further stirred for 24 h at 60 $^{\circ}\text{C}$ with a magnetic stirrer. The resulting dope solutions were then left to cool down to room temperature before membrane casting.

Table 1. Composition of Coated Solution of Styrofoam-Activated Carbon Blended Membranes

Membrane code	Blend composition, wt.%		
	Styrofoam	Activated carbon	NMP
EPS-PAC1	5	0	95
EPS-PAC2	5	4	91
EPS-PAC3	5	8	87
EPS-PAC4	7	0	93
EPS-PAC5	7	4	89
EPS-PAC6	7	8	85
EPS-PAC7	9	0	91
EPS-PAC8	9	4	87
EPS-PAC9	9	8	83

2.3 Membrane Fabrication via Phase Inversion

Composite membranes were prepared using a dip-coating followed by a non-solvent-induced phase separation (NIPS), as shown in Figure 1. Circular nonwoven substrates (25 mm in diameter) were fully immersed into the dope solutions for 10 s and withdrawn at a fixed speed to produce a uniform wet layer coating over all the samples. The coated substrates were immediately transferred into a 500 mL pure water bath kept at room temperature to induce phase inversion and membrane formation.

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To ensure a full extraction of residual NMP solvent, the membranes were left immersed in the water bath for 24 h before drying them in an oven at 100 °C for 2 h. All immersion, bath extraction, and drying conditions were kept constant for the entire procedure. A total of nine membrane formulations were prepared by varying the concentration ratios of Styrofoam binder (5, 7, and 9 wt.%) and PAC filler (0, 4, and 8 wt.%). For each formulation, n = 3 replicate membrane specimens were prepared and tested to ensure reproducibility.

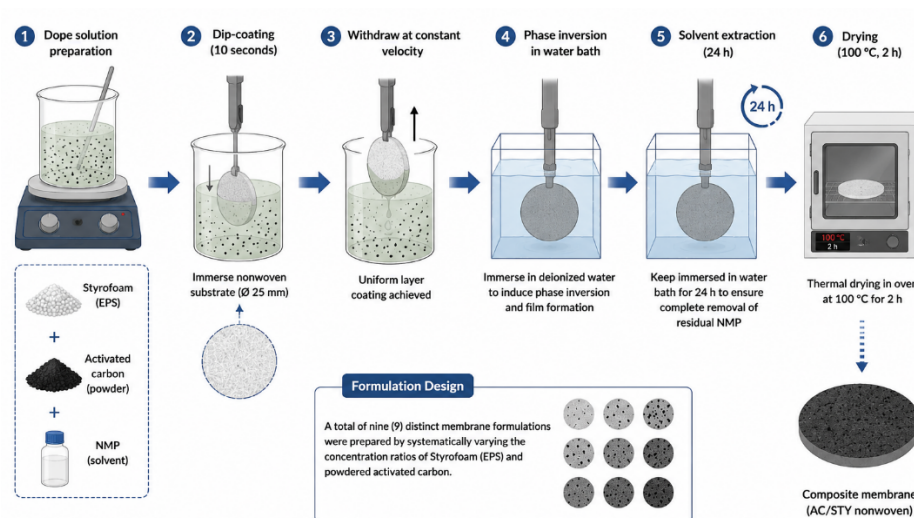


Fig. 1. Schematic illustration of the composite membrane fabrication process

2.4 Preparation of microplastic samples

To assess removal efficacy of upcycled Styrofoam flat-sheet membranes for aqueous microplastics, synthetic microplastic contaminated wastewater was prepared nominally of 3 g/L concentration. 3.0 g heterogeneous polymer mix of equal mass ratios (1.0 g) of milled PP, PS and HDPE with particle sizes varying from 1 μm to 5000 μm were suspended in 1.0 L of distilled water.

To aid dispersion of the inherently hydrophobic and high surface tension poly-olefin powders, 0.05 mL (0.005 v/v%) of a liquid detergent was added to ensure uniform particle wetting. The addition of a trace amount surfactant replicates domestic greywater matrices containing surfactant-bonded microplastics which tend to remain in suspension rather form surface flocs. The suspension was stirred to obtain a stable feed prior commencing each filtration trial.

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2.5 Microplastic separation test

The filtration performance was evaluated using the Styrofoam membrane assembled in the filtration setup shown in Figure 2. Microplastic solution (3 g/L) was pushed through the membrane surface, housed in a filter holder, by means of a glass syringe. To determine the Total Suspended Solids (TSS), the mass of each Styrofoam membrane was recorded before and after filtration. In this case, the TSS value represents the mass of solid microplastics retained on the membrane surface per volume of filtered sample. The TSS concentration is calculated from the mass differential of the membrane before and after filtration, divided by the sample volume, and adjusted with a conversion factor to have appropriate units as presented in Equation (1):

$$TSS (mg/L) = \frac{\text{solid weight (mg)} \times 1000}{\text{sample volume (ml)}} \quad (1)$$

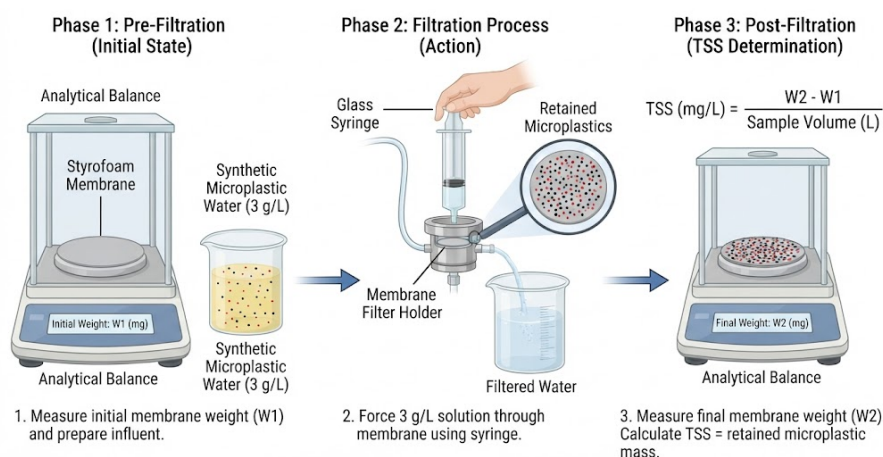


Fig. 2. Illustration of microplastic separation test

3 Result and Discussion

3.1 Turbidity Reduction and Rejection Efficiency

The initial microplastic solution had a severe level of turbidity: 811.5 NTU. This indicates that the water contained a high amount of suspended particulate that reduces light clarity. Filtering microplastics through the bare nonwoven fabric reduced the levels of turbidity to only 802.4 NTU. This corresponds to the low rejection efficiency of filtration by the bare nonwoven of only 1%. Morphological analysis of the bare nonwoven fabric revealed that it contains an open structure of loosely interwoven fibers with large inter fiber voids. Therefore, the bare nonwoven fabric only acts as a coarse strainer, through which the majority of the suspended microplastics is not retained by the fabric.

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On the contrary, coating the nonwoven substrate with recycled Styrofoam and PAC fundamentally improved filtration performance. For each composite membrane composition, namely, 5, 7, and 9 wt.% of Styrofoam and 0, 4, and 8 wt.% of PAC, the permeate turbidity was reduced to 0.0 NTU, which corresponds to a near 100% rejection efficiency. A dramatic decrease in the content of suspended particulate is explained by the fact that the wet phase inversion led to the formation of a continuous polymeric thin film, which covers the inter fiber gaps of the nonwoven substrate by sealing them with the binder (Styrofoam). Moreover, incorporating PAC into the binder allowed filling the voids of the polymeric matrix, thus enhancing the barrier effect against the passage of microplastics through the membrane [19].

Concerning the public health and regulatory requirements, the performance of the Styrofoam/PAC composite membranes is outstanding, as it successfully fulfilled national standards for drinking water. According to the regulations, the maximum allowable level of turbidity for any drinking water is strictly set to at < 3 NTU. Although the bare nonwoven fabric control run considerably exceeded this level by more than 260 times, all the composite membranes of Styrofoam/PAC successfully reduced the levels of macro particulates to 0.0 NTU. This means that using a common waste product, such as upcycled polystyrene foam, one can manufacture an affordable composite membrane, which will fulfill its function of primary water treatment by restoring water clarity to the level of domestic drinking water [20].

Nevertheless, the value of 0.0 NTU for the composite membranes indicates the limits of detection by the nephelometric method of turbidity measurement. Namely, measuring water clarity in NTU is based on measuring the amount of light scattered at 90° by the particulate suspended in the water solution. Thus, obtaining a result of 0.0 NTU means that all the light-scattering matter in the solution has been removed. However, it does not necessarily mean that 100% of microplastics have been retained by the membrane. In particular, sub-micron microplastics with a refractive index close to that of water may pass through the membrane without contributing to the light scattering at 90°. Hence, measuring the decrease in water clarity is a good indicator of the membrane's ability to retention of macro particulate with high surface area. However, in the case of microplastics, the determination of filtration efficiency requires additional gravimetric TSS (Total Suspended Solids) retention measurements and analysis of microscopic particulate.

3.2 Gravimetric Total Suspended Solids (TSS) Retention

While nephelometric turbidity measurements demonstrated complete optical clarification (0.0 NTU) across all modified membranes, gravimetric TSS analysis provided the required analytical sensitivity required to quantify true microplastic rejection. The pristine nonwoven control substrate showed low TSS retention of 64.44 mg/L). This limited capture capacity is a direct result of the open fibrous network of raw fabric which lacks adequate structural barrier to retain fine suspended particulates. In contrast, modifying the nonwoven support with a Styrofoam matrix and PAC significantly increased TSS rejection across all membranes, confirming that composite surface coating is important for an effective microplastic entrapment.

The concentration of the Styrofoam polymer binder played a primary role in establishing the physical sieving capability of the composite layer. In formulations without carbon filler (0 wt.% PAC), increasing the Styrofoam concentration from 5 wt.% to 7 wt.% and 9 wt.% led to a progressive increase in mean TSS retention of 105.57 mg/L to 123.33 mg/L and 346.67 mg/L, respectively. Higher polymer loadings increase casting dope viscosity, which slows down the solvent and nonsolvent exchange rate during phase separation [21]. This delayed demixing mechanism suppresses macrovoid formation and produces denser top skin layer with smaller effective pore size, thereby improving mechanical strain sieving and forcing a greater mass of microplastic particles to be retained on the surface of the membrane [22].

The addition of PAC (74 μm average particle size) as a filler further boosted gravimetric TSS retention by increasing matrix tortuosity. Within the 5 wt.% Styrofoam series, increasing the PAC loading from 0 wt.% to 4 wt.% and 8 wt.% elevated the mean TSS retention from 105.57 mg/L to 160.00 mg/L and 268.80 mg/L, respectively. Similarly, in the 7 wt.% Styrofoam series, TSS retention increased from 123.33 mg/L (0 wt.% PAC to 328.87 mg/L (4 wt.% PAC) and 305.57 mg/L (8 wt.% PAC). Grafted carbon particles act as physical obstacles within the Styrofoam matrix, filling interstitial voids, narrowing internal flow channels and creating a tortuous network that traps suspended microplastics within the surface layer [23].

Peak gravimetric TSS retention was achieved at the maximum concentration pairing of 9 wt.% Styrofoam binder and 8 wt.% PAC fillers, recording an overall formulation mean of 391.10 mg/L (13.04 % mass retention) and a maximum single-run of 463.30 mg/L (15.44%). At this ratio, the high polymer density provides a sturdy matrix which securely anchors the abundant carbon particles, optimizing surface compaction without structural breakdown.

A non-linear trend was observed in the 9 wt.% Styrofoam series at 4 wt.% PAC loading, where mean TSS retention temporarily dropped to 215.53 mg/L (7.18%). Optical micrographs of this specific formulation (Figure 7b) confirm that within the highly viscous 9 wt.% binder solution, 4 wt.% PAC forms localized isolated carbon agglomerates rather than a continuous network. These dense clusters create non uniform and exposed surface topography, unreinforced polymer areas around the agglomerate perimeters. These boundary micro-defects act as low-resistance preferential flow pathways, allowing fine microplastics to bypass the sieving surface before higher filler loading (8 wt.%, Figure 7c) restores homogeneous particle distribution and closes these interfacial gaps [24].

The gravimetric TSS trends align directly with post filtration microscopic characterization, which showed distinct capture regimes across formulations. While the bare nonwoven control only retained coarse fragment such microplastics (0.289 mm), the composite Styrofoam/PAC membranes successfully entrapped much smaller granular and fibrous microplastics ranging down to 0.015–0.031 mm. With higher concentrations of Styrofoam and PAC forming denser, multi-layered filtration barriers, microplastic particles accumulated into dense surface cakes, resulting in higher recorded mass differentials (ΔW). Ultimately, gravimetric TSS analysis proved to be a far more discriminating evaluation metric than optical turbidity for evaluating membrane

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performance, confirming that combining high binder density (9 wt.%) with well-dispersed filler loading (8 wt.%) maximizes total microplastic mass rejection.

3.3 Morphological Analysis and Microplastic Retention

The surface morphology of the composite membranes and their ability to retain microplastic were characterized by digital microscopy and correlated with gravimetric TSS retention performance. Figure 3 compares the morphology of the bare, nonwoven control substrate (open, porous mesh with loosely woven polymer fibers and large interstitial voids) with the physical changes incurred by introducing upcycled Styrofoam. The relatively high surface porosity of the nonwoven fabric resulted in poor physical sieving selectivity (1.04-1.22% turbidity rejection) as the mesh allowed fine particulate matter to pass freely while only capturing coarse microplastic fragments (289 μm ; Figure 3b).

The addition of recycled binder affected the membrane surface by progressively sealing the surface porosity as demonstrated by comparing the control (Figure 3) with Figures 4-6. A 5wt.% binder solution resulted in thin polymer coatings that left the underlying nonwoven fiber mesh largely visible (Figure 4). Increasing the binder content (7wt.% and 9wt.%) resulted in continuous polymeric films that achieved complete substrate coverage, significantly reducing the effective pore sizes of the membranes prior to the addition of PAC filler.

The inclusion of inorganic PAC filler within the membrane matrix allowed the composite to claim the remaining micro-voids and increase surface tortuosity. Membranes prepared without PAC filler (0%) displayed smooth, featureless surface morphologies (Figures 4a, 5a, and 6a) corresponding to low microplastic accumulation and reduced TSS retention capacity. The few microplastics retained by such membranes were primarily comprised of loose fibers measuring between 15-62 μm . The addition of 4% PAC filler resulted in the formation of localized filler agglomerates across discrete regions of the membrane surface (Figures 4b, 5b, and 6b) that entrapped heterogeneous, granular microplastics (21 μm , 74 μm).

Increasing the filler content further (8%) promoted lateral dispersion of individual PAC particles throughout the Styrofoam matrix (Figures 4c, 5c, and 6c) while eliminating localized agglomeration, maximizing the composite's physical entrapment properties. The high filler content (8%) combined with increased binder content (9wt.%) enabled the 9% Styrofoam matrices to demonstrate a synergistic effect, with the binder providing the mesh with structural coverage while the PAC filler claimed the remaining micro-voids present within the membrane (Figure 6c).

This composition demonstrated the highest mean TSS retention (391.10 mg/L; maximum of 463.3 mg/L) by effectively entrapping microplastics of varied dimensions (1 μm up to 2107 μm) within the membrane's entanglement matrix. Particle dimensions, as well as the length and width of the retained microplastic, were determined by analyzing a minimum of $n = 100$ randomly selected retained particles by membrane using the ImageJ v1.53k digital image processing software at calibrated optical magnifications.

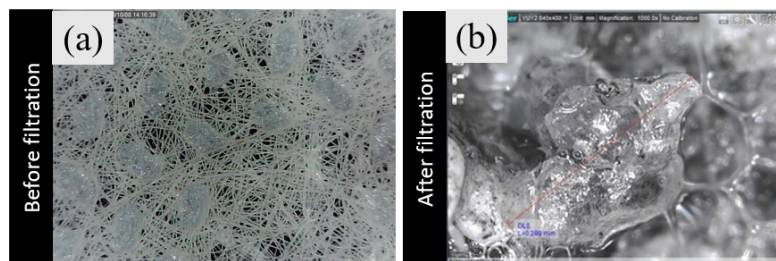


Fig. 4. Optical micrographs of the pristine nonwoven fabric substrate (a) before filtration and (b) after filtering microplastic-contaminated water.

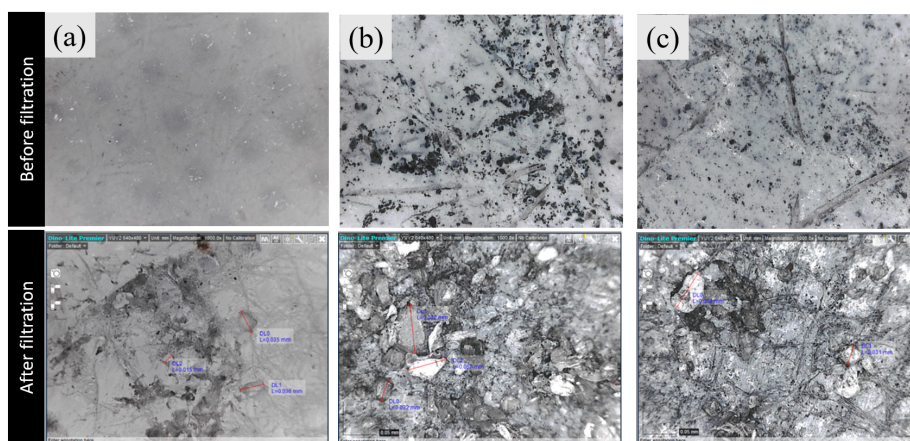
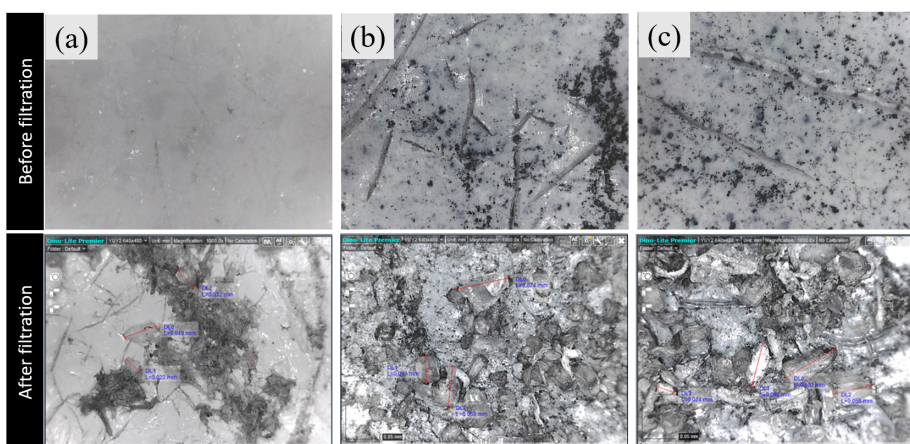


Fig. 5. Surface morphology and microplastic retention of 5 wt.% Styrofoam membranes at varying PAC loadings: (a) 0 wt.% PAC, (b) 4 wt.% PAC, and (c) 8 wt.% PAC before and after filtration.



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Fig. 6. Surface morphology and microplastic retention of 7 wt.% Styrofoam membranes at varying PAC loadings: (a) 0 wt.% PAC, (b) 4 wt.% PAC, and (c) 8 wt.% PAC before and after filtration.

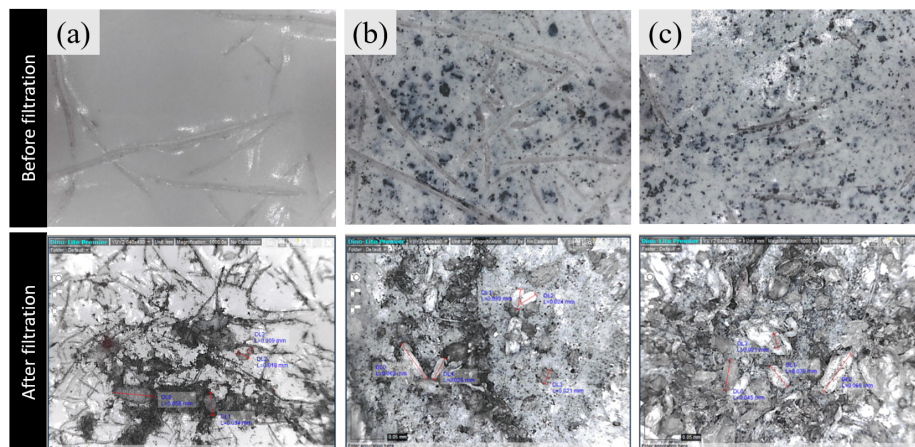


Fig. 7. Surface morphology and microplastic retention of 9 wt.% Styrofoam membranes at varying PAC loadings: (a) 0 wt.% PAC, (b) 4 wt.% PAC, and (c) 8 wt.% PAC (optimal formulation) before and after filtration.

4 Conclusions

This study demonstrated the upcycling of Styrofoam waste into composite filtration membranes integrated with PAC (74 μm) for water filtration and microplastic rejection. While the unmodified nonwoven substrate showed negligible separation (1.04-1.22% turbidity rejection), all fabricated Styrofoam/PAC composite membranes provided complete turbidity clarification (0.0 NTU or equivalently 100% nominal turbidity rejection) from synthetic wastewater with an initial turbidity of 811.5 NTU.

Morphological characterization revealed that the upcycled Styrofoam binder established a continuous polymeric film that sealed the fibrous network of the nonwoven substrate while the addition of PAC filled microscopic interstitial voids to increase surface density and tortuosity. Among the formulations tested, the 9 wt.% Styrofoam / 8 wt.% PAC composite had the highest microplastic retention capacity, achieving a mean TSS reduction of 391.10 mg/L (peaking at 463.3 mg/L) which corresponded to 13.0% of the initial 3.0 g/L mass loading. Microscopic analysis showed that the composite membrane intercepted microplastics from a range of particle size from 1 μm to 4910 μm . Overall, repurposing Styrofoam waste into filtration membrane offers a viable strategy for plastic waste upcycling and local water filtration. Future work should aim to optimize water flux, improve anti-fouling performance and evaluate chemical and mechanical stability to enable scale-up in the application of water filtration.

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