

Fabrication and Characterization of PVDF/PVP/TiO₂ Membrane for Ultrafiltration Process

S.S. Alsya¹, E. Yuliwati^{1,2,*}, A. Rizki², S. Martini²

¹Chemical Engineering Department, Universitas Muhammadiyah Palembang
Jalan Jenderal Ahmad Yani 13 Ulu, Palembang, 30263, Indonesia

²Study Program of Chemical Engineering, Postgraduate Universitas Muhammadiyah Palembang
Jalan Jenderal Ahmad Yani 13 Ulu, Palembang, 30263, Indonesia

Submitted: 23/07/2025. Revised edition: 27/01/2026. Accepted: 09/02/2026. Available online: 21/04/2026

ABSTRACT

The growing demand for high-quality water has intensified efforts to advance membrane-based purification technologies, with polyvinylidene fluoride (PVDF) remaining a dominant material despite its intrinsic hydrophobicity and propensity for fouling. This study seeks to improve the functional performance of PVDF membranes through the incorporation of titanium dioxide (TiO₂) nanoparticles, introducing hydrophilic characteristics and promoting hydroxyl radical formation. PVDF/polyvinylpyrrolidone (PVP) membranes were fabricated via the phase inversion method with TiO₂ loadings of 0%, 1%, and 2%, followed by comprehensive characterization using SEM, FTIR, contact angle measurements, and pure-water flux analysis. The incorporation of TiO₂ resulted in a notable enlargement of pore size from 370 nm (0% TiO₂) to 530 nm (1%) and 580 nm (2%). FTIR spectra further verified structural interactions between the PVDF matrix and TiO₂ nanoparticles. Membrane hydrophilicity improved substantially, as reflected in the reduction of contact angle from 78.6° to 67.1° and 43.8°, accompanied by a pronounced increase in water flux from 49 to 148 and 150 L/m²·h. These findings demonstrate that TiO₂ incorporation effectively optimizes the membrane's pore architecture, surface wettability, and permeability, thereby reinforcing its suitability for enhancing PVDF-based ultrafiltration systems in water treatment applications.

Keywords: Ultrafiltration membrane; PVDF; titanium dioxide; SEM, FTIR

1.0 INTRODUCTION

Clean water is one of the most valuable natural assets because of its essential function. Population and industrial growth have increased the demand for clean water. In the last decades, membrane technology application and research have attracted the interest of both academic and industrial cohorts, especially, due to its relatively simple operation, lower energy requirements and maintenance costs compared to conventional systems [1].

Membrane technology has been widely employed, specifically for the separation process as it is faster, more energy efficient and time effective along with no phase change in the solution [2]. Among other membrane types, ultrafiltration membrane process has been used in the separation process of particles in solutions.

* Corresponding to: E. Yuliwati (email: erna_yuliwati@um-palembang.ac.id)
DOI: <https://doi.org/10.11113/jamst.v30n1.323>

Polyvinylidene fluoride (PVDF), one of the polymeric membrane materials, has been known for its excellent performance and thermal, acid and alkali resistance. It is also resilient to numerous kinds of inorganic and organic acids and can be employed at a variety of pH levels [3]. However, PVDF is hydrophobic material which is prone to fouling phenomena [4].

There are many options for improving membrane performance, including adding additional materials or fillers during the membrane manufacturing process. The use of inorganic elements such as nanotubes, Fe₂O₃, TiO₂, ZnO, Al₂O₃, and SiO₂ as membrane additives has also been reported efficient [5].

Furthermore, titanium dioxide (TiO₂) which has reliable hydrophilicity and UV light absorption has been acknowledged for lowering membrane fouling percentage, primarily due to its high hydrophilicity, good antifouling properties, chemical stability, and noteworthy photochemical reactivity [6-7]. In general, pure TiO₂ is commonly used in water treatment as hydroxyl radicals to improve water quality from hazardous and poisonous pollutants [8].

Previous studies acknowledged the positive effect of TiO₂ incorporation in membrane fabrication. However, few studies have quantified the combined effect of TiO₂ dosage and comprehensive characterization analysis using multiple analytical techniques. Therefore, the novelty of this work lies in combining optimized in-house synthesized PVDF membrane/PVP and TiO₂ with various percentages and deeper multi-technique microstructural characterization including SEM, AFM, contact angle, flux and FTIR analysis to provide a holistic view of how TiO₂ incorporation interacts with PVDF membrane to enhance membrane performance and address fouling reduction.

2.0 EXPERIMENTAL

2.1 Materials

The materials used in this study were polyvinylidene fluoride (PVDF), *n*-dimethylacetamide (DMAc), polyvinylpyrrolidone (PVP) and titanium dioxide (TiO₂). All of the chemicals used are of analytical grade.

2.2 Preparation

Firstly, PVDF pellets were dried for a day at 50 °C. Furthermore, dope solution with concentration of 16% was prepared by using 83 mL of DMAc as the solvent, followed by weighing 1.5 grams of PVP. TiO₂ was then added with variations of 1%, 2%, and 0% (without TiO₂). The solution was heated to 50-60 °C and stirred for 24 hours until homogeneous. After that, each mixture underwent ultrasonication for two hours to eliminate any leftover air bubbles. The casting process was carried out. Initially, membrane film was immersed in regular water for 30 seconds to maintain film structure. Secondly, the membrane was soaked in a coagulation bath containing pure water for two days. Finally, the flat sheet membrane was left to dry at ambient humidity for three days.

2.3 Characterizations

Scanning electron microscope (SEM) was used to determine membrane morphology. To begin with, membrane samples were soaked for a few seconds in liquid and clamped on both sides with tweezers until it was frozen, before being cut into 2.5 cm sections. The membrane pieces were then placed to an aluminium plate measuring 30 mm. The samples were subsequently analyzed based on their cross-sectional morphology and followed by identifying the structure on the membrane.

Atomic force microscopy (AFM) could produce high-resolution 3D images of surface structures. A small piece of fiber was cut and adhered on a 1 cm² square paper card using double-sided adhesive tape. The membrane surface was scanned in the size of 5 μm × 5 μm. Surface roughness relates to one the important surface characteristics and gives significant properties to hydrophilic properties and soiling properties on the membrane [9].

Fourier transform Infra-red (FTIR) was used to identify the functional groups present in the control (i.e., without TiO₂, 1% TiO₂, and 2% TiO₂). Similar to the SEM procedure, membrane samples cut to a size of 30 mm were placed on a transparent glass plate of the FTIR device and exposed to infrared light. The analysis was performed at the wavenumber range of 4000-500 cm⁻¹ [10].

Contact angle measurement was conducted by using 50 μl of water droplets sprayed on the surface of the insulating substance. The water droplet profile was captured two minutes after its dropping onto the insulator material surface. The screen displayed the water drop profile and contact angle (180° - γ). Then classified contact angles in three groups, <30° as hydrophilic type, between 30° and 89° as partially wetted type, and > 90° as hydrophobic type [11].

Membrane performance and fouling analysis can be observed via membrane flux. Before testing, membranes were cut into a circular shape to fit into the dead end system tube, and then the four caps were tightly sealed to prevent any water leakage. The flux was performed under 4 bar pressure, and the pure water permeate flux. The constant flux, J (L/m².h) was determined using the following equation [12].

$$J = \frac{V}{At} \quad (1)$$

3.0 RESULTS AND DISCUSSION

3.1 Effect of TiO₂ on Membrane Structure

It can be seen in Figure 1(a) that PVDF membrane cast without TiO₂ appears less homogeneous, showing waviness and uneven thickness. As a result, the membrane surface is not uniform, slightly cloudy in certain areas, and more prone to physical defects [13].

When TiO₂ is added at a concentration of 1% as shown in Figure 1(b), membrane becomes somewhat more uniform, smoother, and less opaque. Meanwhile, membrane with 2% TiO₂ in Figure 1(c) shows the most optimal outcome, with the most uniform dispersion, stable pore formation, and no signs of agglomeration. This demonstrates that TiO₂ improves the hydrophilicity and overall structural quality of the membrane without introducing visual defects [14].

The addition of TiO₂ in the dope solution influences the viscosity of the solution, the immersion rate, and the formation of characteristic pore structure within the membrane [15].

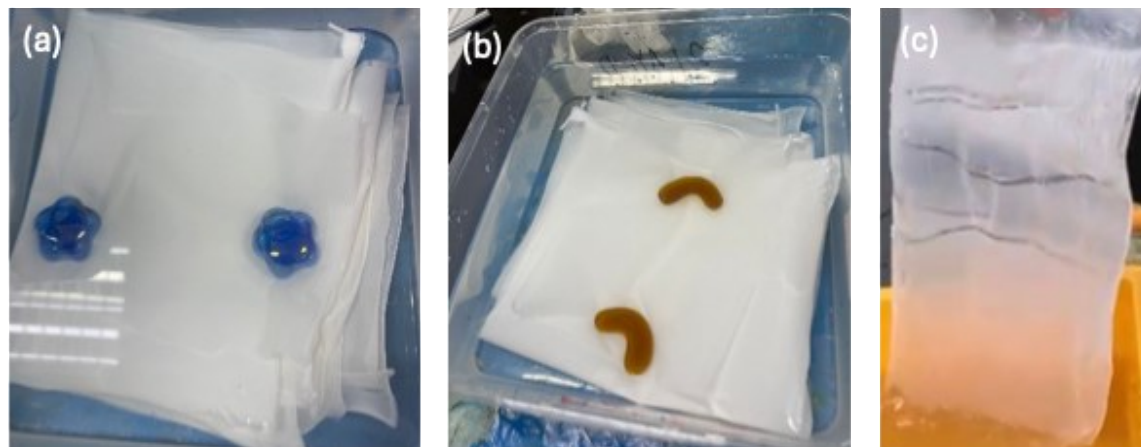


Figure 1. Photographs of flat sheet PVDF membrane with (a) 2% TiO₂ and (b-c) 1% TiO₂

3.2 SEM Analysis

In Figure 2(a), the membrane without TiO₂ shows small black pores on even distribution with relatively uniform sizes with 370 nm. The surface still appears fairly smooth, with no white protrusions [16]. Based on the cross-sectional analysis, Figure 2(b) shows dense and thin top layer [11], with finger-like macrovoids underneath that are quite long and open. Then the bottom part begins to change into a finer porous sponge zone [16].

Furthermore, the pores of PVDF membrane with 1% TiO₂ in Figure 2(c) appear to be slightly higher with a wider range of sizes with 530 nm. There are more white spots that are somewhat clumped together because of an indication TiO₂ agglomeration [17]. When TiO₂ is increased to 1% in Figure 2(d), there are more finger-like macrovoids, extending deeper downward [15]. TiO₂ is hydrophilic, thereby increasing the solvent stimulated the macrovoids to grow larger and longer with more porous sub-layer [18]. While the bottom parts seem more porous or open than the previous one [19].

In Figure 2(e), the PVDF membrane with 2% TiO₂ appears to have more connected porous area and dense with sizes of 580 nm. The white spots are becoming more distinct and larger which significant TiO₂ agglomerates on the surface. Then the overall surface appears to be the roughest and most uneven among the three images [16].

Figure 2(f) is a cross section of the PVDF membrane with 2% TiO₂. In this figure, finger-like macrovoids are much partially disappeared [20], replaced by areas that appear more compact. As well as the sponge zone at the bottom which is quite thick. Then white spots are more visible which indication of TiO₂ agglomeration at high concentrations [11]. In this study, the presence of TiO₂ nanoparticles as a hydrophilic additive with PVDF/PVP membranes gradually changes from smooth and uniformly porous to rougher and highly one. This effect is beneficial for improving hydrophilicity.

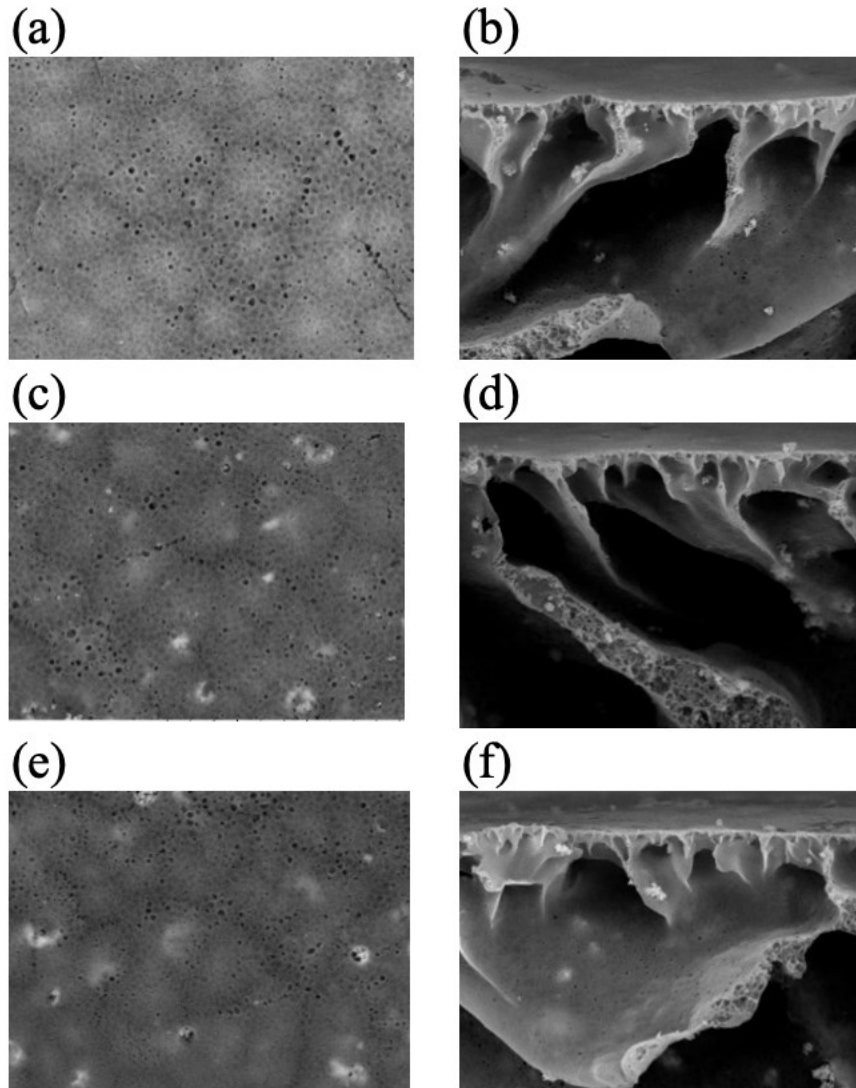


Figure 2. SEM images of PVDF membrane without TiO₂, (a) Surface and (b) Cross Section. PVDF membrane with 1% TiO₂, (c) Surface and (d) Cross Section. PVDF membrane with 2% TiO₂, (e) Surface and (f) Cross Section

3.3 AFM Analysis

The membrane surface topography of the 3-D images was observed using AFM. The high peaks seen as bright regions in the AFM images characterize the nodules, while the pores are seen as dark depressions. As shown in Figure 3(a), the AFM image of PVDF membrane without TiO₂ shows a comparatively flat and smooth surface with uniform texture. The height variations across scan area are minimal, and this figure indicated by a lower mean roughness average value. This is because more granules are observed on the membrane surface. The interfacial pressure acting between macromolecules and TiO₂ nanoparticles tends to increase the orientation of macromolecules, resulting in denser packing of macromolecules and a smoother surface [21].

* Corresponding to: E. Yuliwati (email: erna_yuliwati@um-palembang.ac.id)
DOI: <https://doi.org/10.11113/jamst.v30n1.323>

Figure 3 (b) shows that the TiO₂ nanoparticles appeared on the surface of membrane results in a higher roughness value compared to the PVDF membrane without TiO₂. AFM image of the PVDF membrane with 2% TiO₂ has a nodule-like structure and aggregates of nodules that were formed on outer surface. These surface changes subsequently impact membrane properties such as hydrophilicity and fouling resistance [22].

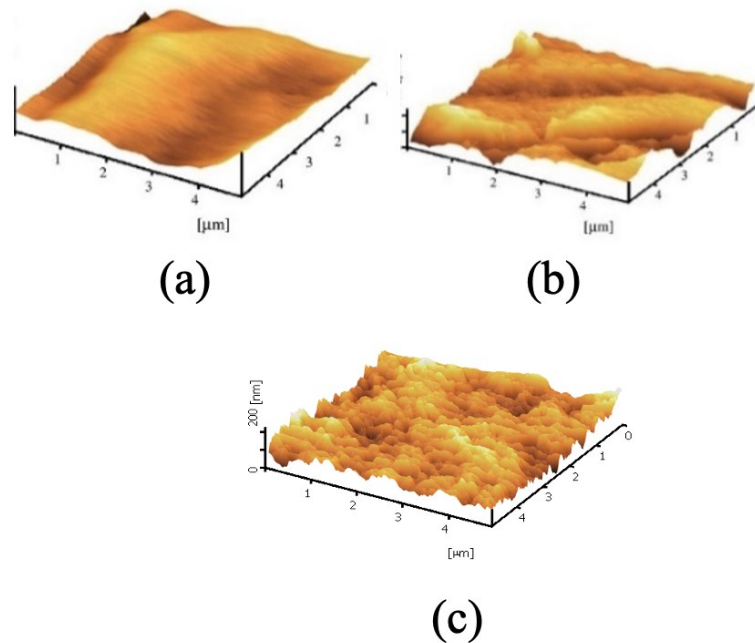


Figure 3. 3D AFM images of PVDF membrane (a) without TiO₂, (b) with 1% TiO₂ and (c) with 2% TiO₂

3.4 Hydrophilicity Analysis

Regarding the hydrophilicity of surface membrane, it has been shown in Figure 4(a) which represents PVDF membrane without TiO₂ has the highest contact angle, with an average value of 78.6°. The contact angle formed on the membrane with 1% TiO₂ decreases to 67.1° which means more hydrophilic level than Figure 4(b). Figure 4(c) shows the water contact angle formed that decreases after the membrane was modified by adding 2% TiO₂ additives to the PVDF membrane dope solution.

It was found that increasing the concentration of PVDF polymer in the casting solution led to the decrease in water contact angle. The results from Figure 4(c) show that minimal contact angle with 2% TiO₂ is 43.8°, which means that the PVDF membrane with 2% TiO₂ is hydrophilic, so the membrane is more reliable to absorb water droplets on the membrane surface.

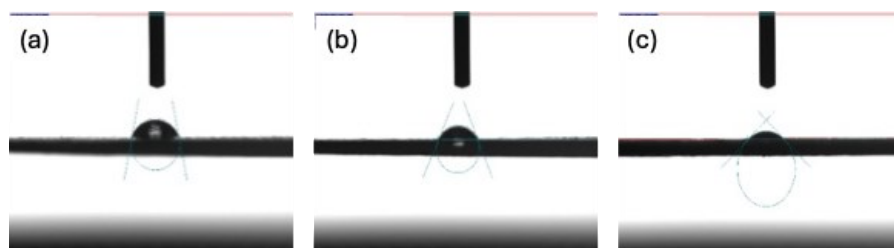


Figure 4. Contact angle of PVDF membrane, (a) without TiO₂, (b) with 1% TiO₂ and (c) 2% TiO₂

3.5 FTIR Analysis

FTIR analysis was conducted to identify the functional groups present in the nanoparticles, and the corresponding spectra can be seen in Figure 5. As shown in the figure, the characteristic absorption bands of pristine PVDF without TiO₂ are clearly evident. The peaks at 3024 cm⁻¹ and 2950 cm⁻¹ correspond to the asymmetric and symmetric stretching vibrations of CH₂ groups, while the band at 1402 cm⁻¹ is associated with CH₂ deformation. The absorption near 1181 cm⁻¹ arises from the stretching vibration of CF₂ groups, and additional PVDF-specific bands are observed at 521, 612, and 873 cm⁻¹ [23].

Furthermore, the FTIR spectra of PVDF incorporating 1% and 2% TiO₂, shown in both Figure 5(b) and 5(c), reveal the emergence of new functional features and structural modifications following the addition of TiO₂. For the membrane containing 1% TiO₂, the characteristic C–F stretching is identified at 1181 cm⁻¹, while the CH₂ deformation band is observed at 1403 cm⁻¹. A peak at 612 cm⁻¹ corresponds to the vibrational mode involving rocking and bending motions of CF₂ groups [24].

Similarly, the spectrum of the membrane with 2% TiO₂ exhibits a deformation vibration of –CH₂ at 1403 cm⁻¹, along with a band at 525 cm⁻¹ attributed to TiO₂ stretching vibrations within the composite matrix. A series of bands between 612 cm⁻¹ and 874 cm⁻¹ further reflects lattice vibrations of TiO₂. The interaction between PVDF and the higher TiO₂ loading (2%) results in a noticeable reduction in the intensity of PVDF and PVP peaks, particularly around 525 cm⁻¹, indicating stronger polymer–nanoparticle interactions as TiO₂ content increases [11].

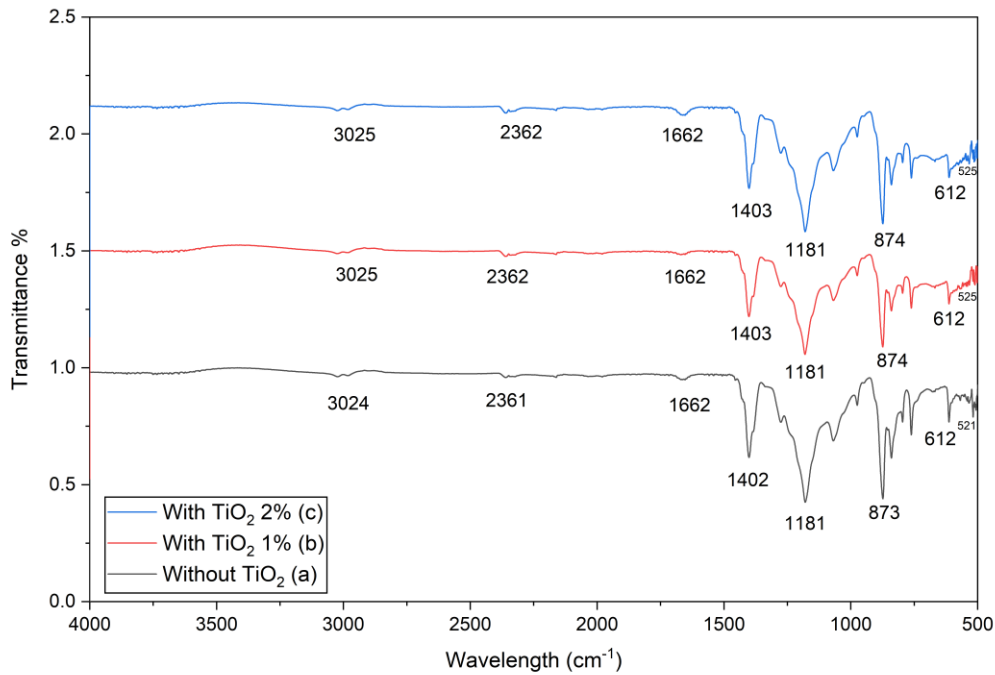


Figure 5. FTIR spectra of PVDF membrane without and with TiO₂

3.6 Flux

The data tabulated in [Table 1](#) confirm that the incorporation of TiO₂ has a pronounced influence on membrane flux performance. The unmodified PVDF membrane exhibits the lowest flux of 49 L/m²·h, whereas the addition of TiO₂ significantly increases permeability, yielding fluxes of 148 and 150 L/m²·h for membranes containing 1% and 2% TiO₂, respectively. This enhancement is attributed to the improved hydrophilicity imparted by TiO₂, which promotes larger and more accessible pore structures, thereby facilitating easier permeate transport through the membrane. The observed flux also confirms that the fabricated membranes fall within the ultrafiltration range and that TiO₂ serves as an effective additive for enhancing membrane permeability.

Table 1. Flux of PVDF membrane with varying TiO₂ concentration

Membrane	Permeate Volume (L)	Membrane Surface Area (m ²)	Time (min)	Flux (L/m ² ·h)
PVDF	0.05	1.3847 x 10 ⁻³	10	49
PVDF-TiO ₂ 1%	0.05	1.3847 x 10 ⁻³	10	148
PVDF-TiO ₂ 2%	0.05	1.3847 x 10 ⁻³	10	160

* Corresponding to: E. Yuliwati (email: erna_yuliwati@um-palembang.ac.id)
 DOI: <https://doi.org/10.11113/jamst.v30n1.323>

4.0 CONCLUSION

This work demonstrates that incorporating low concentrations of TiO₂ (1–2%) into PVDF/PVP membranes significantly enhances their structural, chemical, and filtration performance. The addition of TiO₂ improved pore formation, increased surface hydrophilicity, and strengthened polymer–nanoparticle interactions, as evidenced by SEM, AFM, FTIR, and contact-angle analyses. These modifications resulted in a substantial rise in pure-water flux, increasing from 49 L/m²·h for the unmodified membrane to 148–160 L/m²·h for TiO₂-modified membranes. Overall, TiO₂ serves as an effective hydrophilic additive that improves the permeability and functional quality of PVDF membranes, making them more suitable for ultrafiltration-based water treatment. Further optimization of TiO₂ loading and long-term stability assessment is recommended to fully maximize membrane performance in practical applications. However, the concentration range explored in this work is still limited, and higher or optimized TiO₂ loadings may further influence membrane performance. Therefore, future studies should analyse a broader concentration range and membrane regeneration to evaluate long-term stability to fully realize the potential of PVDF- TiO₂ membranes.

DECLARATION OF COMPETING INTEREST

The authors declare no competing interests.

ACKNOWLEDGEMENT

The authors acknowledge the support and contributions of individuals and institutions that have facilitated the completion of this research.

REFERENCES

- [1] Nani, H., Mahmud, M., & Abdi, C. (2016). Pengaruh pH air gambut terhadap fouling membran ultrafiltrasi. *Jukung (Jurnal Teknik Lingkungan)*, 1(1). <https://doi.org/10.20527/jukung.v1i1.1038>
- [2] Kim, I. C., & Lee, K. H. (2004). Effect of poly(ethylene glycol) 200 on the formation of a polyetherimide asymmetric membrane and its performance in aqueous solvent mixture permeation. *Journal of Membrane Science*, 230(1–2), 183–188. <https://doi.org/10.1016/j.memsci.2003.11.002>
- [3] Suharton, J., Putra, M., Naufaldy, D. A., Pertiwi, D. S., & Noersalim, C. (2018). Penyisihan logam Fe menggunakan membran polyvinylidene fluoride/carbon nanotube (PVDF/CNT). <http://eprints.itenas.ac.id/id/eprint/282>
- [4] Fathanah, U., & Meilina, H. (2021). Karakterisasi dan kinerja membran polyethersulfone termodifikasi aditif anorganik secara blending polimer. *Jurnal Serambi Engineering*, 6(4), 2407–2414. <https://doi.org/10.32672/jse.v6i4.3515>
- [5] Lima, C. A., Goulart, V. P., Correa, L., Pereira, T. M., & Zzell, D. M. (2015). ATR-FTIR spectroscopy for the assessment of biochemical changes in skin due to cutaneous squamous cell carcinoma. *International Journal of Molecular Sciences*, 16(4), 6621–6630. <https://doi.org/10.3390/ijms16046621>

- [6] Lee, E. J., An, A. K., He, T., Woo, Y. C., & Shon, H. K. (2016). Electrospun nanofiber membranes incorporating fluorosilane-coated TiO₂ nanocomposite for direct contact membrane distillation. *Journal of Membrane Science*, 520, 145–154. <https://doi.org/10.1016/j.memsci.2016.07.019>
- [7] Surmenev, R. A., Chernozem, R. V., Skirtach, A. G., Bekareva, A. S., Leonova, L. A., Mathur, S., ... Surmeneva, M. A. (2021). Hydrothermal synthesis of barium titanate nano/microrods and particle agglomerates using a sodium titanate precursor. *Ceramics International*, 47(7), 8904–8914. <https://doi.org/10.1016/j.ceramint.2020.12.011>
- [8] Ayyaru, S., Murugasamy, J., & Ahn, Y. H. (2025). High-antifouling and hydrophilic PVDF ultrafiltration membranes modified with ultra-thin layered ATO nanosheets toward advanced water treatment. *Journal of Industrial and Engineering Chemistry*. <https://doi.org/10.1016/j.jiec.2025.04.060>
- [9] Prabhakar, N., Isloor, A. M., Padaki, M., & Ismail, A. F. (2024). Fabrication of TiO₂@ZIF-67 metal–organic framework composite incorporated PVDF membranes for the removal of hazardous reactive black 5 and Congo red dyes from contaminated water. *Chemical Engineering Journal*, 498, 155270. <https://doi.org/10.1016/j.cej.2024.155270>
- [10] Gayatri, R., Fizal, A. N. S., Yuliwati, E., Zailani, M. Z., Jaafar, J., Hossain, M. S., ... Yahaya, A. N. A. (2024). Effect of polyvinylidene fluoride concentration in PVDF-TiO₂-PVP composite membranes properties and its performance in bovine serum albumin rejection. *Case Studies in Chemical and Environmental Engineering*, 9, 100620. <https://doi.org/10.1016/j.csee.2024.100620>
- [11] Zhou, A., Jia, R., Wang, Y., Sun, S., Xin, X., Wang, M., ... Zhu, H. (2020). Abatement of sulfadiazine in water under a modified ultrafiltration membrane (PVDF-PVP-TiO₂-dopamine) filtration-photocatalysis system. *Separation and Purification Technology*, 234, 116099. <https://doi.org/10.1016/j.seppur.2019.116099>
- [12] Gayatri, R., Fizal, A. N. S., Yuliwati, E., Hossain, M. S., Jaafar, J., Zulkifli, M., ... Ahmad Yahaya, A. N. (2023). Preparation and characterization of PVDF–TiO₂ mixed-matrix membrane with PVP and PEG as pore-forming agents for BSA rejection. *Nanomaterials*, 13(6), 1023. <https://doi.org/10.3390/nano13061023>
- [13] Le, T. M. H., Chuchak, R., & Sairiam, S. (2024). Empowering TiO₂-coated PVDF membranes stability with polyaniline and polydopamine for synergistic separation and photocatalytic enhancement in dye wastewater purification. *Scientific Reports*, 14(1), 15969. <https://doi.org/10.1038/s41598-024-66996-w>
- [14] Santos, E. N., Fazekas, Á. F., Fekete, L., Miklós, T., Gyulavári, T., Gokulakrishnan, S. A., ... Veréb, G. (2024). Enhancing membrane performance for oily wastewater treatment: Comparison of PVDF composite membranes prepared by coating, blending, and grafting methods using TiO₂, BiVO₄, CNT, and PVP. *Environmental Science and Pollution Research*, 31(56), 64578–64595. <https://doi.org/10.1007/s11356-024-35456-3>
- [15] Tran, D. T., Méricq, J. P., Mendret, J., Brosillon, S., & Faur, C. (2021). Influence of preparation temperature on the properties and performance of composite PVDF-TiO₂ membranes. *Membranes*, 11(11), 876. <https://doi.org/10.3390/membranes11110876>

- [16] He, T., Li, X., Wang, Q., Zhou, Y., Wang, X., Wang, Z., ... Cui, Z. (2022). Poly(vinylidene fluoride) membrane fabrication with an ionic liquid via non-solvent thermally induced phase separation (N-TIPS). *Applied Water Science*, 12(3), 42. <https://doi.org/10.1007/s13201-021-01499-x>
- [17] Abba, M. U., Man, H. C., Azis, R. A. S., Idris, A. I., Hamzah, M. H., Yunus, K. F., & Katibi, K. K. (2021). Novel PVDF-PVP hollow fiber membrane augmented with TiO₂ nanoparticles: Preparation, characterization and application for copper removal from leachate. *Nanomaterials*, 11(2), 399. <https://doi.org/10.3390/nano11020399>
- [18] Bilal, A., Yasin, M., Akhtar, F. H., Gilani, M. A., Almohamadi, H., Younas, M., ... Khan, A. L. (2024). Enhancing water purification by integrating titanium dioxide nanotubes into polyethersulfone membranes for improved hydrophilicity and anti-fouling performance. *Membranes*, 14(5), 116. <https://doi.org/10.3390/membranes14050116>
- [19] Le, T. M. H., Wang, Y. N., Li, C., Wang, R., & Sairiam, S. (2024). Durable PVDF photocatalytic membranes with TiO₂@PDA incorporated into/onto for dye degradation under visible light. *Chemical Engineering Journal*, 499, 156215. <https://doi.org/10.1016/j.cej.2024.156215>
- [20] Zhang, J., Zheng, M., Zhou, Y., Yang, L., Zhang, Y., Wu, Z., ... Zheng, J. (2022). Preparation of nano-TiO₂-modified PVDF membranes with enhanced antifouling behaviors via phase inversion: Implications of nanoparticle dispersion status in casting solutions. *Membranes*, 12(4), 386. <https://doi.org/10.3390/membranes12040386>
- [21] Yuliwati, E., Porawati, H., Elfidiyah, E., & Melani, A. (2019). Performance of composite membrane for palm oil wastewater treatment. *Journal of Applied Membrane Science & Technology*, 23(2). <https://doi.org/10.11113/amst.v23n2.147>
- [22] Yuliwati, E., Ismail, A. F., Othman, M. H. D., & Shirazi, M. M. A. (2022). Critical flux and fouling analysis of PVDF-mixed matrix membranes for reclamation of refinery-produced wastewater. *Membranes*, 12(2), 161. <https://doi.org/10.3390/membranes12020161>
- [23] Hesavi, M., Derikvand, E., Babarsad, M. S., Bejestan, M. S., & Zendehtdel, M. (2023). Preparation, characterization and performance of PVDF/Al₂O₃, TiO₂ and clay membrane for removal of toxic metals. *Desalination and Water Treatment*, 313, 82–91. <https://doi.org/10.5004/dwt.2023.30070>
- [24] Suryandari, E. T. (2019). Sintesis membran komposit PVDF-zeolit untuk penghilangan metilen biru. *Al Kimiya: Jurnal Ilmu Kimia dan Terapan*, 6(2), 58–66. <https://doi.org/10.15575/ak.v6i2.6491>
- [25] Liu, X., Kong, L., Zhao, X., Wu, K., & Tan, Z. (2023). A method for alkali hydrolysis modification of PAN/PES/TiO₂ composite ultrafiltration membranes. *Desalination and Water Treatment*, 306, 165–177. <https://doi.org/10.5004/dwt.2023.29784>
- [26] Veréb, G., Kassai, P., Nascimben Santos, E., Arthanareeswaran, G., Hodúr, C., & László, Z. (2020). Intensification of the ultrafiltration of real oil-contaminated water with pre-ozonation and TiO₂/CNT nanomaterial-coated membrane surfaces. *Environmental Science and Pollution Research*, 27(18), 22195–22205. <https://doi.org/10.1007/s11356-020-08047-1>

- [27] Méricq, J. P., Mendret, J., Brosillon, S., & Faur, C. (2015). High performance PVDF-TiO₂ membranes for water treatment. *Chemical Engineering Science*, *123*, 283–291. <https://doi.org/10.1016/j.ces.2014.10.047>
- [28] Kuzminova, A., Dmitrenko, M., Zolotarev, A., Markelov, D., Komolkin, A., Dubovenko, R., ... Penkova, A. (2023). Novel mixed matrix membranes based on poly(vinylidene fluoride): Development, characterization, modeling. *Polymers*, *15*(5), 1222. <https://doi.org/10.3390/polym15051222>
- [29] Fathanah, U., & Meilina, H. (2021). Karakterisasi dan kinerja membran polyethersulfone termodifikasi aditif anorganik secara blending polimer. *Jurnal Serambi Engineering*, *6*(4), 2407–2414. <https://doi.org/10.32672/jse.v6i4.3515>
- [30] Suryandari, E. T. (2019). Sintesis membran komposit PVDF-zeolit untuk penghilangan metilen biru. *Al Kimiya: Jurnal Ilmu Kimia dan Terapan*, *6*(2), 58–66. <https://doi.org/10.15575/ak.v6i2.6491>
- [31] Teow, Y. H., Ooi, B. S., Ahmad, A. L., & Lim, J. K. (2020). Investigation of anti-fouling and UV-cleaning properties of PVDF/TiO₂ mixed-matrix membrane for humic acid removal. *Membranes*, *11*(1), 16. <https://doi.org/10.3390/membranes11010016>
- [32] Behera, R., & Elanseralathan, K. (2022). A review on polyvinylidene fluoride polymer-based nanocomposites for energy storage applications. *Journal of Energy Storage*, *48*, 103788. <https://doi.org/10.1016/j.est.2021.103788>
- [33] Chen, S., Skordos, A., & Thakur, V. K. (2020). Functional nanocomposites for energy storage: Chemistry and new horizons. *Materials Today Chemistry*, *17*, 100304. <https://doi.org/10.1016/j.mtchem.2020.100304>
- [34] Tran, D. T., Méricq, J. P., Mendret, J., Brosillon, S., & Faur, C. (2021). Influence of preparation temperature on the properties and performance of composite PVDF-TiO₂ membranes. *Membranes*, *11*(11), 876. <https://doi.org/10.3390/membranes11110876>
- [35] Elizalde, C. N. B., Al-Gharabli, S., Kujawa, J., Mavukkandy, M., Hasan, S. W., & Arafat, H. A. (2018). Fabrication of blend polyvinylidene fluoride/chitosan membranes for enhanced flux and fouling resistance. *Separation and Purification Technology*, *190*, 68–76. <https://doi.org/10.1016/j.seppur.2017.08.053>