

# Eco-friendly membrane fabrication from polystyrene waste: A circular economy perspective

Anh Thi Kim Tran\*, Nhung Thi Tuyet Hoang and My Linh Nguyen

Department of Environmental Technology, Faculty of Chemical and Food Technology,  
Ho Chi Minh University of Technology and Education, 01 Vo Van Ngan, Thu Duc city, Ho Chi Minh city, Vietnam

(Received March 4, 2025, Revised May 9, 2025, Accepted May 27, 2025)

**Abstract.** This study optimized the manufacturing process of a membrane derived from polystyrene waste for application in a membrane bioreactor for wastewater treatment by adjusting parameters including resin-to-solvent ratio, coagulation time, and membrane thickness. The research results showed that polystyrene plastic demonstrated compatibility with N-Methyl-2-pyrrolidone solvent at a resin-to-solvent (m/V) ratio of 4:25. The ideal coagulation time was found to be 20 min and a thickness of 350  $\mu\text{m}$ . The MBR tank employed a frame of flat sheet membranes made from polystyrene waste with consistent performance throughout the entire operation. On average, it achieved an 80% removal efficiency for COD, 94% for ammonium, and 8% for phosphate and turbidity of 1.5 NTU. These obtained results confirmed that membranes made from plastic waste could be effectively used in a membrane bioreactor (MBR) system for domestic wastewater treatment. Therefore, recycling polystyrene waste as a primary resource for membrane production is a viable concept for both technical and environmental purposes, promoting sustainable growth in the context of a circular economy.

**Keywords:** circular economy; membrane bioreactor; membrane fabrication; polystyrene waste; wastewater treatment

## 1. Introduction

Currently, environmental pollution is a significant concern, threatening biodiversity, climate stability, and a slew of other consequences that are fast affecting civilization. Plastic rubbish, which is distinguished by its constant presence in the environment, epitomizes this quandary and includes items such as plastic bottles, nylon bags, food containers, and cups. This broad contamination, together with other environmental pollutants, has a negative impact on ecosystems and human health around the world. According to Statista Research Department (2024), the global amount of plastic manufactured in 2022 was 400.3 million metric tons, which increased around 1.6% over the previous year. The manufacture of plastics has significantly increased since the 1950s. The remarkable adaptability of this category of materials explains the consistent increase in production on an annual basis (Statista Research Department 2024). However, according to the United Nations 2023, the rates of recycling differ depending on the area, type of plastic, and its intended use; only approximately 9% of the total plastic garbage produced worldwide is recycled, 79% is disposed of in landfills or released into the natural environment and 12% undergoes incineration (United Nations Development Programme 2023).

Along with addressing the issue of plastic waste disposal into the environment, the global scarcity of drinkable water remains a major concern. According to Unicef (2024), about 4 billion people, or more than two-thirds of the

population, are in the situation of water scarcity for at least world's one month annually, and more than 2 billion people live with insufficient water supply. According to forecasts, by 2025, half of the world's population would live in areas with restricted access to water. The problem needs to be strictly considered by 2030, when an estimated 700 million people may be relocated because of extreme water scarcity. By 2040, an alarming one in every four children worldwide will live in areas with severe water stress, emphasizing the importance of resolving this vital issue (Unicef 2024).

In response to this difficulty, researchers explored the creation of innovative technologies for plastic recycling mixed with water treatment. Commonly used recycled polymers such as polyethylene terephthalate (PET), polyvinyl chloride (PVC), polyethylene (PE), high density polyethylene (HDPE)... solve the problem of waste as well as water pollution. A simple and scalable method was employed to produce synthetic graphite from discarded polyethylene terephthalate (PET) bottles. A synthetic process that involved pyrolysis at 900°C was used to effectively convert PET into graphite (Ko *et al.* 2020). Tran *et al.* (2020) sulfonated polystyrene waste to produce ion exchange resin for heavy metal removal with the maximum adsorption capacity of 4.09 mg  $\text{Zn}^{2+}/\text{g}$ , 4.58 mg  $\text{Cu}^{2+}/\text{g}$  and 4.04 mg  $\text{Cd}^{2+}/\text{g}$  (Tran *et al.* 2020). Similarly, polystyrene was subjected to a chemical treatment with sulfuric acid to generate stabilized precursors. These precursors were subsequently carbonized to produce carbonaceous materials with exceptional efficiency. Paraformaldehyde (PFA) was utilized in conjunction with sulfuric acid to enhance the cross-link density in the sulfonated polystyrene (PS) matrix and added methylene to connect phenyl rings. Modified PS was a black, glassy substance with improved cross-linking

\*Corresponding author, Ph.D.,  
E-mail: anhttk@hcmute.edu.vn

density. After carbonization process, the carbon of the stabilized PS was substantially higher (45.3 wt%) than that of original PS (0 wt%) and sulfonated PS without PFA (22.4 wt%) (Lee *et al.* 2023). Singh *et al.* (2020) recycled plastic as an adsorbent by pyrolysis process of PVC, PET and PE for arsenic removal. The uptake capacity was calculated to range between 10.7% and 99.4%. The char formed from a blend of PE and PVC obtained the highest efficiency in arsenic removal with an efficiency of 71.6% to 99.4%. The PE and PET plastic demonstrated the minimal sorption levels, varying from 12.4% to 32.5%. The optimal condition for attaining 99.4% adsorption was a 20-minute equilibrium period in an acidic environment with a pH of 6.0 and a dose of 1.5 grams (Singh *et al.* 2020).

Besides being adsorbents, the plastic waste recycling was also used for membrane fabrication, Garcia-Ivars *et al.* (2017) used recycled polymer as the raw material for membranes making. The obtained membrane exhibited comparable properties to those made from commercial polystyrene. Their findings revealed that the recycled membranes possessed a similar asymmetric structure, with slightly higher porosity ( $52.31 \pm 4.33\%$ ) compared to that of commercial membranes ( $47.54 \pm 5.53\%$ ). Additives helped increase the hydrophilicity of the membranes, reducing fouling and improving the capacity of humic acid removal. The findings suggested that high-impact polystyrene from waste could serve as a raw material instead of using the virgin polystyrene in low-pressure membrane fabrication (Garcia-Ivars *et al.* 2017). Wang *et al.* (2019) made superhydrophobic polypropylene (PP) membranes in the treatment of high-salinity water. Their research focused on developing superhydrophobic composite membranes made of polypropylene with modified surfaces by including SiO<sub>2</sub> nanoparticles. When the membrane was used continuously for a long time in high-salinity water treatment systems, it showed great water resistance and long-lasting anti-fouling properties. Compared to commercial membranes, the fabricated membrane exhibited a significantly reduced fouling rate, with a decrease of up to 20% (Wang *et al.* 2018). The feasibility of porous and hydrophilic membranes production from polystyrene waste was also studied (Khaled *et al.* 2020a). The weight ratio of high-impact polystyrene (HIPS-R) dissolved in N,N-dimethylformamide (DMF) was varied from 20 to 35 wt% in membrane fabrication. Their prior research was expanded by investigating water filtration with recycled polymer microfiltration membranes (Khaled *et al.* 2020b). This study was investigated to remove humic acid (HA) and rhodamine B (RhB) dye by the microfiltration process. The obtained results indicated that the 30 wt% membrane had a higher flux and effectiveness in the removal of humic acid and dyes than that of the 35 wt% membrane. Besides, gas-separation membranes were also produced by hot-pressing technique. The addition of polybutadiene in the waste polystyrene could produce gas separation membranes with a selectivity of 17.14 for the CO<sub>2</sub>/N<sub>2</sub> mixture. The membranes showed a superior waterproof capabilities under water pressures from 1 to 5 bar (Lai *et al.* 2021). Similarly, Zhuang *et al.* (2024) used a single-step electrospinning/electro-spraying method to make a membrane using waste PET and tetrabutyl titanate (TBT) for the separation of

water-in-oil emulsions. The demulsification efficiency attained was 99.8%, and the water flux was 6,392 L/m<sup>2</sup>/h (LMH). The obtained membrane exhibited remarkable mechanical properties, with a filtration efficiency of 128.8% and water flux of 3,500 LMH (Zhuang *et al.* 2024). The common method for membrane fabrication is phase inversion technique with N, N-dimethylacetamide (DMAc), N, dimethylformamide (DMF), dimethyl sulfoxide (DMSO), and N-Methyl-2- pyrrolidone (NMP) solvent. Yadav *et al.* used these kinds of solvent to fabricate distillation membrane with poly(vinylidene fluoride) (PVDF). The salt rejection rate was 98%, and the permeate flux ranged from 16.2 LMH to 27.9 LMH assessed through the utilization of vacuum membrane distillation (VMD) (Yadav *et al.* 2022, 2024).

Mitigating the present water scarcity necessitates a comprehensive strategy, including the investigation of alternate water sources and the effective treatment method of wastewater to eliminate the contamination of existing water reservoirs. A variety of wastewater treatment technologies, such as coagulation-flocculation (Teixeira *et al.* 2024, Vunain *et al.* 2019), ion exchange (Malovanyy *et al.* 2013, Xu *et al.* 2024), biological treatment (Fan *et al.* 2022, Sarvajith *et al.* 2024) and membrane filtration (Ferrera *et al.* 2024, Fito Nure and Nkambule 2023, Yang *et al.* 2023), have been developed and extensively implemented worldwide. Membrane filters have shown considerable promise in delivering pure and ultra-clean water, making them essential in dealing with water scarcity and environmental pollution as well as to help create new water sources. MBR (Membrane Bioreactor) membrane technology represents a notable innovation in wastewater treatment. It combines microorganisms within suspended activated sludge tanks with hollow fiber or flat sheet membrane technology. This integration enables the retention of activated sludge in the biological tank through filtration mechanism of the membrane (Chaleshtori *et al.* 2022, Ittisupornrat and Theepharaksapan 2023). Due to their small pore size (measured in micrometers), the wastewater exiting the membrane achieves high-quality standards (Guembri *et al.* 2020). An assessment was conducted on the efficiency of a membrane bioreactor (MBR) in treating greywater on a small scale to examine the impact of a prominent bacterial biofilm that developed on the Pall ring media located in the permeate stream. The MBR functioned for 125 days, sustaining a hydraulic retention time of 2 days with the removal efficiency exceeding 90% in the concentrations of organic substances, ammonium nitrogen, suspended particles, total coliforms, and *Escherichia coli* (Ittisupornrat and Theepharaksapan 2023). The efficacy of a microalgal-activated sludge membrane bioreactor was examined in the study (Chaleshtori *et al.* 2022). A continuous membrane-assisted system with two different ratios of algae to sludge (ratios of 1:0 and 5:1) was employed for the treatment of both raw and processed wastewater. The most favorable outcome was obtained by cultivating a combination of algae and sludge in untreated wastewater with the ammonium and phosphorus removal efficiencies of 94.36% and 88.37%, respectively. A combination of powdered activated carbon and membrane bioreactor (PAC-MBR) can be used to effectively eliminate metronidazole, acetaminophen, naproxen

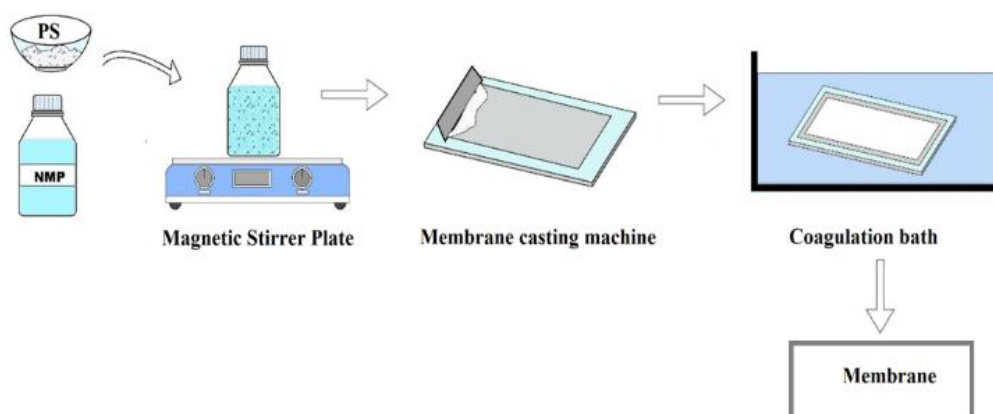


Fig. 1 Non-solvent phase inversion casting process for membrane fabrication

ibuprofen, carbamazepine, and estriol (> 99%) from urine. This method encompasses both physical adsorption and biodegradation, and it can be accomplished in a single step without inducing any instability in the operating system (Jiang *et al.* 2024). A membrane-aerated biofilm reactor (MABR) was also investigated for nitrogen removal from wastewater. The prolonged trial, spanning 47 days, revealed that MABR exhibited an outstanding  $\text{NH}_4^+\text{-N}$  removal effectiveness of 99.5%, in contrast to the control setup without MABR, which achieved 56.5% efficiency (Sinharoy *et al.* 2024).

Despite many benefits of MBRs regarding water quality (notable efficiency in the elimination of organic compounds, nitrogen, bacteria, and viruses) and spatial footprint reduction, the capital cost for membrane installation is high (He *et al.* 2024). Therefore, it is necessary to find a solution for reducing costs and increasing the affordability and accessibility of MBR technology for wider wastewater treatment applications. A feasible strategy to reduce the costs of membrane bio-reactor (MBR) systems in wastewater treatment is recycling the plastic waste as a cost-effective material for membrane production. Although there are some studies on utilizing polystyrene waste for membrane fabrication, there is a deficiency of comprehensive studies focused on optimizing synthesis conditions and implementing these membranes in MBR systems. This study examined the viability of producing membranes for MBRs from polystyrene waste by optimizing parameters like the polystyrene waste to solvent volume ratio (g/mL), phase inversion duration (min), and membrane thickness ( $\mu\text{m}$ ). After membrane fabrication, the study assessed the efficacy and stability of the membrane used in bioreactor for wastewater treatment. This study investigated the feasibility of waste materials recycling in membrane fabrication to improve the economic feasibility and sustainability of MBR technology in wastewater treatment applications.

## 2. Material and methods

### 2.1 Materials

N-Methyl-2-pyrrolidone (NMP) solvent in this study was from Macklin, China and other chemicals was used

with analytical degree. The polystyrene waste was single-use polystyrene dishes bearing the PS (polystyrene) symbol with their purity initially unknown from the trash cans at Ho Chi Minh University of Technology and Education in Ho Chi Minh City, Vietnam.

The domestic wastewater was taken from FPT company in Ho Chi Minh city, Vietnam. The characteristics consists: pH of 6.5-7.5, biological oxygen demand (BOD) of 188-225 mg/L, chemical oxygen demand (COD) of 230-260 mg/L, total suspended solid (TSS) of 122 mg/L, ammonium ( $\text{NH}_4^+$ ) concentration of 60 mg/L, phosphate ( $\text{PO}_4^{3-}$ ) concentration of 14 mg/L.

### 2.2 Membrane fabrication

The membrane was synthesized by phase inversion method as described in the previous study (Katariya and Patel 2022). The disposable polystyrene containers underwent a sequence of preparation procedures. Initially, it was cleansed, dried, and cut into pieces around 5 mm in dimension. Thereafter, the plastic was weighed and transferred into a beaker, where it was dissolved in NMP solvent. The solution was continuously stirred at 360 rpm and maintained at a temperature of  $50^\circ\text{C}$  to achieve homogeneity. Following this, the solution was gently stirred at 120 rpm to eliminate air bubbles from the sample.

The membrane solution was poured onto the 120-mesh polyester film as a support and casted with the appropriate thickness on the casting machine. After that, the obtained membrane was soaked in distilled water for the required duration and left to air dry naturally for 24 hours.

The operational parameters such as ratios of polystyrene waste to volume of solvent (g/mL) from 2/25 to 6/25, phase inversion time from 10 to 60 min, membrane thickness from 100 to 500  $\mu\text{m}$  were varied to optimize the membrane fabrication process. The performance of the membrane was tested by using the vacuum filtration apparatus with a pressure pump (Neuberger, Germany) with a maximum pressure of 1 bar.

### 2.3 Membrane bioreactor

The membrane frame was made of 2 mm PVC Formex covered with silicone combined with wax paper. The

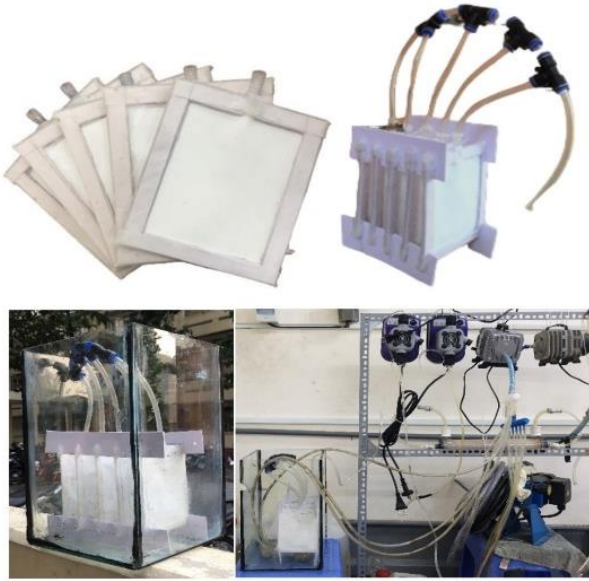


Fig. 2 Pictures of synthesized membrane and MBR setup

surface area of membrane was 0.08 m<sup>2</sup>. Five flat-sheet membranes were installed in the reactor with a volume of 12 L (Fig. 2).

The membrane bioreactor was set up with a continuous flow of 5 L/h, hydraulic retention time (HRT) of 6 h, sludge retention time (SRT) of 30 days, pH of 6.5-7.5, dissolved oxygen (DO) of 3-4 mg/L, initial mixed liquor suspended solid (MLSS) of 6,000 mg/L. The effluent was taken twice a day at 8 a.m. and 2 p.m. to analyze the concentration of contaminants in the wastewater such as COD, NH<sub>4</sub><sup>+</sup>, PO<sub>4</sub><sup>3-</sup>.

After each 6 h of MBR operation, the membrane was taken out of the reactor and gently rinsed with clean water to remove the deposit on the membrane surface, and then backflushed with air flowrate of 40 L/min within 3 min to restore the flux.

#### 2.4 Analysis

The BOD analysis followed the standard dilution method as outlined in APHA standard methods (5210.B), while COD was determined using the dichromate reflux method (APHA 5220.B). Ammonium (NH<sub>4</sub><sup>+</sup>) and phosphate (PO<sub>4</sub><sup>3-</sup>) were determined by titration method using standard method APHA 4500-NH<sub>3</sub> E and APHA 4500-P C, respectively. Color analysis was performed with a spectrophotometer (Aqualytic – AL800), detecting absorbance at 663 nm and referencing calibration curves for quantification purposes. Turbidity was quantified in NTU units utilizing a turbidimeter (Aqualytic- AL250T). The determination of TSS and MLSS (APHA 2540.D) entailed filtering samples through pre-weighed filter paper, drying and weighing the residual particles on the filter paper, and estimating the concentration of suspended solids in mg/L.

The membrane thickness (μm) was measured with a stainless hardened 0-150 mm digital caliper. Scanning electron microscopy (SEM) using a Hitachi FE-SEM S4800 (Tokyo, Japan) was employed to analyze the surface morphology of the membranes. This method collectively

provided comprehensive insights into the structure of the membranes.

The porosity of the membrane was calculated (Khaled *et al.* 2020a):

$$\text{Porosity (\%)} = \frac{\frac{w_W - w_D}{\rho_W} + \frac{w_D}{\rho_P}}{\frac{w_W - w_D}{\rho_W}} \times 100 \quad (1)$$

in which  $w_D$  and  $w_W$  were the mass of dry membrane and wet membrane (in grams),  $\rho_w$  and  $\rho_p$  were density of water and polymer at room temperature (g/cm<sup>3</sup>), respectively.

The rejection of the membrane was analyzed by contaminants removal efficiency:

$$\text{Rejection (\%)} = \frac{C_{in} - C_{out}}{C_{in}} \times 100\% \quad (2)$$

in which  $C_{in}$  and  $C_{out}$  were the initial and effluent turbidity (NTU), or color, COD (mg/L), NH<sub>4</sub><sup>+</sup> (mg/L), PO<sub>4</sub><sup>3-</sup> (mg/L) in the wastewater, respectively.

Water flux (LMH) was calculated:

$$\text{Flux (LMH)} = \frac{V}{t \times A^2} \quad (3)$$

where  $V$  (L) was the volume of the water through the membrane in the determined period  $t$  (h),  $A$  (m<sup>2</sup>) was the total active surface area of the membrane.

### 3. Results and discussion

#### 3.1 Effect of resin to solvent ratio ( $m/V$ ) on the membrane performance

Fig. 3 illustrates the effect of the resin-to-solvent ratio while fabricating the membrane from polystyrene waste in the filtration performance. The increase in this ratio directly affected the membrane's porosity, hence impacting the water flux through the membrane. The resin-to-solvent ratio rose, potentially resulting in a less porous membrane structure and reducing the number of pores accessible for water passage. As a result, the water flux over the membrane reduced with a reduction in porosity. Fig. 3 shows that the water flux was 38,224 LMH at a ratio of 2/25 and decreased to 5,448 LMH to 2,669 LMH when the ratio was 4/25 and 6/25, respectively. This indicated a decrease in flux by roughly 15 times as the resin-to-solvent ratio increased 3 times. The correlation between porosity and water flux was significant because it directly influenced the membrane's effectiveness in filtration process.

The experimental results also demonstrated a substantial impact of the resin-to-solvent ratio on the efficacy of the waste polystyrene membranes regarding color and turbidity reduction. In Fig. 3, at a ratio of 2/25, the efficiency of the color treatment was 27.12%. Subsequent ratios indicated enhanced treatment efficiency: at 4/25, effectiveness rose to 58.44%, and at 5/25, it further climbed to 77.78%. At the maximum ratio (6/25), treatment efficiency significantly declined to 51.44%. Similarly, the efficiency of the membrane in turbidity removal at a ratio of 2/25 was 16.05%. As the resin-to-solvent ratio increased, the

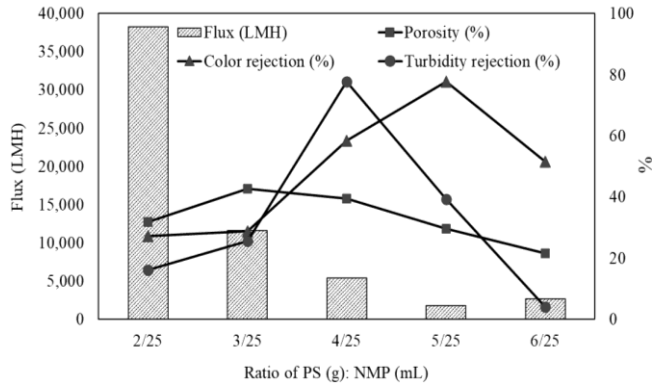


Fig. 3 Effect of the resin to solvent ratio on the performance of the membrane

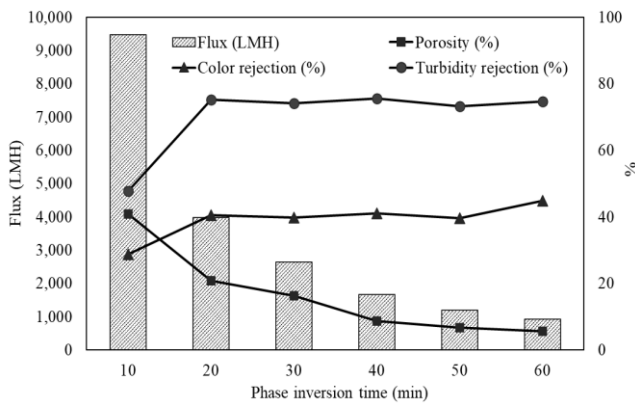


Fig. 4 Effect of phase inversion time on the performance of the membrane

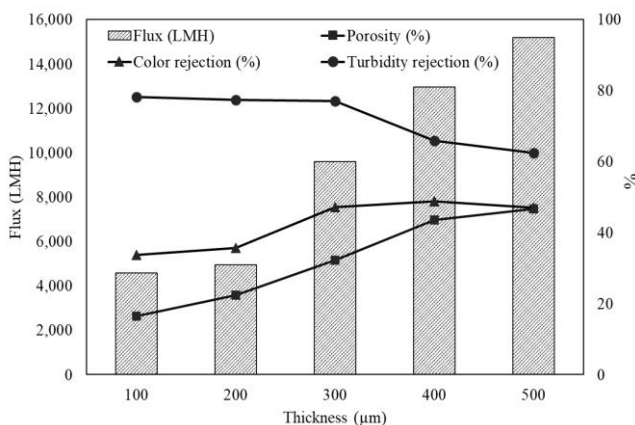


Fig. 5 Effect of membrane thickness on the performance of the membrane

efficiency showed a gradual improvement to 25.63% at the ratio of 3/25 and further to 77.65% at 4/25. Nevertheless, when the ratio was increased to 5/25 and 6/25, the turbidity removal efficiency decreased, which was 39.23% and 4.13%, respectively. The color and turbidity removal effectiveness were enhanced due to the increased amount of polystyrene in the NMP solvent, leading to a more compact membrane surface. This densification significantly decreased porosity and pore size, hence improving the membrane's ability to address both color and turbidity. Nonetheless, the

removal of color and turbidity decreased at resin-to-solvent ratios of 5/25 and 6/25. This problem is due to the excessive thickness of the membrane, which made it fragile. During pressure filtration, the membrane was broken, resulting in water passing through the breakage. Notwithstanding these problems, the membrane showed high efficacy in turbidity removal, indicating that its pore size satisfies the requirements for membrane utilization in MBR applications.

### 3.2 Effect of phase inversion time on the membrane performance

The impact of phase inversion duration ranging from 10 to 60 mins on membrane efficacy was examined to determine the optimal condition for achieving maximum turbidity and color removal, with a polystyrene mass to NMP volume ratio of 4/25 (Fig. 4). According to results in Fig. 4, increasing the coagulation time of solution of polystyrene and NMP from 10 to 60 mins led to a significant reduction in membrane porosity from 44.27% to 4.27%, which resulted in a decrease in the water flux through the membrane. After soaking the membrane for 10 mins, the flux attained 9,463 LMH. After 60 mins of soaking, the water flux was reduced significantly to 917 LMH. These findings emphasize the impact of coagulation time on membrane porosity and water flux, therefore, it is necessary to adjust this parameter to get optimal membrane performance in water treatment applications.

Instantaneous precipitation transpires when the membrane solution interacts with distilled water, leading to the development of a thin layer on the membrane's surface. Coagulation involves the separation of the polymer solution into two phases: solid phase and liquid phase. Prolonged coagulation may lead to the solidification of the membrane structure, hence diminishing the development of inter-connecting pores. If a thick surface layer forms, it can block the pores on the membrane surface, significantly reducing membrane's porosity, therefore increasing the contaminant elimination efficiency. This phenomenon is evident in the color and turbidity removal performance shown in Fig. 4. At a coagulation duration of 10 min, the PS membrane exhibited a color removal effectiveness of 28.66% and a turbidity reduction of 47.62%. Extending the coagulation duration to 20 min enhanced color and turbidity removal efficiency to 40.45% and 75.20%, respectively. Nevertheless, extending the membrane immersion duration in distilled water did not markedly enhance the efficiency of color and turbidity removal, which stabilized at an average of 41.3% and 74.38%. Therefore, 20 min is ascribed to be sufficient time for membrane solution coagulation to obtain the best turbidity and color removal efficiency.

### 3.3 Effect of membrane thickness on the membrane performance

The effect of membrane thickness was studied to find the best conditions for obtaining the optimum turbidity and color removal performance by changing from 100 to 500 μm (Fig. 5). The resin to solvent ratio (m/V) and phase

inversion time were kept at 4/25 and 20 min, respectively.

When the thickness of the membrane layer was increased from 100 to 500  $\mu\text{m}$ , there was a corresponding increase in porosity from 16.54% to 46.72%. This increase in porosity resulted in a gradual rise in water flux from 4,593 LMH to 15,201 LMH. Specifically, when the thickness of the membrane was increased fivefold, the porosity of the membrane increased by 2.84 times, and the flux increased by 3.29 times compared to the original values. Considering the capacity of color and turbidity removal of the membrane, the turbidity removal efficiency tended to decrease from 78.26% to 62.44% when increasing the thickness of membrane from 100 to 500  $\mu\text{m}$ , respectively. However, the color removal efficiency was higher from 33.71% to 46.72% with the thickness of membrane from 100 to 500  $\mu\text{m}$ . This can be explained by the fact that the thicker membranes may have more porous structure as the solvent exits the polymer matrix and increases the osmotic flux. These findings demonstrate a direct relationship between membrane thickness, porosity, and water flux, emphasizing the potential benefits of thicker membranes for increasing throughput in filtration applications. However, when the membrane thickness was increased to 400 and 500  $\mu\text{m}$ , there was a breakage on the membrane when using vacuum filtration, which was the possible reason for increasing flux and reducing the turbidity removal efficiency. The higher color removal efficiency was due to the color adsorption capacity on the membrane surface. Therefore, the suitable membrane thickness was chosen at 300  $\mu\text{m}$ .

### 3.4 Performance of membrane bioreactor

The ideal parameters for membrane fabrication were found to be a resin-to-solvent ratio of 4/25, a coagulation period of 20 minutes, and a membrane thickness of 300  $\mu\text{m}$  based on the outcomes of sections 3.1, 3.2, and 3.3. These values taken together produced interesting results: a flux rate of 9,608 LMH combined with over 80% removal effectiveness for both turbidity and color. These conditions were so used for the feasibility and stability studies in MBR operation.

A continuous 30-day experiment was carried out to assess the viability of a membrane bioreactor using the polystyrene waste-derived membrane for pollutant elimination from domestic wastewater. The MBR tank was operated under specified conditions: chemical oxygen demand (COD) of  $248 \pm 10$  mg/L, ammonium concentration of  $58 \pm 2$  mg/L, phosphate concentration of  $12 \pm 1$  mg/L, mixed suspended solids (MLSS) of 5000 mg/L, and the average flow rate of 0.5 L/h under a constant pressure of 5 bar.

The average permeate flux and suspended solids of the membrane bioreactor (MBR) are presented in Fig. 6, the membrane's average permeate flux was 372 LMH, and the average MLSS was 5,000 mg/L. Initially, MLSS concentration was approximately 6,000 mg/L, but it decreased to an average of approximately 4,863 mg/L after several days of operation. This indicated that despite the intake of wastewater and sludge from the same source, the membrane bioreactor was in the adaptation period, resulting

in a decline in MLSS concentration. The variability was primarily attributed to fluctuations in effluent wastewater characteristics during operation, including variations in water quality and influencing factors such as pH and aeration. The study observed an inverse correlation between these parameters: higher MLSS in MBR corresponds to lower permeate flux due to the attachment of activated sludge on the surface of membrane. It can also be proved when using the membrane for filtering the turbidity, the flux was high with 9,608 LMH, however, when combining in MBR with MLSS of 5,000 mg/L, the flux was only 382 LMH (Fig. 6).

The permeate flux of the membrane bioreactor (MBR) exhibited a significant initial reduction within the first minutes of operation, followed by a gradual decline before being stabilized within the range of 300 LMH to 400 LMH. Subsequent backflushes after 8 hours operation led to the recovery of permeate flux, achieving rates between 360 to 420 LMH (Fig. 7). This recovery suggests that membrane pore clogging was completely reversible. Zhang *et al.* (2014) similarly noted that fouling constitutes the primary resistance in membrane filtration processes, highlighting the reversible nature of the clogging observed in this study (Zhang *et al.* 2014). Belli *et al.* (2014) conducted research on an MBR for municipal sewage treatment, identifying polysaccharides and proteins—major fouling agents in MBRs—in their reactor (Belli *et al.* 2014). Exopolysaccharides (EPS) were specifically identified as the primary contributors to fouling in MBRs (Jiang *et al.* 2023). Notably, in these experiments, the permeate flux over a 30-day period was recovered without resorting to chemical cleaning. These strategies aim to reduce fouling potential and enhance the operational efficiency of MBR systems by using the hydraulic washing and air backwashing method after 8 hours operation. However, the observed fouling behavior indicated the gradual buildup of EPS, biomass, and particles on the membrane surface and within its pores. Over time, these layers may become increasingly compressed and resistant to backwashing. Therefore, a more thorough examination of fouling composition, layer thickness, and cleaning efficacy is essential to enhance the understanding of long-term membrane function.

The average turbidity treatment efficiency was recorded at 99.9%, COD removal efficiency was 77.28%, ammonium nitrogen removal efficiencies reached 93.6%, respectively (Fig. 8). This suggested that integrating membrane and activated sludge could improve the contaminant of organic and ammonium removal performance with short hydraulic retention time of 6 hours. In MBR, microbial community was normally aerobic heterotrophs for carbon breakdown, nitrifying bacteria for ammonia oxidation, and polyphosphate accumulating organisms (PAOs) for phosphorus uptake. By keeping a high level of microbial concentration (MLSS of 5,000 mg/L), a large number of organics could be degraded up to 77.28%, in which in Proteobacteria and Bacteroidetes are often dominant in the sludge responsible for COD removal (Tari *et al.* 2025). Moreover, when MBR was operated with at high sludge ages (SRT) of 30 days, the nitrification process was successfully achieved with 93.6% by ammonia-oxidizing bacteria and nitrite-oxidizing bacteria

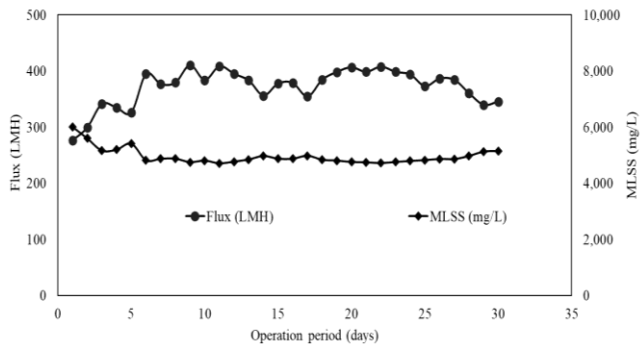


Fig. 6 Flux and MLSS concentration variation of MBR in 30 days operation

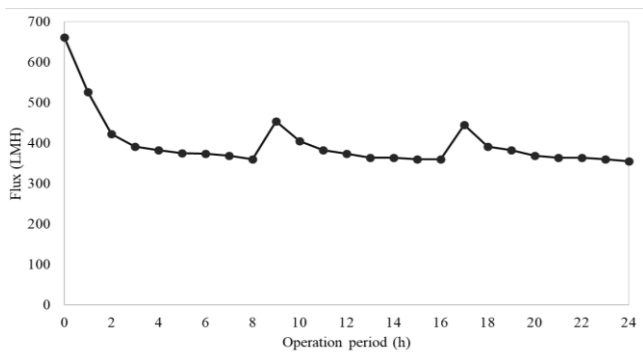


Fig. 7 The fluctuation in flux after backwash after 8 hours operation

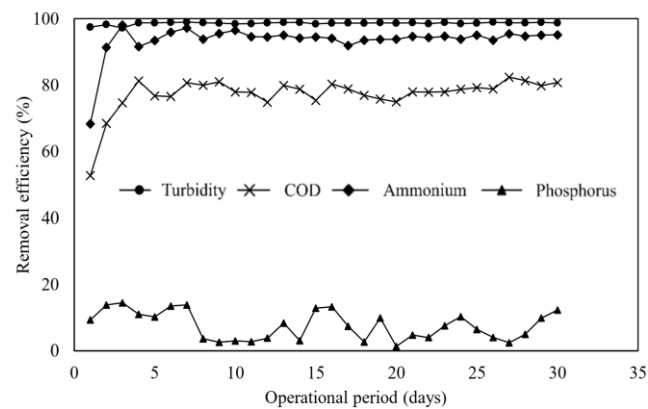


Fig. 8 The contaminants removal efficiency of MBRs in 30 days operation

(Kasiński *et al.* 2025). Tari *et al.* (2025) showed that a moving-bed MBR with increased nitrifier amount could obtain complete ammonium oxidation (>99%  $\text{NH}_4^+$  removal). However, the phosphorus removal efficiency was not high in this MBR system with only 7.59%. This can be explained by the reason that MBR system was operated at high sludge retention time to minimize sludge production, therefore, excessively long SRT could lower biological phosphorus removal performance. The main mechanisms were a decline in PAO abundance/activity due to competition with glycogen accumulating organisms (GAOs) and accumulation of inert or non-active biomass, leading to less phosphorus being removed with wasted sludge (Gong *et al.*

2024, Srivastava *et al.* 2023). Therefore, to improve the phosphorus removal efficiency which is sufficient for effective nutrient management in wastewater treatment, the MBR system can be modified by changing to an anaerobic-anoxic-oxic configuration in which can enhance denitrifying PAO activity and internal carbon utilization, achieving around 94% phosphate removal even at SRT of 30 days (Gong *et al.* 2024).

Typically, the permeate flux remained consistent during the operation and excellent efficiency was exhibited in removing MLSS and maintaining low turbidity in the effluent. Nevertheless, the elimination of additional substances like COD, phosphate, and nitrogen primarily relied on function of activated sludge since the membrane's function was limited to capturing substances that were smaller than its pore size.

### 3.5 Characteristics of membrane from waste

#### FTIR spectrum

FTIR spectrum of the absorbance of the PS membrane was recorded in Fig. 9. Absorption peaks were observed at wave numbers 3059.3 and 3024.8  $\text{cm}^{-1}$ , attributed to aromatic C-H stretching vibrations. Additionally, three absorption peaks were observed at wave numbers 1600.9, 1492.2, and 1450.9  $\text{cm}^{-1}$ , corresponding to aromatic C=C stretching vibrations. The absorption peaks at wave numbers 753.3 and 696.2, which are caused by C-H out-of-plane bending vibrations, point to the presence of a single substituent on the benzene ring (Smith, 2021). The presence of a peak at 965.8  $\text{cm}^{-1}$ , was indicative of trans-1,4 units (Wang *et al.* 2019), which can demonstrate the presence of polybutadiene - an additive that helps increase the resistance of PS.

#### SEM images

A sponge-like structure with apparent longitudinal cavities was revealed in the membrane cross-sections. Although they are prevalent in the membrane, the water does not completely permeate through the membrane. Especially, it was discovered that a coating stops these vertical pore points from developing on the membrane surface. This is primarily caused by instantaneous precipitation on the membrane surface, which impacts both the number of pores and the membrane's quality. Kinetic changes during phase inversion are important for the formation of membrane structures. The slow rate of exchange between solvents/non-solvents, i.e. soaking/precipitation process is the reason for the formation of the sponge shape. In addition, the slow speed prevents the formation of voids in the cross-section.

The morphologies of the membrane after being immersed in activated sludge for 60 days after being washed with 0.5% HCl solution were observed via SEM. After 60 days in activated sludge, the membrane was fouled with activated sludge, therefore, the flux was reduced. Upon washing with 0.5% HCl, the activated sludge on the membrane was removed and turned to the original with the clean surface (Fig. 10). From Fig. 10, it can be seen that the fouled membrane was easy to be cleaned with diluted acid, therefore, in the operation period, the membrane in the

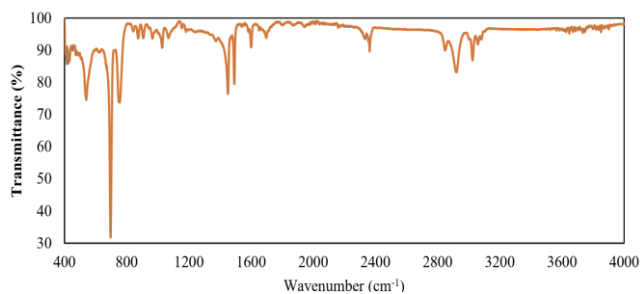


Fig. 9 FTIR of the original membrane in MBR

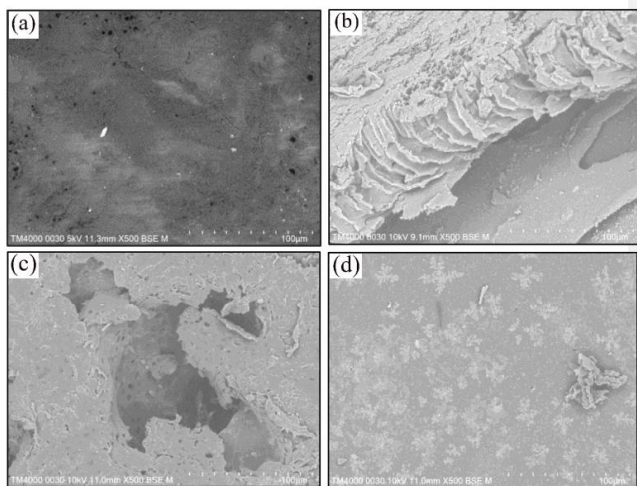


Fig. 10 SEM images of the original membrane in MBR (a), the original membrane with cross-section (b), the used membrane in activated sludge (c) and membrane after being washed with 0.5% HCl (d)

MBR system should be frequently rinsed to recover the performance.

### 3.6 The feasibility of membrane fabrication from polystyrene waste in the view of environmental protection

Due to the growing demand for filtration membranes in wastewater treatment across many industries, it is essential to ensure an adequate supply of raw materials to support the production process of these membranes. In this study, using raw materials obtained from polystyrene waste not only promotes the sustainable growth of membranes but also significantly decreases the amount of waste plastic. In an age where sustainability is of the utmost importance, it is possible to recycle the solid wastes as a valuable, innovative resource. Integrating the reuse of plastic in membrane fabrication can effectively align with sustainable development goals, promoting sustainable production and consumption patterns. Recycling plastic can not only safeguard the environment but also help preserve current natural resources.

In this research, filtration membranes made from waste plastic (polystyrene waste) show high feasibility when applied in practice with MBR system for domestic wastewater treatment to replace existing commercial membranes on the market. In the obtained results, the filter membrane in MBR has a water flux of 372 LMH higher

than that of commercial 0.4 $\mu$ m microfiltration (MF) membrane (Kubota Corp, Japan) with a flux of  $11.25 \pm 1.67$  LMH during the MBR operation (Ittisupornrat and Theeparaksapan, 2023) and 0.1 $\mu$ m MF membrane (Origin Water, China) with filtration flux of 8-10 LMH at MLSS over 15 g/L in a pilot scale MBR operation (He *et al.* 2023). The high efficiency in turbidity removal showed positive results with an average efficiency of over 75%. After MBR treatment, the effluent with a turbidity of around 1.5 NTU, COD of  $50 \pm 2$  mg/L, ammonium concentration of  $3.5 \pm 0.12$  mg/L, phosphate concentration of  $11 \pm 0.5$  mg/L. The results confirm the technological viability of recycling polystyrene waste to produce membranes with enhanced treatment capabilities, hence illustrating its potential for sustainable wastewater management.

The financial aspect should be considered in addition to the technical and environmental feasibility when fabricating a membrane from plastic waste. In this study, the membrane preparation was a straightforward phase inversion method that utilized NMP as a solvent, without the need for costly additives or surface modification steps. The raw material, post-consumer polystyrene waste, was broadly accessible at minimal to no cost. Consequently, the basic material cost of membrane fabrication from waste was less than that of the commercial membrane. Additionally, the cost reduction for plastic waste recovery not only encompasses the cost of membrane production but also the cost of treating the plastic waste, which in turn reduces the potential for the use of fossil fuels in polystyrene production and environment pollution. The proposed membrane production method not only demonstrates technical proficiency but also aligns with circular economy concepts, offering an environmentally advantageous approach for the valorization of plastic waste.

In the future, this technology could be more broadly used in decentralized and small-scale wastewater treatment systems, especially in areas with significant plastic waste challenges. Nonetheless, various challenges remain in the realm of extensive implementation and commercialization. This encompasses the optimization of membrane cleaning techniques to reduce scaling and fouling potential, the automation of the casting process for large-scale manufacturing, the improvement of long-term membrane durability, and the assurance of uniform waste plastic quality. Membrane surface properties before and after should be also studied, consisting of zeta potential, contact angle, surface roughness, and pore size distribution, and mechanical stability to confirm the membrane's structural integrity and aging characteristics. The initial findings suggest that the flux of the polystyrene membranes from waste can be recovered, when employed with appropriate backwashing methods. Resolving these challenges is essential to enhance the process's efficiency and make the capital and operational cost competitive with conventional membrane technologies.

## 4. Conclusions

In this work, the polystyrene waste was used to fabricate membrane which can be applied for the membrane bioreactor applied in wastewater treatment. The manufacturing process

of the membrane was influenced by various parameters, including the resin-to-solvent ratio, the coagulation time of the membrane in distilled water, the membrane thickness, etc... The polystyrene plastic was compatible with NMP solvent with the resin-to-solvent (mg: mL) ratio of 4:25, the optimal time coagulation was 20 min and the thickness of the membrane was 350  $\mu\text{m}$ . The MBR tank utilized the flat sheet membranes model constructed from polystyrene waste membrane. The results indicated that the sludge exhibited stable operation throughout the operating period, the average removal efficiency was around 80% for COD removal, 94% for ammonium removal and ~8% for phosphate removal. The typical turbidity after filtering was around 1.5 NTU. This confirmed that membranes fabricated from waste can be used in MBR for domestic wastewater treatment with high performance. Therefore, using polystyrene waste as a raw material for membrane fabrication is a feasible idea for technical and environmental solution, achieving sustainable development in the context of circular economy.

## Acknowledgments

The authors very much appreciate the support from Nguyen Tuan Anh and Pham Dinh Thang for their assistance in samples analysis. This work is part of the T2025-112 project, which received funding from Ho Chi Minh City University of Technology and Education, Vietnam.

## References

- Belli, T.J., Bernardelli, J.K.B., Amaral, P.A.P., Costa, R.E., Amaral, M.C.S. and Lapolli, F.R. (2014), "Biological nutrient removal in a sequencing batch membrane bioreactor treating municipal wastewater", *Desalin. Water Treat.*, **55**(6), 1654-1661. <https://doi.org/10.1080/19443994.2014.952961>
- Chaleshtori, N.S., Shamskilani, M., Babaei, A. and Behrang, M. (2022), "Municipal wastewater treatment and fouling in microalgal-activated sludge membrane bioreactor: Cultivation in raw and treated wastewater", *J. Water Process Eng.*, **49**, 103069. <https://doi.org/10.1016/j.jwpe.2022.103069>
- Fan, Z., Zeng, W., Liu, H., Jia, Y. and Peng, Y. (2022), "A novel partial denitrification, anammox-biological phosphorus removal, fermentation and partial nitrification (PDA-PFPN) process for real domestic wastewater and waste activated sludge treatment", *Water Res.*, **217**, 118376. <https://doi.org/10.1016/j.watres.2022.118376>
- Ferrera, E., Ruigómez, I. and Vera, L. (2024), "Pilot scale application of a rotating hollow fibre membrane for direct membrane filtration of domestic wastewater", *J. Water Process Eng.*, **5**, 104755. <https://doi.org/10.1016/j.jwpe.2023.104755>
- Fito Nure, J. and Nkambule, T.T.I. (2023), "The recent advances in adsorption and membrane separation and their hybrid technologies for micropollutants removal from wastewater", *J. Ind. Eng. Chem.*, **126**, 92-114. <https://doi.org/10.1016/j.jiec.2023.06.034>
- Garcia-Ivars, J., Wang-Xu, X. and Iborra-Clar, M.I. (2017), "Application of post-consumer recycled high-impact polystyrene in the preparation of phase-inversion membranes for low-pressure membrane processes", *Sep. Purif. Technol.*, **175**, 340-351. <https://doi.org/10.1016/j.seppur.2016.11.061>
- Gong, B., Zhang, K., Su, M., Yang, J., Peng, C. and Wang, Y. (2024), "Efficient nitrogen and phosphorus removal performance and microbial community in a pilot-scale anaerobic/ anoxic/oxic (AOA) system with long sludge retention time: Significant roles of endogenous carbon source", *Environ. Res.*, **263**, 120164. <https://doi.org/10.1016/j.envres.2024.120164>
- Guembri, M., Saidi, N., Neifar, M., Jaouani, A., Heran, M. and Ouzari, H.I. (2020), "Performance evaluation of submerged membrane bioreactor for model textile wastewater treatment", *Membr. Water Treat.*, **11**(2), 123-130. <https://doi.org/10.12989/mwt.2020.11.2.123>
- He, C., Wang, K., Wang, W., Luo, J., Fang, K. (2023), "Chemically enhanced high-loaded membrane bioreactor (CE-HLMBR) for A-stage municipal wastewater treatment: Pilot-scale experiments and practical feasibility evaluation", *Sep. Purif. Technol.*, **307**, 122853. <https://doi.org/10.1016/j.seppur.2022.122853>
- He, J., Zhang, J., Cui, F., Tan, X., Zheng, X., Cheng, R. (2024), "Global techno-economic analysis of MBR for hospital wastewater treatment", *Sci. Total Environ.*, **956**, 177172. <https://doi.org/10.1016/j.scitotenv.2024.177172>
- Ittisupornrat, S. and Theeparaksapan, S. (2023), "Greywater treatment performance of a pilot-scale membrane bioreactor and characteristics of bacterial biofilm signatures in permeate effluent", *J. Water Process Eng.*, **55**, 104098. <https://doi.org/10.1016/j.jwpe.2023.104098>
- Jiang, J., Sohn, W., Almunashiri, A., Phuntsho, S., Wang, Q., Fregui, S., El-Saliby, I. and Shon, H.K. (2024), "Feasibility study of powdered activated carbon membrane bioreactor (PAC-MBR) for source-separated urine treatment: A comparison with MBR", *Desalination*, **580**, 117544. <https://doi.org/10.1016/j.desal.2024.117544>
- Jiang, Y., Zhang, X., Poh, L.S. and Jern Ng, W. (2023), "Effect of free nitrous acid on extracellular polymeric substances production and membrane fouling in a nitrification membrane bioreactor", *Chemosphere*, **340**, 139913. <https://doi.org/10.1016/j.chemosphere.2023.139913>
- Kasiński, S., Kowal, P. and Czerwionka, K. (2025), "Advanced technologies for nitrogen removal and recovery from municipal and industrial wastewater", *Materials*, **18**(7), 1422. <https://doi.org/10.3390/ma18071422>
- Katariya, H.N. and Patel, T.M. (2022), "Cellulose acetate membrane preparation by phase inversion to estimate optimized parameters and its performance study", *Membr. Water Treat.*, **13**(3), 139-145. <https://doi.org/10.12989/mwt.2022.13.3.139>
- Khaled, M., Noby, H., Aissa, W.A. and El-Shazly, A.H. (2020a), "Facile fabrication of porous and hydrophilic polystyrene membranes using recycled waste", *Mater. Sci. Forum*, **1008**, 39-46. <https://doi.org/10.4028/www.scientific.net/MSF.1008.39>
- Khaled, M., Noby, H., Mansor, E.S., El-Shazly, A.H. and Aissa, W.A. (2020b), "Water purification using recycled polymeric microfiltration membranes", *Int. J. Appl. Energy Syst.*, **2**, 122-126. <https://doi.org/10.21608/IJAES.2020.169930>
- Ko, S., Kwon, Y.J., Lee, J.U. and Jeon, Y.P. (2020), "Preparation of synthetic graphite from waste PET plastic", *J. Ind. Eng. Chem.*, **83**, 449-458. <https://doi.org/10.1016/j.jiec.2019.12.018>
- Lai, W.H., Hong, C.Y., Tseng, H.H. and Wey, M.Y. (2021), "Fabrication of waterproof gas separation membrane from plastic waste for CO<sub>2</sub> separation", *Environ. Res.*, **195**, 110760. <https://doi.org/10.1016/j.envres.2021.110760>
- Lee, G., Park, S.I., Shi, H.Y., Joh, H.I., Kim, S.S. and Lee, S. (2023), "Simultaneous reactions of sulfonation and condensation for high-yield conversion of polystyrene into carbonaceous material", *J. Ind. Eng. Chem.*, **122**, 426-436. <https://doi.org/10.1016/j.jiec.2023.02.042>
- Malovanyy, A., Sakalova, H., Yatchyshyn, Y., Plaza, E. and Malovanyy, M. (2013), "Concentration of ammonium from

- municipal wastewater using ion exchange process”, *Desalination*, **329**, 93-102.  
<https://doi.org/10.1016/j.desal.2013.09.009>
- Sarvajith, M., Nandini, D. and Nancharaia, Y.V. (2024), “Comparative evaluation of activated sludge and aerobic granular sludge for biological treatment of real domestic wastewater with oxytetracycline dosing”, *J. Environ. Chem. Eng.*, **12**, 112482. <https://doi.org/10.1016/j.jece.2024.112482>
- Singh, E., Kumar, A., Khapre, A., Saikia, P., Shukla, S.K. and Kumar, S. (2020), “Efficient removal of arsenic using plastic waste char: Prevailing mechanism and sorption performance”, *J. Water Process Eng.*, **33**, 101095.  
<https://doi.org/10.1016/j.jwpe.2019.101095>
- Sinharoy, A., Min, J.H. and Chung, C.M. (2024), “Enhanced nitrogen removal from high-strength ammonia containing wastewater using a membrane aerated bioreactor (MABR)”, *Membr. Water Treat.*, **15**(2), 59-66.  
<https://doi.org/10.12989/mwt.2024.15.2.059>
- Smith, B.C. (2021), “The infrared spectra of polymers III: Hydrocarbon polymers”, *Spectroscopy*, **36**(11), 22-25.  
<https://doi.org/10.56530/spectroscopy.mh7872q7>
- Srivastava, G., Kapoor, A. and Kazmi, A.A. (2023), “Improved biological phosphorus removal under low solid retention time regime in full-scale sequencing batch reactor”, *Sustainability*, **15**(10), 7918. <https://doi.org/10.3390/su15107918>
- Statista (2024), Global plastic production 1950-2022, Statista Research Department, Hamburg, Germany.  
<https://www.statista.com/statistics/282732/global-production-of-plastics-since-1950/>
- Tari, K., Samarghandi, M.R., Reza Shokoohi, R., Asgari, G., Poorasgari, E., Karami, P., Afshar, S. (2025), “Nutrient removal performance and microbial composition analysis in hybrid membrane bioreactor for municipal wastewater treatment”, *Bioprocess Biosyst. Eng.*, **48**(4), 665-678.  
<https://doi.org/10.1007/s00449-025-03135-3>
- Teixeira, M.R., Ismail, A., Medronho, B., Alves, L., Pedrosa, J.F.S., Ferreira, P.J.T., Serrão Sousa, V. and Rosa da Costa, A.M. (2024), “Nanofibrillated cationic cellulose derivatives as flocculants for domestic wastewater treatment”, *J. Water Process Eng.*, **58**, 104817.  
<https://doi.org/10.1016/j.jwpe.2024.104817>
- Tran, A.T.K., Pham, T.T., Nguyen, Q.H., Hoang, N.T.T., Bui, D.T., Nguyen, M.T., Nguyen, M.K. and Van der Bruggen, B. (2020), “From waste disposal to valuable material: Sulfonating polystyrene waste for heavy metal removal”, *J. Environ. Chem. Eng.*, **8**, 104302. <https://doi.org/10.1016/j.jece.2020.104302>
- Unicef (2024), Water scarcity - Addressing the growing lack of available water to meet children’s needs, Unicef, New York, U.S.S. <https://www.unicef.org/wash/water-scarcity>
- United Nations Development Programme (2023), Why aren’t we recycling more plastic?, United Nations Development Programme, New York, U.S.A.  
<https://stories.undp.org/why-arent-we-recycling-more-plastic>
- Vunain, E., Masoamphambe, E.F., Mpeketula, P.M.G., Monjerezi, M. and Etale, A. (2019), “Evaluation of coagulating efficiency and water borne pathogens reduction capacity of Moringa oleifera seed powder for treatment of domestic wastewater from Zomba, Malawi”, *J. Environ. Chem. Eng.*, **7**(3), 103118.  
<https://doi.org/10.1016/j.jece.2019.103118>
- Wang, F., Chang, L., Hu, Y., Wu, G. and Liu, H. (2019), “Synthesis and properties of in-situ bulk high impact polystyrene toughened by high cis-1,4 polybutadiene”, *Polymers*, **11**(5), 791. <https://doi.org/10.3390/polym11050791>
- Wang, Y., He, G., Shao, Y., Zhang, D., Ruan, X., Xiao, W., Wu, X. and Jiang, X. (2018), “Enhanced performance of superhydrophobic polypropylene membrane with modified antifouling surface for high salinity water treatment”, *Sep. Purif. Technol.*, **214**, 11-20. <https://doi.org/10.1016/j.seppur.2018.02.011>
- Xu, X., Chen, G., Wei, J., Qin, Y., Tang, R., Wang, L., Wei, H., Zhou, C., Wu, J., Zhao, X. and Zhou, Z. (2024), “Effects of competitive cations and dissolved organic matter on ammonium exchange and up-concentration properties of ion exchangers from domestic wastewater under multicycle exchange - regeneration operation”, *Sep. Purif. Technol.*, **345**, 127274.  
<https://doi.org/10.1016/j.seppur.2024.127274>
- Yadav, M., Upadhyaya, S., Singh, K., Chaturvedi, K.T. and Vashishtha, M. (2022), “Morphological study of synthesized PVDF membrane using different non-solvents for coagulation”, *Membr. Water Treat.*, **13**(4), 173-181.  
<https://doi.org/10.12989/mwt.2022.13.4.173>
- Yadav, M., Upadhyaya, S. and Singh, K. (2024), “Preparation and characterization of PVDF Flat sheet membrane for VMD: Effect of different non-solvent additives and solvents in dope solution” *Membr. Water Treat.*, **15**(4), 163-176.  
<https://doi.org/10.12989/mwt.2024.15.4.163>
- Yang, Y., Deng, W., Zhang, J., Dzakpasu, M., Chen, R., Wang, X.C. and Hu, Y. (2023), “A novel precoated anaerobic dynamic membrane bioreactor for real domestic wastewater treatment: In-situ formation, filtration performance and characterization of dynamic membrane”, *Chem. Eng. J.*, **466**, 143313.  
<https://doi.org/10.1016/j.cej.2023.143313>
- Zhang, Y., Zhang, M., Wang, F., Hong, H., Wang, A., Wang, J., Weng, X. and Lin, H. (2014), “Membrane fouling in a submerged membrane bioreactor: Effect of pH and its implications”, *Bioresour. Technol.*, **152**, 7-14.  
<http://doi.org/10.1016/j.biortech.2013.10.096>
- Zhuang, Z., Wu, K., Zhang, T., Li, Y., Yang, D., Yue, X. and Qiu, F. (2024), “One-step fabrication of robust Stenocara beetle-inspired membrane deriving from polyethylene terephthalate (PET) waste for enhancing emulsion separation”, *Sep. Purif. Technol.*, **351**, 128128.  
<https://doi.org/10.1016/j.seppur.2024.128128>