

Article

Synthesis of Polysulfone/PVP/Metal–Organic Framework Membranes for Batik Wastewater Treatment

Sutrasno Kartohardjono ^{1,*} , Angelia Angelia ¹, Shakila Salma Hanifa ¹, Khalila Siti Bramantyo ¹ and Woei Jye Lau ² 

¹ Department of Chemical Engineering, Faculty of Engineering, Universitas Indonesia, Depok 16424, Indonesia; angelia21@ui.ac.id (A.A.); shakila.salma@ui.ac.id (S.S.H.); khalila.siti@ui.ac.id (K.S.B.)

² Advanced Membrane Technology Research Center, Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia, Skudai 81310, Malaysia; lwoeijye@utm.my

* Correspondence: sutrasno@che.ui.ac.id

Abstract

This study produced and analyzed composite membranes composed of polysulfone (PSf), polyvinylpyrrolidone (PVP) and Metal–Organic Framework (ZIF-8) for treating effluent generated by the Batik industry. The incorporation of ZIF-8 was performed to enhance membrane efficiency. The findings indicated that ZIF-8 markedly enhanced hydrophilicity and pure water flux of membranes. The M-0.5 membrane containing 0.5 g of ZIF-8 demonstrated superior performance, with a water contact angle of 49.4° and a porosity of 83.5%. In contrast, the ZIF-8-free membrane (M-0) displayed a water contact angle and porosity of 66.3° and 76.7%, respectively. These combined characteristics enabled the M-0.5 membrane to achieve the highest pure water flux of 197.1 L m^{−2} h^{−1} at 5 bar. All membranes attained complete total suspended solids (TSS) rejection at 100% efficiency. Turbidity rejection rates ranged from 75% to 92%, whilst color rejection rates ranged from 65.7% to 87.6%. The maximum chemical oxygen demand (COD) rejection observed was 57.9%, achieved by the M-0.25 membrane (0.25 g of ZIF-8) at an operational pressure of 4 bar. Meanwhile, for permeability and hydrophilicity, the ideal loading is 0.5 g of ZIF-8 (M-0.5). This concentration yielded the optimal equilibrium of porosity (83.5%), the minimal water contact angle (49.4°), and the maximal pure water flux (197.1 L m^{−2} h^{−1}). Nonetheless, the TDS rejection rate was rather low at 8.0–21.1%. The membrane effectively preserved effluent pH stability between 7.9 and 8.3. The aggregation of ZIF-8 at elevated concentrations diminished mechanical strength and selectivity. Additional optimization is required to equilibrate these performance indicators.

Keywords: batik wastewater; hydrophilicity; MOF; PSf; PVP



Received: 24 April 2026

Revised: 25 May 2026

Accepted: 12 June 2026

Published: 17 June 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

The Batik industry in Indonesia is an essential component of the textile sector, with significant cultural and economic importance. Batik was designated as a UNESCO intangible heritage of humanity in 2009 for its Outstanding Universal Values [1]. While Batik industry provides a substantial livelihood for craftspeople across Indonesia, its business growth is concomitant with an increase in liquid waste output [2]. Effluent from the Batik dyeing process typically contains synthetic colors, complex organic compounds, and inorganic chemicals that are difficult to biodegrade. Batik wastewater is considerably more complex than conventional printing or dyeing effluent owing to the traditional “wax-resist” dyeing

technique. Batik employs a diverse array of synthetic dyes (naphtol, indigosol, and remasol) in conjunction with organic mordants and byproducts from the wax-removal process, in contrast to contemporary commercial dyeing, which often uses homogeneous reactive dyes. These generate a high-molecular-weight organic burden that is notably resistant to biodegradation.

The improper wastewater treatment can lead to significant contamination of aquatic ecosystems, evidenced by elevated turbidity, high chemical oxygen demand (COD), increased biochemical oxygen demand (BOD), and diminished dissolved oxygen (DO). This state can disturb ecological equilibrium and pose harmful risks to aquatic organisms and people, as certain dyes are carcinogenic [3]. Present techniques for managing Batik wastewater predominantly employ traditional processes, including coagulation–flocculation, adsorption, and biological treatment. Each of these processes has distinct advantages, including the ability to reduce concentrations of color and organic debris. Nonetheless, their efficiency remains constrained [4].

The coagulation–flocculation approach can reduce color levels by 70–85%, the adsorption procedure achieves approximately 80%, and the biological method attains roughly 60–75% for COD reduction [5]. The COD levels of the Batik wastewater typically range between 150 and 300 mg/L [6]. In contrast, the quality criterion for liquid waste in the textile industry, as stipulated by the Ministry of Environment (Indonesia) Regulation No. 5 of 2014, is a maximum of 100 mg/L [7]. Among the most promising separation and purification technologies to treat wastewater, membrane technology has emerged as a significant advancement due to its numerous benefits. With its compact size, low energy requirement, and high treatment efficiency, membrane technology offers numerous prospects in wastewater treatment. It has the potential to bridge the economical and sustainability gap, offering environmental friendliness and easy accessibility to many [8].

Industrial microfiltration and ultrafiltration membranes are mainly produced from organic polymers such as polyvinylidene fluoride (PVDF), polysulfone (PSf), polyether sulfone (PES), polyacrylonitrile (PAN), and polytetrafluoroethylene (PTFE). Polysulfone (PSf) membranes are among the most prevalent membrane materials. PSf is especially preferred for its exceptional properties, including robust mechanical strength, thermal stability, and chemical stability [9]. The PSf membranes also are comparatively economical in relation to other polymer-based membranes [10]. It offers a cost-effective alternative without sacrificing quality and exhibit elevated selectivity–permeability ratios. The asymmetric PSf membranes can be readily made via the phase inversion process [11]. This technique entails submerging the polymer casting solution in a coagulation bath containing a non-solvent solution, i.e., water [12]. Nonetheless, a significant issue associated with PSf membranes is their hydrophobic nature [9]. This attribute is significantly detrimental to filtration, as it may constrain the rate of water passage through the membrane and result in lower water flux [13]. The hydrophobic nature of PSf membranes can also attract hydrophobic organic pollutants, leading to surface fouling [14].

Membrane additives are compounds incorporated into membrane materials to enhance their performance. Their presence can improve various membrane properties. For instance, the incorporation of a polyvinylpyrrolidone (PVP) into PSf membranes has been demonstrated to enhance pore formation and membrane hydrophilicity [15]. It occurs because PVP functions as a pore-forming agent, facilitating enhanced regulation of pore size and distribution within the PSf membrane. It also developed a more homogeneous and optimized pore structure [16]. While PVP enhances hydrophilicity and antifouling characteristics, it concurrently reduces the mechanical strength of the membrane [17]. The incorporation of PVP may reduce elongation, making the membrane rigid and potentially brittle [7].

To mitigate these constraints, researchers have investigated integrating sophisticated materials, including Metal–Organic Frameworks (MOFs), into membranes [18]. MOFs are a category of porous crystalline materials consisting of metal ions and organic linkers [19]. They are recognized for their remarkably high surface area, adjustable porosity, and chemical usefulness. Among the several categories of MOFs, Zeolitic Imidazolate Framework-8 (ZIF-8) has garnered considerable interest regarding membrane improvement. This results from their superior attributes, such as thermal and chemical durability, arising from robust bonds between their constituents, namely Zn(II) metal ions and 2-methylimidazole linkers [20].

ZIF-8 incorporated membranes are exceptionally efficient for separating diverse compounds across numerous industrial applications [21]. Gozali Balkanloo et al. [22] demonstrated that incorporating ZIF-8 into PSf membranes increased porosity from 30% to 69% and markedly reduced the contact angle, indicating increased hydrophilicity. The study also showed that incorporating ZIF-8 enhanced the membrane's antifouling characteristics. Separately, a study demonstrated that, for long-term use, incorporating ZIF-8 enhanced membrane elongation [23,24]. The objective of this study is to study the impacts of ZIF-8 loadings on the properties of PSf/PVP membranes for the treatment of Batik wastewater. The dope solutions were prepared using DMAc as the solvent and the membranes were fabricated via the phase-inversion method.

2. Materials and Methods

Polysulfone (PSf, UDEL P-1700 NT11) used in this work was obtained from Solvay (Brussels, Belgium). Polyvinyl pyrrolidone (PVP, MW: 29,000 g/mole) as an additive, and *N*, *N*-Dimethylacetamide (DMAc) as the solvent were received from Sigma Aldrich (St. Louis, MI, USA) and Merck Jakarta, Indonesia, respectively. Zeolitic Imidazolate Framework-8 (ZIF-8) with a particle size of approximately 2 µm was provided by CV Inovasi Teknologi Nano, Kota Medan, Indonesia.

2.1. Pretreatment of Batik Wastewater

The pre-treatment of Batik wastewater was performed using the coagulation–flocculation process. To implement this approach, 300 mL of Batik wastewater was placed in a beaker at ambient temperature, and the pH was adjusted to 4. Then, 500-ppm polyaluminum chloride (PAC) was added to the solution and agitated at 200 rpm for 1 h. The selection of pH and concentration was based on a previous study that found the coagulation–flocculation process for batik wastewater was optimal under these conditions [7]. The agitation velocity was subsequently reduced to 40 rpm for 10 min. The solution was allowed to remain undisturbed for 30 min to facilitate settling. The resulting solution was subsequently filtered using a filter paper to isolate the suspended particles. The pre-treated Batik wastewater samples were then assessed for pH and total dissolved solids (TDS) concentration using a Water Quality Meter AZ86031 (AZ Instrument, Taichung, Taiwan). COD and color levels were determined using a UV-vis Spectrophotometer (Bell Engineering, Monza, MI, Italy). Meanwhile, the total suspended solids (TSS) concentration was measured using a glass fiber filter.

2.2. Membrane Preparation

The preparation of the PSf/PVP/ZIF-8 membrane involved mixing PSf, PVP, and ZIF-8 powder in DMAc solvent in a 250 mL beaker. The mixture was stirred at 200 rpm for 30 min at 20 °C. The composition of the dope solution for PSf/PVP/ZIF-8 membranes is presented in Table 1. The procedure continued by increasing the stirring speed to 300 rpm and raising the temperature gradually from 20 °C to 60 °C over 20 min. A constant temperature of

60 °C was then held until a homogeneous solution was achieved. To ensure homogeneity, the stirring speed was further increased to 500 rpm and kept for 5 h. Following this, the polymer solution was allowed to sit at room temperature for 12 h to eliminate bubbles. The membrane's thickness was set by adjusting the membrane roller to "6" on the scale, corresponding to 150 µm. The dope solution was then poured onto a dry glass plate and smoothed using the membrane roller. The glass plate together with polymeric film was soaked in deionized water for 12 h. At last, the PSf flat sheet membrane was dried at room temperature for 6 h [7].

Table 1. The composition of dope solution.

Code	PSf (g)	PVP (g)	DMAc (mL)	ZIF-8 (%wt)
M-0	14	1	85	0
M-0.25	14	1	85	0.25
M-0.5	14	1	85	0.5
M-1.0	14	1	85	1.0

2.3. Membrane Characterization

Field Emission Scanning Electron Microscopy (FE-SEM, FEI inspect F50, Hillsboro, OR, USA) was employed to examine the surface morphology of the membranes. The functional group analysis was conducted using Fourier Transform Infra-Red (FTIR, Nicolet™ iS50 FTIR Spectrometer, Madison, WI, USA) to identify the functional groups that are present in the synthesized membrane and also to observe any structural changes upon the addition of ZIF-8. The surface wettability of the PSf/PVP/ZIF-8 membranes was evaluated using water contact angle goniometer. The porosity of the PSf/PVP/ZIF-8 membranes was evaluated using the dry-wet mass method. Meanwhile, the mechanical strength of the membranes were measured by Universal Tensile Meter (Shimadzu 10 kN, Kyoto, Japan), and the membrane roughness were measured by Atomic Force Microscope (AFM).

To observe membrane morphology by SEM, the membrane sample is cut into small pieces; for cross-section analysis, the membrane is usually broken in liquid nitrogen to obtain a neat fracture without damaging the pore structure, revealing the active layer and porous sublayer. For FTIR examination, the dried membrane is used directly. Infrared light is passed through the sample to detect absorbance at specific wavelengths (range 500–4000 cm^{−1}). For AFM examination, a small piece of dry membrane is placed on a flat surface. The AFM instrument uses a cantilever to scan the membrane surface, detecting nanoscale peaks and valleys. The contact angle was measured by dropping water droplets at ten different points of the membrane surface. The angle formed by the water droplet was measured using an angle-measuring application. To determine the mechanical strength of the membrane, it is cut into specific shapes in accordance with tensile testing standards. The sample is then slowly pulled until it breaks.

The porosity of the PSf/PVP/ZIF-8 membranes was evaluated using the dry-wet mass method. This method is based on the principle that the pores within a membrane can be filled with liquid, usually water. At the same time, the polymer matrix itself does not absorb a significant amount of liquid. The overall porosity of the membrane (ε , %) was calculated using the following equation [25]:

$$\varepsilon = \frac{W_w - W_d}{\rho_w A l} \times 100 \quad (1)$$

where W_w and W_d are the weights of wet and dry membrane, respectively, ρ_w is water density, and A and l are the area and thickness of the membrane, respectively.

2.4. Membrane Performance Evaluation

The membrane's performance in the ultrafiltration process was evaluated by examining the fluxes of pure water and batik wastewater, as well as the rejection of TSS, turbidity, color, COD, TDS, and pH. The dead-end ultrafiltration process for the flux and rejection studies was conducted using a laboratory-scale stirred-cell filtration system, Amicon® Stirred Cell 50 mL (Merck, Darmstadt, Germany), as illustrated in the schematic diagram and an actual laboratory photograph shown in Figure 1. The system operates in a specific dead-end filtration mode, driven by a pressurized nitrogen (N₂) gas cylinder, with the operating pressure precisely regulated and monitored via a pressure gauge. The pressurized gas enters the inlet port located at the top platform of the filtration module, forcing the feed solution downward towards the ultrafiltration membrane, which has an effective filtration area of 15.2 cm². To maintain solution homogeneity and minimize concentration polarization or membrane fouling, the filtration module is integrated with a floating magnetic blade driven by a magnetic stirrer plate, providing continuous agitation. The filtered liquid, or permeate, continuously exits through the outlet port at the bottom of the module and is directed into a collection beaker positioned on an electronic digital balance, which is connected to a computer system for real-time automated data acquisition of permeate mass versus time. To ensure data accuracy and reproducibility, all experimental runs were performed in triplicate, and the reported values represent the mean ± standard deviation.

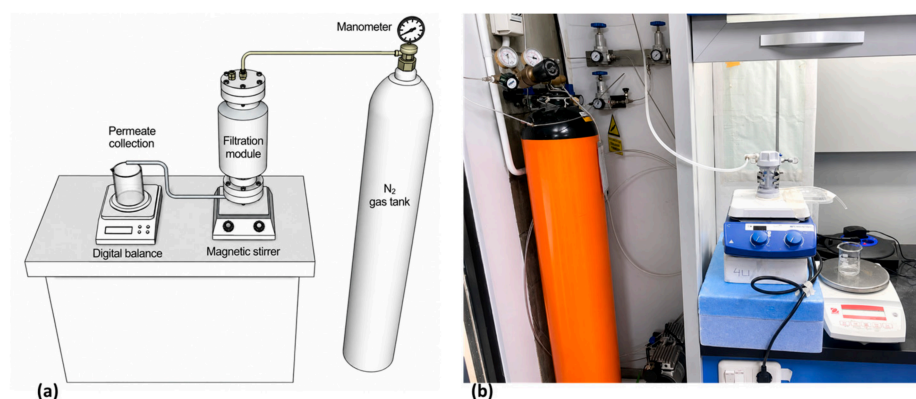


Figure 1. Dead-end ultrafiltration stirring cell experimental setup: (a) schematic diagram, and (b) digital photograph of the actual laboratory installation.

The membrane fluxes, J , and rejections, % R , were calculated by Equations (2) and (3):

$$J = \frac{Q}{A_m} \quad (2)$$

$$\%R = \left(1 - \frac{C_{out}}{C_{in}}\right) \times 100 \quad (3)$$

where Q and A_m are the permeate flow rate of water passing through the membrane and membrane area, and C_{in} and C_{out} are the parameter concentrations at the inlet and outlet in the UF process, respectively. To ensure the reliability and reproducibility of the results, all performance tests were conducted using three parallel samples, and the results were averaged.

3. Results and Discussion

Figure 2 illustrates the surface morphology of the resulting membranes composed of different ZIF-8 loadings, examined at a magnification of 30,000×. The pristine membrane (M-0) exhibits a comparatively smooth surface with uniformly scattered holes of diverse

sizes. The pore architecture seems well developed and linked. The lack of particle characteristics verifies that the membrane surface comprises just PSf and PVP. The development of pores is attributable to the incorporation of PVP into the membrane. Minimal roughness is also noticed on the membrane. This roughness attribute signifies the effective development of pores. The mean pore diameter of the M-0 membrane is around 0.36 μm .

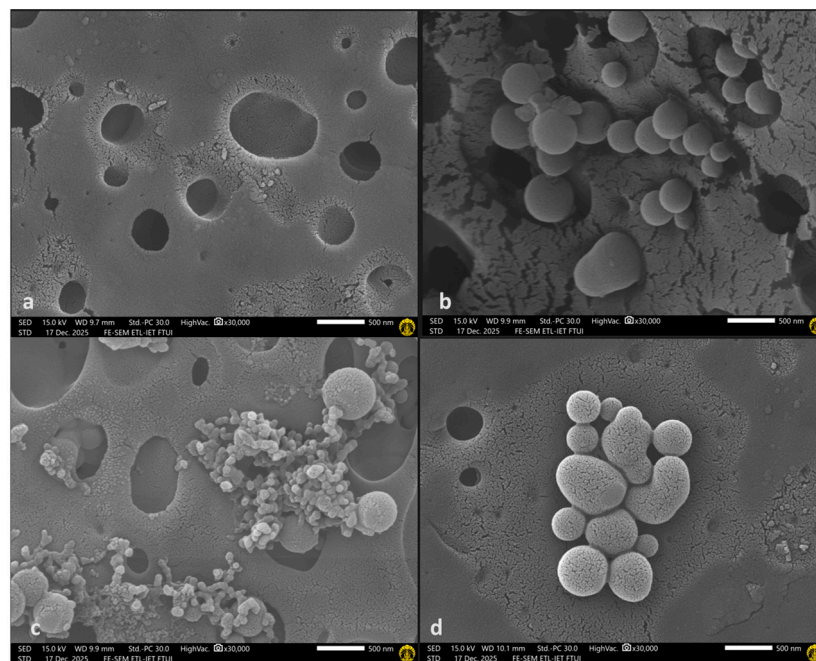


Figure 2. The surface morphology of different membranes: (a) M-0, (b) M-0.25, (c) M-0.5, and (d) M-1.0.

Upon the incorporation of ZIF-8 into the membrane (M-0.25), distinctly spherical particles are visible on the membrane surface. These particles represent the incorporation of ZIF-8 into the polymer matrix. The ZIF-8 particles are notably well-dispersed, suggesting strong compatibility between ZIF-8 and the polymer matrix at modest loading levels. Aside from that, the pore structure remains discernible, indicating that the incorporation of ZIF-8 at this concentration does not impede the pore formation process. Compared with M-0, the M-0.25 membrane exhibits a more pronounced roughness and an irregular surface, suggesting a greater number of regions with the potential to develop pores. Furthermore, spherical ZIF-8 clusters are observed populating the membrane's pores. The pore obstruction of M-0.25 is not predominant due to its good dispersion of nanoparticles. The M-0.25 membrane possesses an average pore diameter of roughly 0.51 μm .

The M-0.5 membrane exhibits smaller and more uniformly distributed ZIF-8 clusters. At this loading, it reduces pore obstruction while simultaneously facilitating pore development throughout the membrane. The tiny and well-dispersed clusters are less likely to obstruct the pore entrances. It permits liquid to traverse both the polymer pores and the micropores of ZIF-8. The M-0.5 membrane exhibits a smoother overall surface morphology than the M-0.25 membrane. This membrane possesses an average pore diameter of around 0.39 μm .

At the maximum ZIF-8 loading (M-1 membrane), a more significant agglomeration of ZIF-8 particles is seen. It creates substantial aggregates on the membrane's surface. These agglomerates exhibit a less uniform distribution and occupy a considerable surface area of the membrane. The M-1 membrane exhibits exceedingly few holes. The M-1 membrane possesses the smallest average hole size of 0.31 μm . Nonetheless, this figure

may not be representative, as the FE-SEM measurements of the M-1 membrane revealed only two pores.

The scanning electron microscope (SEM) cross-section of a membrane shown in Figure 3 illustrates its internal architecture. The upper layer of the membrane exhibits density, suggesting a selective barrier function, while the underlying structure is open and porous, possibly enhancing its permeability and support. These characteristics indicate a conventional asymmetric membrane configuration, with a slender active layer over a more substantial, porous sublayer.

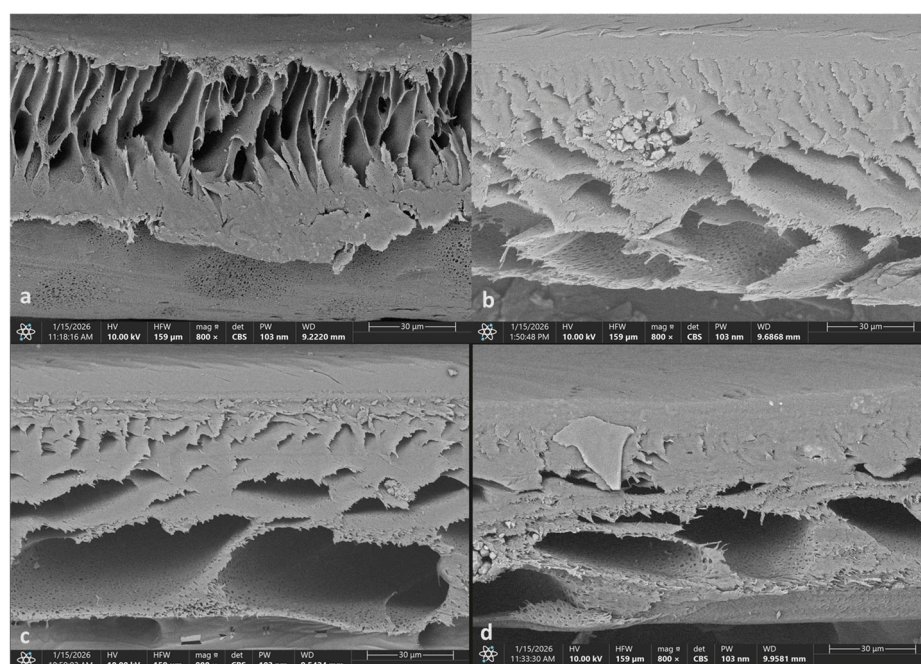


Figure 3. The cross-section morphology of different membranes: (a) M-0, (b) M-0.25, (c) M-0.5, and (d) M-1.0.

Figure 4 shows the FTIR spectra of the membranes. As can be seen, no chemical linkages were formed between PSf/PVP and ZIF-8 during membrane construction. Although the pristine membrane (M-0) lacks ZIF-8, the functional groups associated with the ZIF-8 organic linker, including C-N and C=N vibrations, appear in comparable wavenumber regions to those of the PSf/PVP membrane. It leads to an overlap of absorption bands instead of the emergence of new peaks. Consequently, the existence of ZIF-8 is confirmed by the marginal rise in peak intensity. PSf comprises successive aromatic and aliphatic units that repel water and hydrophilic substances. The recurring aromatic rings (phenyl groups) are connected by ether (-O-) and sulfonyl (-SO₂-) groups. The existence of PSf is confirmed by absorption peaks at around 1103 cm⁻¹ and 1486 cm⁻¹ in all four membrane variations, which signify the presence of C=C stretching functional groups. The prominence of these peaks is particularly evident in the M-0.5 membrane. The absorption peaks at around 1238 cm⁻¹ and 1293 cm⁻¹ signify the presence of C-O-C and SO₂ functional groups, respectively [26]. The presence of PVP in all membrane samples is confirmed by the absorption band found at around 1662 cm⁻¹, corresponding to the C=O functional group. This peak is consistently observed across all membrane changes, indicating that ZIF-8 incorporation does not alter the chemical structure of PVP. The absorption band near 1148 cm⁻¹ signifies the presence of the C-N functional group. This functional group is linked to both PVP and the imidazole connector of ZIF-8. Correspondingly, the peak at around 1583 cm⁻¹ is attributed to C=N, a hallmark of the imidazole ring found in ZIF-8. Despite the absence of ZIF-8 in the M-0 membrane, these functional groups manifest in

analogous wavenumber regions. The absorption peak at around 2966 cm^{-1} is attributed to the C-H group, originating from both the polymer backbone and the methyl group of the 2-methylimidazole linker in ZIF-8. It indicates that peaks around $2800\text{--}3100\text{ cm}^{-1}$ are attributed to the alkane, alkene, and aromatic stretches of the imidazole unit in ZIF-8 [27].

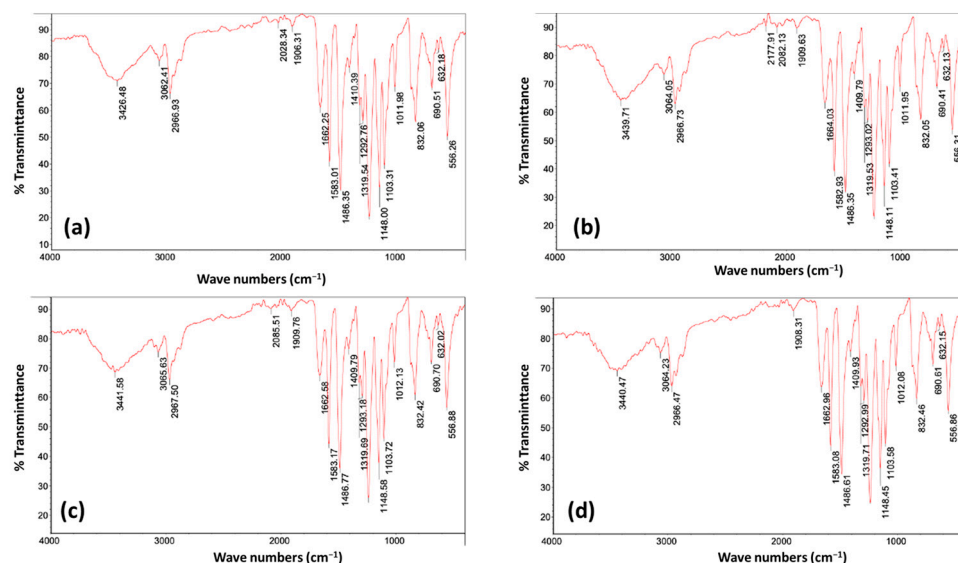


Figure 4. The FTIR spectrum of different membranes: (a) M-0, (b) M-0.25, (c) M-0.5, and (d) M-1.0.

Table 2 presents the water contact angle of the resulting membranes. All four membranes exhibit contact angles below 90° , indicating their hydrophilic nature. The pristine membrane (M-0) has a water contact angle of roughly 66.3° . This value is the largest across the membranes with ZIF-8 inclusion, indicating that M-0 is the least hydrophilic membrane. With increasing ZIF-8 composition in M-0.25 and M-0.5 membrane, the contact angles decrease to 58.2° and 49.4° , respectively. The FE-SEM results indicate that the M-0.25 membrane had a rougher surface than the M-0 membrane. Augmented roughness improves water dispersion by enlarging the effective surface area in contact with water [28].

Table 2. The water contact angle and porosity of PSf/PVP/ZIF-8 membranes.

Membrane	Average Contact Angle ($^\circ$)	Average Porosity (%)
M-0	66.3 ± 1.3	76.7 ± 1.5
M-0.25	58.2 ± 1.5	79.5 ± 2.1
M-0.5	49.4 ± 1.6	83.5 ± 2.6
M-1.0	64.6 ± 1.2	79.3 ± 1.5

The M-0.5 membrane exhibits a reduced contact angle attributable to less pore obstruction on the membrane surface compared to the M-0.25 membrane, as evidenced by the FE-SEM images. Nevertheless, the contact angle for the M-1 membrane shows a significant increase, approaching that of the pristine membrane. Notwithstanding the elevated ZIF-8 composition, the augmentation in contact angle indicates a decline in surface hydrophilicity. At elevated ZIF-8 concentrations, particle agglomeration increases due to inadequate dispersion, resulting in reduced adequate exposure of hydrophilic membrane surface areas and decreased surface wettability. This behavior has been observed in mixed-matrix membranes, where MOF fillers agglomerate at high loadings, resulting in reduced wettability [29]. The FE-SEM results clearly demonstrate substantial ZIF-8 clusters on the M-1 membrane surface, with only a few pores visible.

Table 2 also shows the porosity of the PSf/PVP/ZIF-8 membranes. The pristine membrane (M-0) had a porosity of 77%, the lowest among the membranes. The value escalates with the inclusion of ZIF-8, attaining 80% at a loading of 0.25 wt% and peaking at 84% at 0.5 wt%. The porosity ultimately decreases to 79% upon attaining a ZIF-8 loading of 1 wt%. This reduction can be attributed to particle agglomeration at increased ZIF-8 concentrations. The excessive incorporation of ZIF-8 may increase the viscosity of the casting solution [30]. It may obstruct the interaction between the solvent and the non-solvent during phase inversion, thereby reducing pore formation and resulting in smaller pores and diminished porosity [31].

The elongation of PSf/PVP/ZIF-8 membranes, which represents the ductility and flexibility of the membrane, is presented in Figure 5. An increased elongation at break indicates that the membrane can sustain greater deformations before failure. Figure 5a illustrates that membrane elongation is optimal at the M-0.5 membrane. The M-1 membrane exhibits minimal elongation at approximately 15%. Lower concentrations of ZIF-8 enhance membrane elongation by promoting effective dispersion within the membrane matrix, thereby disrupting polymer chains and increasing flexibility. Similar results have been reported elsewhere, where a 0.5 wt% ZIF-8 loading showed one of the highest elongation values, followed by a significant decrease in elongation at 1 wt% loading [23]. This outcome aligns with the FE-SEM findings, indicating that the M-0.5 and M-0 membranes had smoother surfaces than the M-0.25 and M-1 membranes. An uneven membrane surface reduces its flexibility.

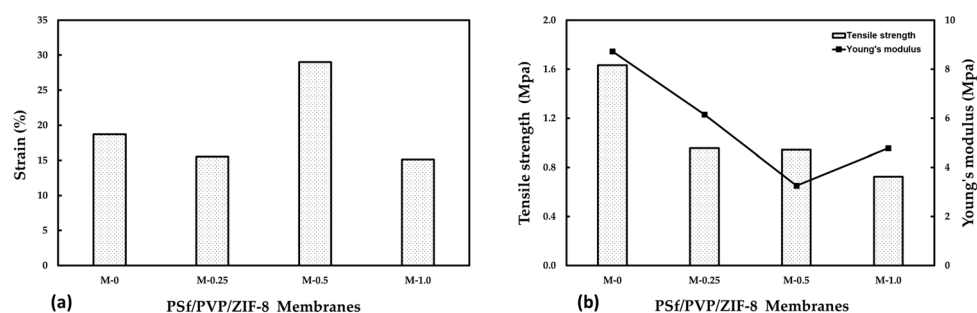


Figure 5. Properties of different membranes: (a) strain and (b) tensile strength and Young's modulus.

Figure 5b illustrates the tensile strength and Young's modulus of PSf/PVP/ZIF-8 membranes. The M-0 membrane exhibits the greatest tensile strength. The incorporation of ZIF-8 leads to a decrease in tensile strength for M-0.25 and M-0.5. The M-1.0 membrane exhibits the lowest tensile strength. It suggests that excessive loading of ZIF-8 adversely impacts the tensile strength of PSf/PVP membranes. FE-SEM images reveal that the M-1.0 membrane exhibits the highest degree of agglomeration, leading to stress concentration at the agglomerates and a consequent reduction in tensile strength [23]. Meanwhile, the M-0 membrane demonstrates the highest Young's modulus, signifying a more rigid structure. The introduction of ZIF-8 at reduced loadings results in a decrease in Young's modulus, indicating increased membrane flexibility.

Figure 6 illustrates the 3D surface topography of membranes derived from AFM testing for PSf/PVP/ZIF-8 composites. The pristine membrane (M-0) possesses a comparatively flat surface characterized by subtle undulations or waves. There are no notable or coarse characteristics. The M-0.25 membrane is the coarsest of the trio. The surface features are pronounced, with irregular peaks and valleys, indicating a highly rough, uneven structure. The M-0.5 membrane has a smoother texture than both M-0 and M-0.25 membranes. The surface exhibits greater uniformity and flatness, with diminished noticeable characteristics. It is likely the smoothest membrane. The M-1.0 membrane demonstrates greater roughness

than both M-0 and M-0.5, but is significantly smoother than M-0.25. The surface exhibits dispersed characteristics, including craters and pits, resulting in a unique texture.

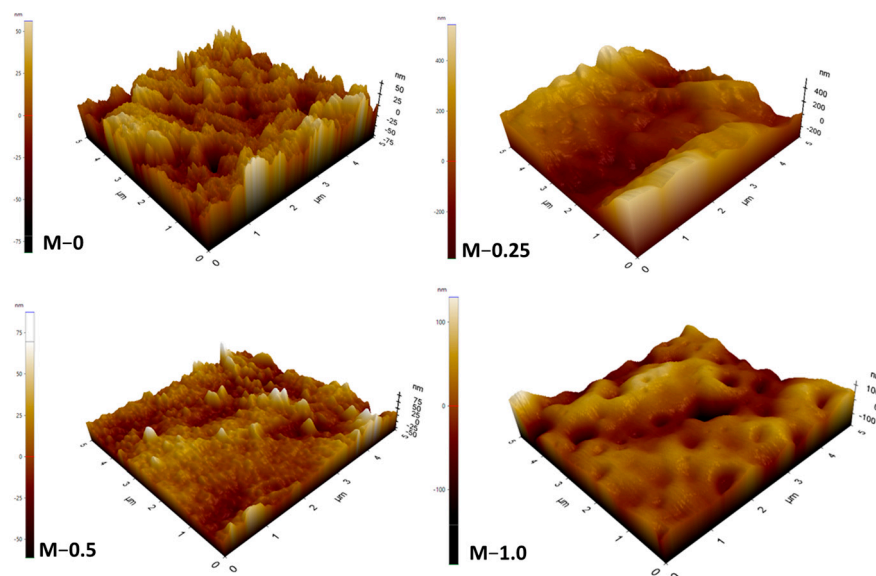


Figure 6. The AFM 3D images of PSf/PVP/ZIF-8 membranes.

Table 3 presents quantitative data on surface roughness utilizing three principal parameters, i.e., R_a , R_q , and R_z . R_a (Arithmetic Average Roughness) represents the arithmetic mean of the absolute values of the profile deviations from the mean line. A greater value corresponds to a rougher overall surface. R_q (Root Mean Square Roughness) denotes the root mean square of surface roughness. R_z is more responsive to extreme peaks and valleys than R_a . It represents the difference between the highest point (peak) and the lowest point (valley) in the measured profile, hence offering data on the greatest vertical roughness range.

Table 3. The surface roughness parameters of PSf/PVP/ZIF-8 membranes.

Membrane	R_a (nm)	R_q (nm)	R_z (nm)
M-0	23.94	37.22	255.94
M-0.25	33.31	48.18	306.40
M-0.5	38.27	31.32	218.46
M-1.0	29.02	43.99	339.91

Visually, the 3D images show significant changes in surface texture with the addition of ZIF-8 particles. The M-0 membrane displays a fairly uniform structure with small, densely packed protrusions. The M-0.25 and M-0.5 membranes show increasing variations in surface height, with the M-0.5 sample exhibiting sharper peaks and a more random distribution. The M-1.0 membrane exhibits unique characteristics, with the presence of wider crater-like structures or valleys, indicating a drastic change in morphology at higher concentrations. There is an increasing trend in roughness (R_a) from M-0 (23.94 nm) to a peak at M-0.5 (38.27 nm). It indicates that adding ZIF-8 to a certain point effectively increases surface roughness. However, at M-1.0, the R_a value decreases to 29.02 nm. This change in surface roughness is crucial in membrane technology. Rougher surfaces (such as M-0.5) generally provide a larger contact surface area, thereby increasing water flux. However, too high a roughness can also increase the risk of fouling (clogging), as dirt particles are more easily trapped in the valleys on the membrane surface [32]. This data

provides an important basis for determining the optimal ZIF-8 concentration to balance filtration performance and membrane durability.

Figure 7a illustrates the pure water flux of different. It is evident that, across all membranes, water flux increases with increasing pressure. It indicates that water movement across the membranes is driven by pressure and follows the conventional behavior of porous polymeric membranes. The trend shows that the membranes maintain structural stability throughout the studied pressure range and do not undergo significant pore collapse. The pristine membrane (M-0) demonstrates the minimal flux across all pressure differences. A study also reported that PSf membranes incorporating 1 wt% PVP exhibited a markedly low water flux of approximately $20 \text{ L} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ [33]. The comparatively low flow rate of M-0 membrane is attributed to the lack of ZIF-8 particles, resulting in diminished overall porosity, as previously noted in the porosity assessment. Conversely, the integration of ZIF-8 markedly improves membrane flux, particularly for M-0.25 and M-0.5. The M-0.25 membrane exhibits a notable increase in flux relative to M-0, achieving $121.3 \text{ L} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ at 5 bar. Despite the M-0.25 membrane exhibiting the largest average pore size of $0.51 \mu\text{m}$ among all membranes, its flow performance is suboptimal due to significant ZIF-8 particle aggregation and pore obstruction, as evidenced by the surface morphology.

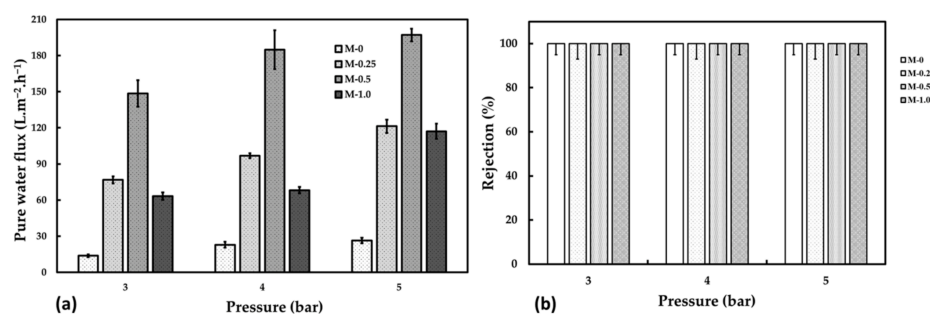


Figure 7. Filtration performance of different membranes: (a) pure water flux and (b) TSS rejection.

Among all membranes, the M-0.5 membrane exhibits the highest flux across all pressure levels, reaching a maximum of $197.1 \text{ L} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ at 5 bar, reflecting its superior overall porosity. This performance pertains to the ideal distribution of ZIF-8 particles within the polymer matrix, as evidenced by FE-SEM, resulting in a more homogeneous pore architecture and enhanced effective porosity. The uniformly dispersed ZIF-8 particles create additional transport pathways and improve membrane hydrophilicity without substantially obstructing the pores. The flux is also related to the membrane roughness, as shown by the surface roughness parameters (R_a) in Table 3. M-0.5 has the roughest surface, so it has large porosity, but provides a small contact angle, so that the membrane is more hydrophilic and provides the highest water flux [34]. Conversely, although the M-1.0 membrane has the highest ZIF-8 loading, its flow is inferior to that of the M-0.5 and M-0.25 membranes. Although the flux of M-1.0 rises at 5 bar, its overall performance remains inferior to that of M-0.5. This behavior occurs at high ZIF-8 loading, leading to particle agglomeration and pore obstruction, as demonstrated by FE-SEM. These agglomerates impede efficient water transport routes and elevate flow resistance. The FESEM data indicate that the M-1.0 membrane has the smallest average pore size among the membranes. Conversely, the flux of the M-1 membrane is the second lowest, followed by the M-0 membrane.

As shown in Figure 7b, the TSS rejection of membranes is demonstrated at a range of different operating pressures. Under various operating conditions, the PSf-PVP/ZIF-8 membrane successfully removed TSS, achieving 100% rejection. Although the TSS concentration in the permeate was measured at 0 mg/L , the initial TSS concentration was

252 mg/L. The process of ultrafiltration is largely carried out through size exclusion, in which particles larger than the membrane pore size are retained on the membrane surface [35]. According to scanning electron microscope (SEM) findings, the membrane has a relatively tight pore structure, preventing suspended particles from passing through. These particles are subsequently retained at the membrane surface, forming a cake layer that can increase the membrane's filtration capacity during filtration [36].

Figure 8a illustrates the outcomes of assessing the influence of modifications in the composition of the PSf-PVP/ZIF-8 membranes and operating pressure on the percentage of turbidity rejection in Batik wastewater. The membranes exhibit a high turbidity rejection efficiency, with rejection rates of 75–92%. The starting turbidity was 42 NTU, while the permeate turbidity after membrane filtration ranges from 3 to 10 NTU. Overall, increasing the operating pressure from 3 to 5 bar does not consistently improve rejection rates. In certain membrane topologies, elevated pressures typically led to only a marginal reduction in removal efficiency. The enhanced permeation driving force may facilitate the passage of smaller colloidal particles through the membrane pores, particularly if the membrane exhibits a more open pore distribution due to ZIF-8 incorporation [37]. Turbidity in wastewater mostly results from suspended and colloidal particles, including color leftovers and organic fragments, that scatter light [38]. The principal mechanism of ultrafiltration is size-based filtration (size exclusion), which effectively retains turbidity-inducing particles larger than the membrane pores. It elucidates the elevated rejection values attained for all membrane variants [39]. The correlation with TSS data, indicating 100% rejection, suggests that eliminating suspended particles significantly reduces turbidity. Nonetheless, turbidity may also be affected by small colloidal particles that are not fully identified as TSS, resulting in a turbidity rejection value that does not reach 100% as observed with TSS. The turbidity and TSS measurements exhibit a robust association in assessing the membrane's efficiency in eliminating suspended particles from batik wastewater [40].

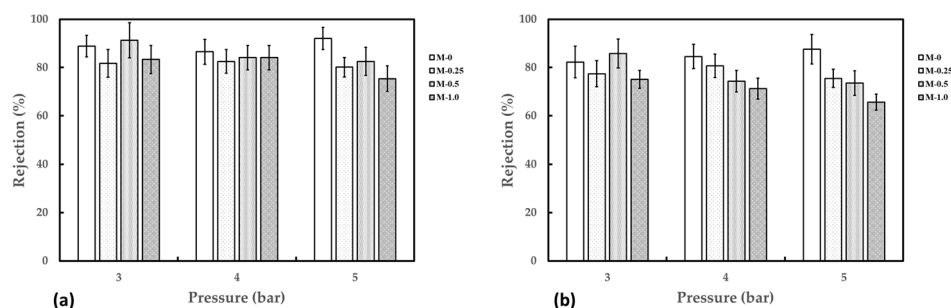


Figure 8. Separation performance of different membranes, (a) the turbidity rejection and (b) color rejection.

Figure 8b presents the results of testing the influence of modifications to the composition of the PSf-PVP/ZIF-8 membrane and the operating pressure on the percentage of color rejection in batik liquid waste. The membranes exhibit a high color rejection efficiency, with rejection rates ranging from 65.7% to 87.6%. The starting color concentration was 556 Pt-Co, and the post-ultrafiltration permeate color value ranged from 69 to 191 Pt-Co. Typically, at elevated pressures, there is a marginal reduction in removal efficiency. The phenomenon can be explained by the fact that elevated pressure increases the driving force of permeate flow, thereby facilitating the passage of smaller dye molecules through the membrane pores. The coloration in Batik effluent typically originates from water-soluble reactive dyes with relatively low to medium molecular weights. The color removal mechanism in ultrafiltration membranes is driven not only by size exclusion but also by interactions between dye molecules and the membrane surface, including electrostatic interactions and

adsorption. The incorporation of ZIF-8 into the PSf-PVP matrix may enhance surface area and provide additional adsorption sites, thereby improving rejection efficiency in certain membrane configurations. Nevertheless, if the pore architecture becomes more permeable due to elevated ZIF-8 concentration or increased pressure, certain dye molecules may still traverse the membrane. The efficiency of color removal is predominantly determined by the membrane's structural attributes, including pore size and distribution, rather than solely by augmenting the operating pressure. These results demonstrate that the PSf-PVP/ZIF-8 membrane effectively reduces the color intensity of batik wastewater; however, it cannot achieve complete removal due to residual dissolved dye fractions that can permeate the ultrafiltration membrane.

Figure 9a illustrates the test results regarding the influence of ZIF-8 content and operating pressure on COD rejection in Batik wastewater. Alterations in membrane composition and operational pressure influence the efficiency of the PSf-PVP/ZIF-8 membrane in eliminating organic compounds from batik wastewater. The baseline COD value is around 765 mg/L, while the post-ultrafiltration permeate COD concentration ranges from 322 to 648 mg/L, resulting in a rejection rate of 15.3% to 57.9%. The M-0.25 membrane removes COD more effectively than others. This composition's COD rejection percentage was 49.6% at 3 bar, 57.9% at 4 bar, and 57.9% at 5 bar. ZIF-8 at a given loading may improve the membrane's organic chemical selectivity in batik effluent. The M-0.5 membrane had the lowest rejection rate, 15.3% at 3 bar. At 4 bar, rejection jumped to 32.6%, then dropped to 30.0% at 5 bar. It implies that raising ZIF-8 may not always enhance membrane separation efficiency. M-0 membrane COD rejection ranged from 28.8% to 34.8%, peaking at 3 bar. M-1.0 membrane rejection ranged from 26.9% to 39.2%, peaking at 4 bar. This pattern implies that membrane types separate best at 4 bar. Operating pressure and membrane structural features affect COD removal efficiency, as rejection values vary. Increasing operating pressure from 3 to 5 bar does not always improve COD rejection. Pressure enhances the permeation driving force, allowing tiny organic molecules to pass through membrane pores into the permeate. ZIF-8 alters pore architecture and increases membrane porosity in the PSf-PVP membrane matrix. ZIF-8's porous construction improves membrane permeability, allowing permeate to flow. Increased permeability does not necessarily enhance separation selectivity. Polymeric membrane systems exhibit trade-offs between permeability and selectivity [41]. The results match SEM images of the membrane's porous surface. Small organic molecules can cross the membrane with the permeate due to the pore structure, resulting in a COD rejection % that does not increase with ZIF-8 composition. This study found that the M-0.25 membrane composition performs best, while ZIF-8 augmentation increases permeability but decreases membrane selectivity. Several membrane configurations remove COD better at 4 bar.

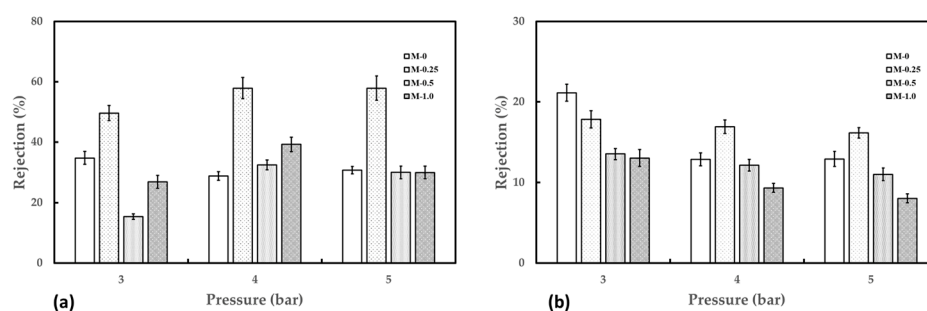


Figure 9. (a) COD rejection and (b) TDS rejection of different membranes.

Figure 9b shows the TDS rejection for each membrane composition and variation in operating pressure. The membrane exhibits a modest TDS removal efficiency, with

rejection rates ranging from 8.0% to 21.1%. The initial TDS was 614 mg/L, and the TDS concentration in the permeate post-filtration ranged from 484 to 565 mg/L. It indicates that the majority of solutes were still able to traverse the membrane pores during the filtration procedure. Test results indicated that elevating the operating pressure from 3 to 5 bar do not substantially influence TDS rejection. Under certain conditions, increasing pressure appears to reduce the rejection rate. Increased pressures enhance the permeation driving power, facilitating the transport of more solutes with the permeate flow. As a result, the TDS concentration in the permeate rises while the rejection value diminishes.

Incorporating ZIF-8 into the membrane matrix can influence the pore architecture formed during phase inversion. The use of ZIF-8 particles enhances the membrane's porosity and permeability, thereby facilitating the passage of permeate through its pores. Nonetheless, this enhancement in permeability does not invariably correlate with an augmentation in separation selectivity, allowing certain dissolved molecules or ions to traverse the membrane alongside the permeate. TDS mostly consists of dissolved inorganic ions, including Na^+ , K^+ , and Cl^- , which have small molecular sizes, making them difficult to retain by ultrafiltration membranes that operate on a size-exclusion principle. Filtration membranes, apart from nanofiltration and reverse osmosis, have comparatively larger pore sizes, rendering them less efficient at removing low-molecular-mass compounds and salt ions that influence TDS values [42]. Consequently, the ultrafiltration method typically exhibits inferior TDS removal effectiveness compared to other metrics such as TSS or turbidity, which involve larger particle sizes.

The difference in trends between COD and TDS rejection as operating pressure increases is attributed to distinct separation mechanisms at the membrane surface. The rejection of COD, typically associated with organic molecules of larger particle sizes, tends to increase or stabilize due to physical filtration mechanisms, in which an increase in pressure results in a greater increase in water flux than in the penetration rate of organic pollutants retained by the pore size [43]. In contrast, TDS rejection decreases with increasing pressure, because TDS comprises minute dissolved ions that are strongly influenced by concentration polarization. Elevated pressure leads to the accumulation of ions at the membrane interface, thereby enhancing the concentration gradient and driving greater passage of dissolved solids across the membrane, ultimately resulting in a reduced TDS rejection [44].

Figure 10a demonstrates the impact of fluctuations in ZIF-8 mass and operating pressure on the pH of permeate from ultrafiltration of Batik wastewater. Before filtration, the wastewater pH is approximately 8.3. The permeate pH ranged from 7.9 to 8.3, resulting in minimal pH fluctuations. The ultrafiltration process does not significantly alter the acidity of the wastewater across the several membranes tested and at changing operating pressures. The pH values for all membrane modifications are predominantly neutral to slightly alkaline, closely resembling the beginning conditions of the effluent. The separation mechanism in ultrafiltration membranes is primarily size exclusion. This method is more efficient at retaining suspended particles and large organic molecules than ions like H^+ and OH^- , which affect the solution's pH. ZIF-8, a MOF material, possesses a robust microporous structure and exhibits considerable resistance to pH ranges from neutral to slightly alkaline. Consequently, the incorporation of ZIF-8 into the PSf-PVP matrix does not markedly affect the ionic equilibrium in solution, resulting in the permeate pH remaining near the original setting. These results demonstrate that the PSf-PVP/ZIF-8 membrane effectively preserves the pH stability of the treated water, ensuring it remains within an acceptable range for subsequent treatment stages and environmental discharge.

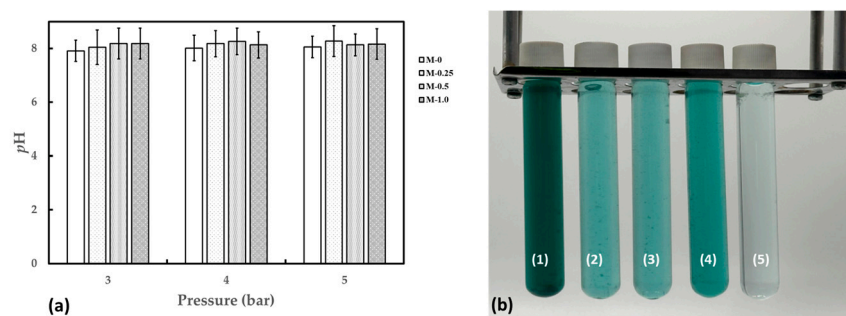


Figure 10. (a) pH of permeate produced by different membranes. (b) The initial batik wastewater to UF results: (1) initial batik wastewater, (2) after five times dilution, (3) after pH adjustment, (4) after coagulation–flocculation, and (5) after UF process.

Figure 10b shows five test tubes exhibiting notable differences in color deterioration and water turbidity. Tube (a) contains wastewater from a batik company in Central Java, Indonesia, characterized by a clear, viscous blue-green liquid, signifying a high concentration of dissolved chemicals. As one progresses to the right, in tube (b), where the batik wastewater has undergone a fivefold dilution, a gradual degradation of color is observed, transitioning from a dense blue-green to a lighter hue in tube (c) following pH adjustment, and further to tube (d) post-coagulation–flocculation, ultimately resulting in an almost colorless solution in the far-right tube, tube (e), after the ultrafiltration process. This process is accompanied by alterations in turbidity: tubes (b) and (c) exhibit significant cloudiness due to suspended particles, signifying the presence of sediment or colloids. The turbidity in tube (d) reduces somewhat, resulting in a softer turquoise hue. The rightmost tube, designated as tube (e), exhibits the clearest or just marginally hazy liquid, nearly colorless, signifying a total depletion of pigment as a result of the color and turbidity elimination process in the UF procedure. Table 4 shows the results of the parameters tested at an operating pressure of 3 bar.

Table 4. The parameters concentration at initial, after pretreatment, and after UF at operating pressure of 3 bar.

Parameters	Initial	After Pretreatment	After UF
TSS, ppm	276	252	0
Turbidity, NTU	48	42	3.3–10.3
Color, Pt-Co	562	556	69–191
COD, ppm	858	765	322–648
TDS, ppm	578	614	484–565
pH	8.0	8.3	7.9–8.3

4. Conclusions

This study effectively synthesized and analyzed the properties of PSf/PVP/ZIF-8 composite membrane for the treatment of Batik wastewater. The incorporation of ZIF-8 significantly enhanced the membrane's hydrophilicity and pure water flux. The M-0.5 membrane, with optimal ZIF-8 content, achieved the highest hydrophilicity (water contact angle of 49.4°) and optimal porosity of 83.5%, resulting in a maximum pure water flux of $197.1 \text{ L} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ at 5 bar. All membranes demonstrated excellent TSS rejection during wastewater treatment, achieving 100% performance. Turbidity rejection ranged from 75% to 92%, whereas color rejection ranged from 65.7% to 87.6%. The M-0.25 membrane exhibited the highest COD rejection (57.9%); however, TDS rejection was comparatively low, ranging from 8.0% to 21.1%. Despite the trade-off between mechanical strength and selectivity at elevated ZIF-8 concentrations, these results affirm the considerable promise of

the PSf/PVP/ZIF-8 membrane; additional optimization is necessary to reconcile multiple performance metrics

Author Contributions: Conceptualization, S.K. and W.J.L.; methodology, S.K. and W.J.L.; formal analysis, S.K., A.A., S.S.H. and K.S.B.; investigation, A.A., S.S.H. and K.S.B.; resources, S.K.; data curation, S.K., A.A., S.S.H. and K.S.B.; writing—original draft preparation, S.K., S.S.H., K.S.B. and W.J.L.; writing—review and editing, S.S.H. and W.J.L.; visualization, supervision and funding acquisition, S.K. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the Universitas Indonesia through the PUTI Project under Contract No. PKS-374/UN2.RST/HKP.05.00/2025.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data supporting findings of this study will be provided upon request from the corresponding authors.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
DMAc	<i>N, N</i> -Dimethylacetamide
DO	Dissolved oxygen
MOF	Metal–Organic Framework
PAN	polyacrylonitrile
PES	polyether sulfone
PVDF	polyvinylidene fluoride
PSf	polysulfone
PTFE	polytetrafluoroethylene
PVP	polyvinylpyrrolidone
TDS	Total dissolved solid
TSS	Total suspended solid

References

1. Permatasari, P.A.; Cantoni, L. Indonesian tourism and batik: An online map. *E-Rev. Tour. Res.* **2019**, *16*, 2019.
2. Syed Shaharuddin, S.I.; Shamsuddin, M.S.; Drahman, M.H.; Hasan, Z.; Mohd Asri, N.A.; Nordin, A.A.; Shaffiar, N.M. A review on the Malaysian and Indonesian batik production, challenges, and innovations in the 21st century. *Sage Open* **2021**, *11*, 215824402111040128. [[CrossRef](#)]
3. Tariq, M.F.; Javed, F.; Rizzo, L.; Tahir, M.W.; Ikhlaiq, A. Textile wastewater treatment by heterogeneous catalytic ozonation using microcellulose loaded ZIF 67 catalyst. *J. Environ. Manag.* **2025**, *380*, 125031. [[CrossRef](#)] [[PubMed](#)]
4. Musawwa, M.M.; Sarkawi, M.; Arrunillah, D.; Sazawa, K.; Mohan, G.; Kuramitz, H. Review of traditional batik wastewater treatment in Indonesia to address environmental and health hazards and support sustainable practices of micro, small, and medium enterprises. *Discov. Environ.* **2026**, *4*, 18. [[CrossRef](#)]
5. Zaharia, C.; Musteret, C.-P.; Afrasinei, M.-A. The use of coagulation–flocculation for industrial colored wastewater treatment—I the application of hybrid materials. *Appl. Sci.* **2024**, *14*, 2184. [[CrossRef](#)]
6. Setianingsih, N.; Hadiyanto; Budihardjo, M.; Yuliasni, R.; Vistanty, H.; Mukimin, A.; Sudarno. Characteristics and performance of aerobic granular sludge technology in the treatment of real batik textile wastewater. *Int. J. Environ. Sci. Technol.* **2025**, *22*, 2917–2930. [[CrossRef](#)]
7. Febriasari, A.; Huriya; Ananto, A.H.; Suhartini, M.; Kartohardjono, S. Polysulfone–polyvinyl pyrrolidone blend polymer composite membranes for batik industrial wastewater treatment. *Membranes* **2021**, *11*, 66. [[CrossRef](#)] [[PubMed](#)]
8. Obotey Ezugbe, E.; Rathilal, S. Membrane technologies in wastewater treatment: A review. *Membranes* **2020**, *10*, 89. [[CrossRef](#)] [[PubMed](#)]

9. Urkiaga, A.; Iturbe, D.; Etxebarria, J. Effect of different additives on the fabrication of hydrophilic polysulfone ultrafiltration membranes. *Desalin. Water Treat.* **2015**, *56*, 3415–3426. [[CrossRef](#)]
10. Deepthi, P.; Viji, K.; Vijesh, A.; Anjana, P.; Kumar, V.; Malladi, S. A Review on Advancements in Polysulfone-Based Membranes for Gas Separation Applications. *Asian J. Chem.* **2024**, *36*, 2717–2730. [[CrossRef](#)]
11. Tan, X.; Rodrigue, D. A review on porous polymeric membrane preparation. Part I: Production techniques with polysulfone and poly (vinylidene fluoride). *Polymers* **2019**, *11*, 1160. [[CrossRef](#)] [[PubMed](#)]
12. Guillen, G.R.; Pan, Y.; Li, M.; Hoek, E.M. Preparation and characterization of membranes formed by nonsolvent induced phase separation: A review. *Ind. Eng. Chem. Res.* **2011**, *50*, 3798–3817. [[CrossRef](#)]
13. Field, R.W.; Pearce, G.K. Critical, sustainable and threshold fluxes for membrane filtration with water industry applications. *Adv. Colloid Interface Sci.* **2011**, *164*, 38–44. [[CrossRef](#)] [[PubMed](#)]
14. Wang, H.; Wang, W.; Wang, L.; Zhao, B.; Zhang, Z.; Xia, X.; Yang, H.; Xue, Y.; Chang, N. Enhancement of hydrophilicity and the resistance for irreversible fouling of polysulfone (PSF) membrane immobilized with graphene oxide (GO) through chloromethylated and quaternized reaction. *Chem. Eng. J.* **2018**, *334*, 2068–2078. [[CrossRef](#)]
15. Tiron, L.; Vlad, M.; Baltă, Ș. Research on hydrophilic nature of polyvinylpyrrolidone on polysulfone membrane filtration. In *Proceedings of the IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Philadelphia, PA, USA, 2018; p. 012059.
16. Malik, T.; Razzaq, H.; Razzaque, S.; Nawaz, H.; Siddiq, A.; Siddiq, M.; Qaisar, S. Design and synthesis of polymeric membranes using water-soluble pore formers: An overview. *Polym. Bull.* **2019**, *76*, 4879–4901. [[CrossRef](#)]
17. Du, C.; Wang, Z.; Liu, G.; Wang, W.; Yu, D. One-step electrospinning PVDF/PVP-TiO₂ hydrophilic nanofiber membrane with strong oil-water separation and anti-fouling property. *Colloids Surf. A Physicochem. Eng. Asp.* **2021**, *624*, 126790. [[CrossRef](#)]
18. Cheng, Y.; Datta, S.J.; Zhou, S.; Jia, J.; Shekhah, O.; Eddaoudi, M. Advances in metal–organic framework-based membranes. *Chem. Soc. Rev.* **2022**, *51*, 8300–8350. [[CrossRef](#)] [[PubMed](#)]
19. Murdock, C.R.; Hughes, B.C.; Lu, Z.; Jenkins, D.M. Approaches for synthesizing breathing MOFs by exploiting dimensional rigidity. *Coord. Chem. Rev.* **2014**, *258*, 119–136. [[CrossRef](#)]
20. He, T.; Huang, Z.; Yuan, S.; Lv, X.-L.; Kong, X.-J.; Zou, X.; Zhou, H.-C.; Li, J.-R. Kinetically controlled reticular assembly of a chemically stable mesoporous Ni (II)-pyrazolate metal–organic framework. *J. Am. Chem. Soc.* **2020**, *142*, 13491–13499. [[CrossRef](#)] [[PubMed](#)]
21. Song, Y.; He, M.; Zhao, J.; Jin, W. Structural manipulation of ZIF-8-based membranes for high-efficiency molecular separation. *Sep. Purif. Technol.* **2021**, *270*, 118722. [[CrossRef](#)]
22. Balkanloo, P.G.; Marjani, A.P.; Mahmoudian, M. Fabrication, characterization, and performance evaluation of polysulfone nanocomposite membranes containing different sizes of ZIF-8 to desalination and heavy metals removal from wastewater. *Chem. Eng. J.* **2024**, *496*, 153835. [[CrossRef](#)]
23. Nordin, N.A.H.M.; Ismail, A.F.; Mustafa, A.; Murali, R.S.; Matsuura, T. Utilizing low ZIF-8 loading for an asymmetric PSf/ZIF-8 mixed matrix membrane for CO₂/CH₄ separation. *RSC Adv.* **2015**, *5*, 30206–30215. [[CrossRef](#)]
24. Li, K.; Ma, Y.; Zhao, W.; Yang, L.; Zhang, J.; Zhang, Q.; Ma, X.; Jiao, L.; Yin, Z.; Cheng, B. Simultaneously enhanced gas separation performance and long-term stability by thermally treated ZIF-8-based nanocomposite membranes. *Sep. Purif. Technol.* **2025**, *353*, 128586. [[CrossRef](#)]
25. Vasin, S.I.; Filippov, A.N. Hydrodynamic Permeability of the Membrane as a System of Rigid Particles Covered with Porous Layer (Cell Model). *Colloid J.* **2004**, *66*, 266–270. [[CrossRef](#)]
26. Casetta, J.; Pochat-Bohatier, C.; Cornu, D.; Bechelany, M.; Miele, P. Enhancing Water Treatment Performance of Porous Polysulfone Hollow Fiber Membranes through Atomic Layer Deposition. *Molecules* **2023**, *28*, 6133. [[CrossRef](#)] [[PubMed](#)]
27. Khan, I.U.; Othman, M.H.D.; Jilani, A.; Ismail, A.; Hashim, H.; Jaafar, J.; Zulhairun, A.; Rahman, M.A.; Rehman, G.U. ZIF-8 based polysulfone hollow fiber membranes for natural gas purification. *Polym. Test.* **2020**, *84*, 106415. [[CrossRef](#)]
28. Peethan, A.; Aravind, M.; George, S.D. Surface wettability and superhydrophobicity. In *Advances in Superhydrophobic Coatings*; RSC: Philadelphia, PA, USA, 2023.
29. Shahid, S.; Nijmeijer, K.; Nehache, S.; Vankelecom, I.; Deratani, A.; Quemener, D. MOF-mixed matrix membranes: Precise dispersion of MOF particles with better compatibility via a particle fusion approach for enhanced gas separation properties. *J. Membr. Sci.* **2015**, *492*, 21–31. [[CrossRef](#)]
30. Esposito, R.; Musteata, V.; Chisca, S.; Nunes, S.P. Rheology of polytriazole/ZIF-8 solutions and dynamics of mixed-matrix composite films. *ACS Appl. Polym. Mater.* **2021**, *3*, 6045–6055. [[CrossRef](#)]
31. Nasir, A.M.; Adam, M.R.; Hubadillah, S.K. Grand Challenges in the Development of Adsorptive Membrane for Water and Wastewater Treatment. *J. Appl. Membr. Sci. Technol.* **2023**, *27*, 89–101. [[CrossRef](#)]
32. Woo, S.H.; Park, J.; Min, B.R. Relationship between permeate flux and surface roughness of membranes with similar water contact angle values. *Sep. Purif. Technol.* **2015**, *146*, 187–191. [[CrossRef](#)]
33. Aminudin, N.N.; Basri, H.; Harun, Z.; Yunus, M.Z.; Sean, G.P. Comparative study on effect of PEG and PVP as additives on polysulfone (PSF) membrane structure and performance. *J. Teknol. (Sci. Eng.)* **2013**, *65*, 2448–2455. [[CrossRef](#)]

34. Shen, A.; Ye, M.; Zhang, Z.; Zhao, B.; Ma, Y.; Li, Z.; Wang, W.; Cui, W. Covalent CNT-CONH-MoS₂ electrocatalytic membrane for hazardous wastewater treatment: Synergistic filtration and degradation of dyes and phenolic contaminants. *J. Environ. Chem. Eng.* **2025**, *13*, 118074. [[CrossRef](#)]
35. Buffle, J.; Perret, D.; Newman, M. The use of filtration and ultrafiltration for size fractionation of aquatic particles, colloids, and macromolecules. In *Environmental Particles*; CRC Press: Boca Raton, FL, USA, 2019; pp. 171–230.
36. Cai, Z.; Wee, C.; Benjamin, M.M. Fouling mechanisms in low-pressure membrane filtration in the presence of an adsorbent cake layer. *J. Membr. Sci.* **2013**, *433*, 32–38. [[CrossRef](#)]
37. Lee, T.H.; Oh, J.Y.; Hong, S.P.; Lee, J.M.; Roh, S.M.; Kim, S.H.; Park, H.B. ZIF-8 particle size effects on reverse osmosis performance of polyamide thin-film nanocomposite membranes: Importance of particle deposition. *J. Membr. Sci.* **2019**, *570*, 23–33. [[CrossRef](#)]
38. Boyd, C.E. Suspended solids, color, turbidity, and light. In *Water Quality: An Introduction*; Springer: Berlin/Heidelberg, Germany, 2019; pp. 119–133.
39. Liu, Y.; Li, X.; Yang, Y.; Ye, W.; Ji, S.; Ren, J.; Zhou, Z. Analysis of the major particle-size based foulants responsible for ultrafiltration membrane fouling in polluted raw water. *Desalination* **2014**, *347*, 191–198. [[CrossRef](#)]
40. Zakaria, N.; Rohani, R.; Wan Mohtar, W.H.M.; Purwadi, R.; Sumampouw, G.A.; Indarto, A. Batik effluent treatment and decolorization—A review. *Water* **2023**, *15*, 1339. [[CrossRef](#)]
41. Baker, R.W. *Membrane Technology and Applications*; John Wiley & Sons: Hoboken, NJ, USA, 2023.
42. Zhao, J.; Lin, R.; Tian, W.; Zhu, X.; Luo, X.; Liu, Y. Anthracene-Modified Metal–Organic Framework with fof Topology for Highly Efficient Adsorption and Separation of Organic Dyes. *Cryst. Growth Des.* **2023**, *23*, 4417–4423. [[CrossRef](#)]
43. Tran, N.H.; Ngo, H.H.; Urase, T.; Gin, K.Y.-H. A critical review on characterization strategies of organic matter for wastewater and water treatment processes. *Bioresour. Technol.* **2015**, *193*, 523–533. [[CrossRef](#)] [[PubMed](#)]
44. Pushpalatha, N.; Sreeja, V.; Karthik, R.; Saravanan, G. Total dissolved solids and their removal techniques. *Int. J.* **2022**, *2*, 13–20. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.