

Effect of Additive Polyvinylpyrrolidone (PVP) on Structure and Mechanical Strength of Polyethersulfone (PES) Membrane for Hemodialysis

Zahrotin Nisa¹

Yeni Rahmawati^{*,1}

Hernanda Aldian Syah¹

Susianto Susianto¹

Ali Altway¹

Fadlilatul Taufany¹

Siti Nurkhamidah¹

¹ Department of Chemical Engineering, Faculty of Industrial Technology and Systems Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, East Jawa, 60111, Indonesia

*e-mail: y_rahmawati@its.ac.id

Submitted 6 January 2026

Revised 27 June 2026

Accepted 28 July 2026

Abstract. The global increase in chronic kidney disease (CKD) has intensified the demand for hemodialysis therapy, which relies on semi-permeable membranes commonly fabricated from hydrophobic polymers such as polyethersulfone (PES). Although PES offers excellent mechanical strength and thermal stability, hydrophilic additives such as polyvinylpyrrolidone (PVP) are often incorporated to improve membrane hydrophilicity and biocompatibility. This study investigates the effect of PVP molecular weight (PVP-10 kDa and PVP-40 kDa) as an additive on the characteristics and performance of PES/NMP hollow fiber membranes for hemodialysis applications. To evaluate the effects of PVP, membranes were fabricated under varying solvent ratios (18/82 and 21/79 w/w) and air gap distances (19, 30, 50 cm) via dry-wet spinning phase inversion. The membranes were characterized in terms of morphology using scanning electron microscopy (SEM), mechanical properties, hydrophilicity, and dialysis performance. The results show that the optimal membrane was obtained using PVP-K10 at an 18/82 (w/w) PES/NMP ratio with a 19 cm air gap, achieving urea and creatinine clearance of 45.37% and 57.5%, respectively, and BSA rejection of 72.89%. The SEM analysis confirmed the presence of an ultrafiltration membrane-type finger-like structure. Overall, the optimized PES/PVP hollow fiber membrane exhibited low-flux ultrafiltration characteristics. These results indicate that the membrane produced has the potential to be further developed into a high-flux ultrafiltration membrane with different variables for hemodialysis applications.

Keywords: Air Gap, Hemodialysis, Hollow Fiber Membrane, Polyethersulfone, Polyvinylpyrrolidone

INTRODUCTION

Chronic kidney disease (CKD) has become a global health problem, with nearly 700 million people worldwide estimated to

experience acute kidney injury (AKI) and end-stage renal failure (Francis *et al.*, 2024). The true incidence is likely to be higher because of the limitations of early detection programs in some countries. Hemodialysis has become

a method for treating patients who progress to end-stage kidney disease (ESKD). This method involves the use of a semi-permeable hollow fiber membrane that removes uremic toxins that are not required by the body, such as urea and creatinine, but retains vital blood proteins, such as albumin and fibrinogen (Canaud *et al.*, 2021; Davenport, 2023). For this purpose, membranes need to be hemocompatible, highly selective, non-protein-absorptive, biocompatible, and have the right pore size (Lusiana *et al.*, 2016).

Polyethersulfone (PES) is one of the most utilized membrane polymers owing to its superior mechanical strength, thermal stability, chemical resistance, and simplicity of production (Xu & Qusay, 2004). However, its intrinsic hydrophobic nature increases protein adsorption upon contact with blood, resulting in platelet adherence, fouling, and a slow reduction in membrane flow and lifetime (Wang *et al.*, 2009; Irfan & Idris, 2015). A popular solution to this issue is the use of hydrophilic chemicals, such as polyvinylpyrrolidone (PVP). Kahraman *et al.* (2022) demonstrated corresponding enhancements in porosity, hydrophilicity, and creatinine clearance, while Hasheminasab *et al.* (2020) reported smoother membrane surfaces with PVP addition.

The molecular weight of PVP significantly influences membrane structure and performance, largely by altering the rheological behavior and viscosity of the dope solution, where PVP of different molecular weights modifies the spinning solution viscosity and regulates the resulting membrane morphology (Zhang *et al.*, 2022). This molecular-weight dependence in turn governs pore formation, with the membrane pore number and area reported to increase as PVP molecular weight rises (Chakrabarty *et al.*, 2008). Ong *et al.* (2014) demonstrated

that PVP-K10 creates smaller pores, whereas PVP-K360 produces much larger pores in Polyvinylidene fluoride (PVDF) membranes. This trend also applies to PES-based systems, where the PVP molecular weight dictates pore size, hydrophilicity, and solute penetration (Kinanti *et al.*, 2025). Furthermore, Kahraman *et al.* (2022) noted that adding PVP enhanced membrane hydrophilicity, thereby improving creatinine penetration and clearance.

Manufacturing parameters significantly affect the properties of hollow fiber membranes beyond material composition. Hollow fiber membranes are typically fabricated using the dry-wet spinning phase inversion. This process, known as non-solvent-induced phase separation (NIPS), transforms a liquid polymer solution into a solid via liquid-liquid demixing (Mulder, 1996). During fabrication, the bore liquid enters the spinneret, and the nascent fiber is first exposed to air (dry stage) before solidifying inside a non-solvent coagulation bath (wet stage) (Mulder, 1996).

Among these factors, the air gap, which is the distance between the spinneret output and the surface of the coagulation bath, is particularly important. The length of the air gap controls the length of the nascent membrane's exposure to ambient air and hence directly impacts pore size and shape. Increasing the air gap size leads to increased porosity and improved water flux and decreases the water contact angle of the hollow fiber membrane, therefore boosting the hydrophilicity (Raharjo *et al.*, 2023).

Although many studies have investigated the effect of PVP on the preparation of PES membranes, studies directly comparing PVP-K10 and PVP-K40 with the same composition and operating conditions are rare in the literature, especially in the context of

hemodialysis. In addition, most studies only describe the characteristics or performance of the materials separately. This study systematically investigates the behavior of PVP with different molecular weights (10 kDa and 40 kDa) at various PES/NMP solvent ratios (18/82 and 21/79 w/w) and air gap distances (19, 30, and 50 cm) to determine the optimal fabrication settings for hemodialysis membranes.

MATERIALS AND METHOD

Materials

In this research, we utilized polyether sulfone (PES) sourced from T&T Industry Group, with a molecular weight of 65,000 g/mol. N-Methyl-2-pyrrolidone (NMP) (Merck KGa, Darmstadt, Germany (Molecular Weight: 99.13 g/mol) was used as the solvent. In addition, polyvinylpyrrolidone (PVP) was used, specifically PVP-K10 (MW 10 kDa) and PVP-K40 (MW 40 kDa) from Sigma-Aldrich. This research endeavors to determine the concentrations of bovine serum albumin (BSA) sourced from Sigma-Aldrich, urea obtained from Merck KGaA, and creatinine also derived from Merck KGaA. Aquadest and isopropyl alcohol from Bratachem were used as non-solvents. Liquid nitrogen was used for scanning electron microscopy (SEM) operation. All reagents and chemicals used in this study were of pro analytical grade. Biuret reagent for bovine serum albumin (BSA) analysis was obtained from Rofa Laboratories. Urea was prepared using a mixture of p-dimethylaminobenzaldehyde (DMAB, Sigma-Aldrich), hydrochloric acid (HCl, Merck), and absolute ethanol (Sigma-Aldrich). Creatinine standard solutions were prepared using Labkit reagents (Chemelex, Spain).

Preparation of Dope Solution

Hollow fiber membranes are formed

through a dry-wet phase inversion process. For the dope solution, variations were made in the PES concentration using NMP solvent, namely 18/82% and 21/79% (w/w). Variations were also made in the addition of PVP additives, namely without additives, PVP-K10, and PVP-K40, with a composition of 1.5% to PES, as well as variations in the air gap, which consisted of 19, 30, and 50 cm. Mixing was performed until the solution was homogeneous at a stirring temperature of 85°C and a rotation speed of 460 rpm. The solution was left to stand for 24 hours to remove the trapped air bubbles.

Table 1. Variations in composition and operating conditions in membrane fabrication

PES/NMP (%wt)	PVP types	Air gap (cm)
18/82	without	19
21/79	PVP10	30
-	PVP40	50

Membrane Fabrication

Hollow fiber membranes were fabricated using a spinneret with a bore fluid diameter of 0.4 mm and dope solution diameter of 0.6 mm, which was operated through a dry-wet spinning system (Fig. 1).

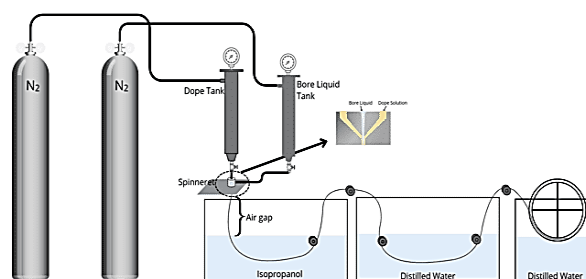


Fig. 1: Schematic Diagram of Hollow Fiber Spinning

The spinneret was placed above a non-solvent bath, with a height that could be

adjusted according to air gap variations of 19, 30, and 50 cm. Distilled water was used as the bore liquid during the extrusion process. After extrusion, the membrane was immersed in a non-solvent isopropanol bath for 2 minutes, followed by rinsing with distilled water for 1 day to remove residual NMP.

Membrane Characterization

a. Viscosity

The viscosity of the polymer solution was measured using an NDJ-8S viscometer. A total of 150 mL of the prepared polymer solution was placed into a glass beaker, after which the measurement was performed according to the instrument's standard operating procedure.

b. Membrane Morphology

The surface and cross-sectional morphologies of the membranes were examined using scanning electron microscopy (SEM, SU35000, Hitachi, Japan). Before observation, the membranes were fractured in liquid nitrogen to obtain a clean cross-section and subsequently mounted onto a sample holder. The samples were then sputter-coated with a thin layer of gold to enhance their conductivity and image resolution. SEM analysis was performed to visualize the pore structure and surface characteristics of the membranes.

c. Pore Size Measurement

Pore size measurements were conducted using ImageJ software to determine the pore size distribution and fiber diameter from SEM results.

d. Mechanical Strength

The mechanical strength of the PES membrane was evaluated by measuring its tensile strength. The test was performed

using HT 2402 (Hung TA) according to ASTM D882.

e. Porosity

Porosity describes the fraction of the membrane volume occupied by pores. The methods of analyzing porosity and water content are similar. The membrane is cut into 2x2 cm pieces, soaked in distilled water for 24 h, and weighed for wet weight. The membrane was then dried in an oven at 60°C and weighed to obtain its dry weight. Here, the equation is (Maisarah *et al.*, 2024):

$$\varepsilon = \frac{\left(\frac{W_w - W_d}{\rho_w}\right)}{\left(\frac{W_w - W_d}{\rho_w}\right) + \left(\frac{W_d}{\rho_p}\right)} \times 100\% \quad (1)$$

Where, W_w is the wet membrane weight (g), W_d is the dry membrane weight (g), ρ_w is the water density (g/L), and ρ_p is the polymer density (g/L).

f. Water Content

The analysis of water content is essential for assessing the membrane's capacity for water absorption, or the amount of water it can absorb. This examination employs the following equation (Mntambo *et al.*, 2019):

$$\text{Water content (\%)} = \frac{W_w - W_d}{W_w} \times 100\% \quad (2)$$

Where, W_w is the wet membrane weight (g), and W_d is the dry membrane weight (g).

g. Water Contact Angle (WCA)

The water contact angle was used to determine the hydrophilicity of the membrane, which is indicated by a contact angle of $0^\circ < \theta < 90^\circ$. This test was performed by dropping 10 μL water droplets using micropipettes on the membrane surface and

measuring the angle of the water droplets using ImageJ software.

Membrane Performance

a. Pure Water Permeability (PWP)

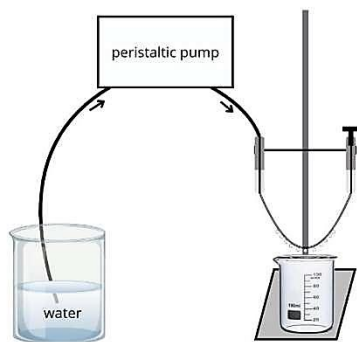


Fig. 2: Permeability test equipment scheme

Pure Water Permeability (PWP) tests were conducted to assess the capacity of water to infiltrate the membrane via its pores under specified pressure conditions. The calculation was performed using the following equation (Xu *et al.*, 2025):

$$PWP = \frac{Q}{A \times \Delta t \times \Delta P} \quad (3)$$

Where A is the surface area (m^2); Q is the amount of filtered water (L); Δt is the duration of the process (h); ΔP is the pressure difference during filtration.

b. Membrane Clearance and Rejection

Membrane clearance was assessed using urea and creatinine as model solutes. The concentration of urea was quantified by measuring absorbance at 415 nm after reaction with DMAB reagent. In contrast, the concentration of creatinine was evaluated at 460 nm after its reaction with WR reagent. The concentrations derived from calibration curves were used to assess the clearing performance. The equation used is as follows (Raharjo *et al.*, 2023):

$$\text{Clearance (\%)} = \left(\frac{C_0 - C_t}{C_0} \right) \times 100 \% \quad (4)$$

Where C_0 is the concentration of solute at the initial time, and C_t is the concentration at a specific time (mg/L).

Rejection is defined as the fraction of solute concentration that cannot pass through the membrane. Membrane rejection was tested using bovine serum albumin (BSA). The quantity of BSA in the feed and permeate solutions was quantified spectrophotometrically at 310 nm after reaction with WR reagent. The resulting concentrations were used to determine the membrane rejection coefficient. The equation used is as follows:

$$\text{Rejection (\%)} = \left(1 - \frac{C_p}{C_f} \right) \times 100\% \quad (5)$$

Where, C_p is the permeate concentration after filtration, and C_f is the feed concentration before filtration (mg/L).

The ultrafiltration coefficient (K_{UF}) reflects the water permeability of a dialysis membrane. It is defined as the ultrafiltration rate (Q_{UF}) divided by the transmembrane pressure (ΔP) and normalized to the membrane area (A) (Aryanti *et al.*, 2025):

$$K_{UF} = \frac{Q_{UF}}{\Delta P} \frac{1}{A} \quad (6)$$

Membranes with $K_{UF} < 10 \text{ mL} \cdot \text{h}^{-1} \cdot \text{mmHg}^{-1}$ are considered low-flux, while those with K_{UF} above $15\text{--}20 \text{ mL} \cdot \text{h}^{-1} \cdot \text{mmHg}^{-1}$ are categorized as high-flux, indicating higher capacity for fluid removal.

The sieving coefficient (SC) describes the capacity of a hemodialysis membrane to permit solute transport. It is expressed as the ratio between the solute concentration in the filtrate and plasma water (Aryanti *et al.*, 2025):

$$SC = \frac{C_f}{C_p} \quad (7)$$

Where C_f represents the solute concentration in the filtrate, and C_p represents the solute concentration in the plasma. An SC value of 1 reflects complete solute passage through the membrane, whereas a value close to 0 signifies total solute retention.

RESULTS AND DISCUSSION

ATR-FTIR

Fig. 3 shows the incorporation of PVP into the PES hollow fiber membranes was confirmed by the characteristic carbonyl (C=O). The absorption band at approximately 1669-1672 cm^{-1} and the typical PES peaks at 1578, 1485, 1237 and 1149 cm^{-1} correspond to the vibrations of the aromatic ring, ether linkages, and sulfone groups (Huang *et al.*, 2017). These distinctive bands are similar to the results reported for PES/PVP membrane systems, where the carbonyl peak is an important signal of PVP in the membrane matrix (Bensaadi *et al.*, 2016). The observation of the carbonyl band on both the inner and outer sides imply that PVP remained in the hollow fiber structure after membrane manufacturing.

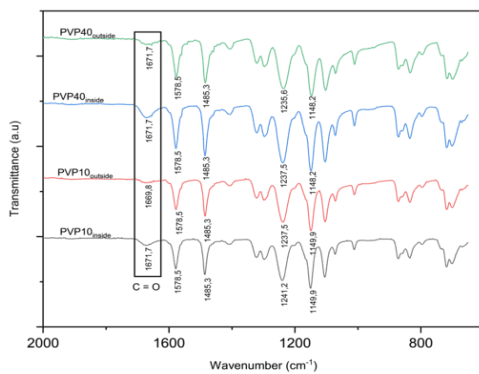


Fig. 3: Comparison of FTIR spectra of PES/PVP-K10 and PES/PVP-K40

Membrane Characterization

The dope solution viscosity increased significantly from 1416 to 3321 cP with the polymer content changing from 18/82 to 21/79 w/w, as shown in Fig. 4, due to increased interaction between polymer chains (Mulder, 1996). The molecular weight of PVP was also a critical factor; PVP-K10 reduced the viscosity at higher concentrations, whereas PVP-K40 enhanced it (Bohr *et al.*, 2023). These changes in viscosity directly controlled membrane porosity (Fig. 5). Lower viscosities facilitated fast solvent-nonsolvent exchange during NIPS, resulting in macrovoid-rich structures with 91-94% porosity (Reuvers & Smolders, 1987; Guillen *et al.*, 2011). In contrast, the increased viscosity of the 21/79 (w/w) PVP-K40 system decreased the diffusional kinetics, avoided macrovoids, and produced denser membranes with 87.2% porosity.

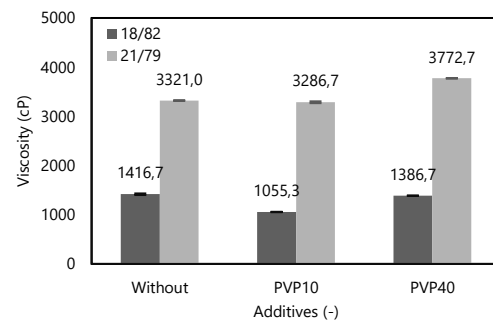


Fig. 4: Viscosity of dope solution at various composition

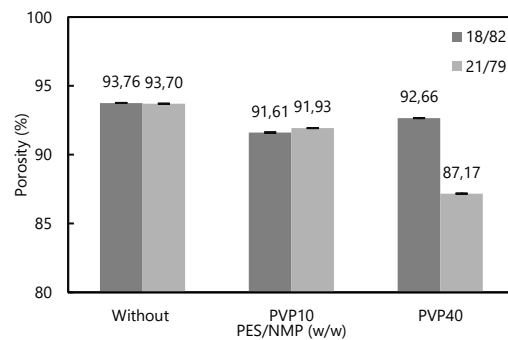


Fig. 5: Result of porosity of membrane at varying concentrations and additives at 30 cm air gap.

Measured water contents (Fig. 6) showed a distribution that could not be explained by viscosity alone. Although the 18/82 (w/w) PVP-K40 membrane induced higher viscosity and reduced structural porosity, it showed the greatest water content (91.9%) compared to the membrane without additive (85.7%) and PVP-K10 (84.0%). The inconsistency arises from the molecular structure of PVP. Higher molecular weight PVP has a higher density of hydrophilic pyrrolidone (lactam) groups, which create additional hydrophilic sites within the membrane matrix and enhance water absorption independent of overall porosity (Ong *et al.*, 2014). In contrast, PVP-K10 showed just a modest increase in water absorption, consistent with its principal function as a pore-forming agent, rather than a hydrophilizing modifier. As highlighted by Dehghan and Barzin (2021), low molecular weight PVP significantly affects pore diameter and permeability, with a considerably lower contribution to surface hydrophilicity than higher molecular weight variations.

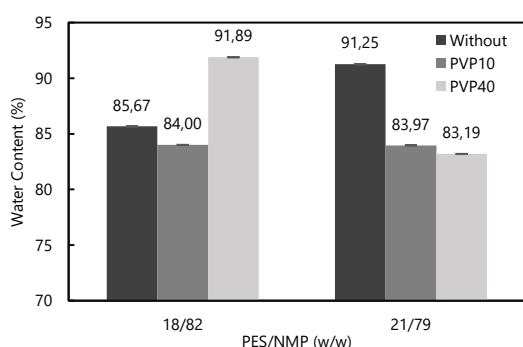


Fig. 6: Result of water content of Membrane at varying concentrations and additives at 19 cm air gap

The surface hydrophilicity was determined using water contact angle measurements (Fig. 7). The additive-free membrane exhibited the lowest angle (64.02°) at the 18/82 (w/w) ratio, followed by

PVP-K10 (67.18°) and PVP-K40 (68.96°). The unexpected increase in wettability with PVP addition is attributed to the rapid phase inversion kinetics at lower polymer concentrations, leading to an open finger-like structure that promotes wettability through capillary effects rather than additive chemistry (Guillen *et al.*, 2011; Kahrs *et al.*, 2020). Conversely, at 21/79 (w/w) the trend was reversed, with PVP-K40 yielding the lowest angle (64.24°), which was substantially lower than the additive-free (68.96°) and PVP-K10 (69.10°) membranes. This indicates that the lactam groups of PVP-K40 control the surface wettability during gradual phase inversion (Ong *et al.*, 2014). Finally, the hydrophilicity of the membrane represents a compromise between morphological effects (fast demixing) and additive chemistry (slow kinetics). PVP-K40 is more efficient than PVP-K10 in enhancing hydrophilicity in general, especially at higher concentrations, when the diffusion-controlled kinetics reinforces the surface effect of PVP-K40.

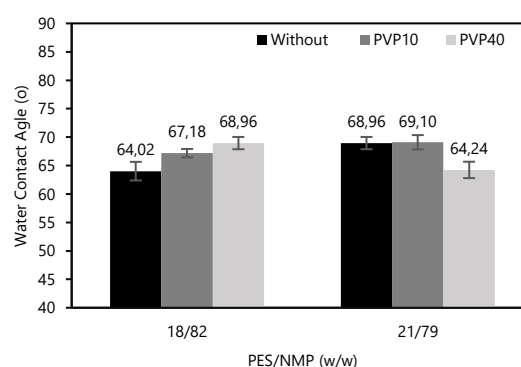


Fig. 7: Result of water contact angle of membrane at varying concentrations and additives at 19 cm air gap

Membrane Morphology

Fig. 8 and Fig. 9 show distinct pore characteristics among the samples. Sample B exhibited pore sizes predominantly within the ultrafiltration range of 0.01–0.1 μm , with

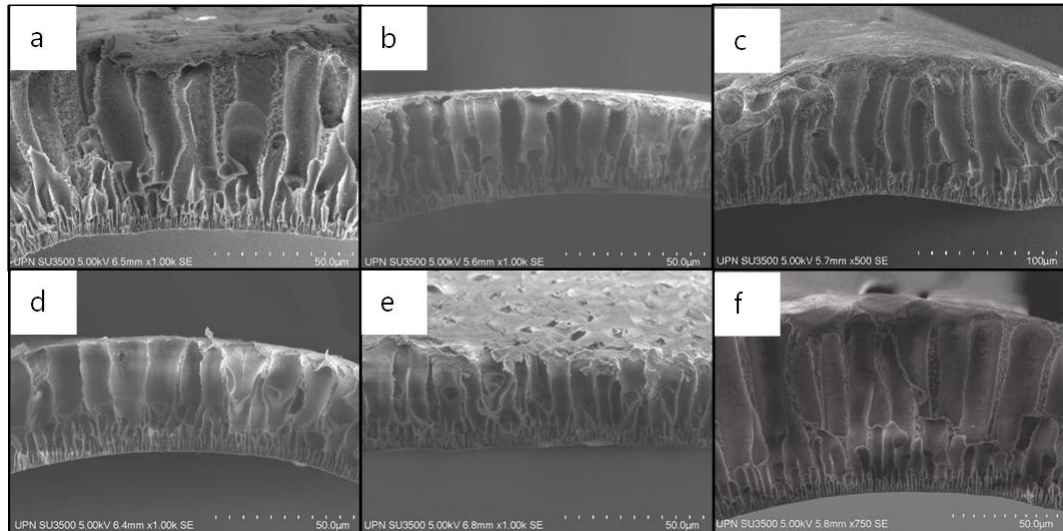


Fig. 8: Morphology of the Membrane on the Cross-Section (a) PES/NMP 18/82-without-19 cm (b) PES/NMP 18/82-PVP10-19 cm (c) PES/NMP 18/82-PVP10-30 cm (d) PES/NMP 18/82-PVP10-50 cm (e) PES/NMP 18/82-PVP40-19 cm (f) PES/NMP 21/79-PVP10-19 cm

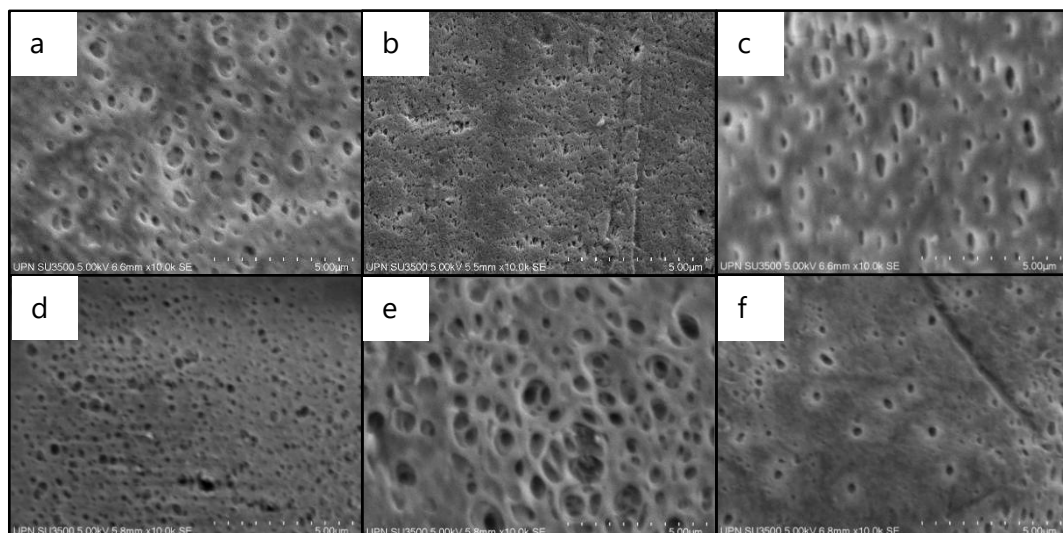


Fig. 9: Morphology of the membrane on the surface-section (a) PES/NMP 18/82-without-19 cm (b) PES/NMP 18/82-PVP10-19 cm (c) PES/NMP 18/82-PVP10-30 cm (d) PES/NMP 18/82-PVP10-50 cm (e) PES/NMP 18/82-PVP40-19 cm (f) PES/NMP 21/79-PVP10-19 cm

uniform distribution and interconnected structures. This morphology is most desirable for hemodialysis applications, enabling efficient removal of uremic toxins while retaining albumin (Aryanti *et al.*, 2025). The optimized role of PVP-K10 as a pore-forming agent and the controlled air-gap condition promoted balanced phase separation, generating a sponge-like structure with

finger-like pores.

Similar morphological improvements have been reported with moderate pore-former concentrations and carefully tuned spinning conditions (Raharjo *et al.*, 2023). Samples A and D showed pores distributed across both the ultrafiltration and microfiltration ranges. Although some of their pore populations fell within 0.01–0.1 μm , a

significant fraction exceeded 0.1 μm , leading to non-uniform pore structures. Morphological inconsistency reduces selectivity, as larger pores increase the risk of albumin leakage despite some ultrafiltration-sized pores functioning effectively (Bacal *et al.*, 2024). Sample C, on the other hand, predominantly exhibited oversized pores above 0.1 μm , clearly placing it within the microfiltration category and making it unsuitable for hemodialysis due to severe risks of protein loss. Sample E further displayed irregular oversized pores, dominated by values exceeding 0.1 μm , confirming its unsuitability (Mulder, 1996). The irregular structures of Samples A, C, D, and E can be attributed to either excessive pore-former addition or extended air gaps that accelerate solvent/nonsolvent exchange and trigger uncontrolled macrovoid growth, as supported by recent studies (Kahrs & Schwellenbach, 2020). Taken together, while A and D partially meet the ultrafiltration criteria, and C and E exceed the desired pore range, only Sample (b) demonstrates the uniform pore size distribution and morphology required for safe and effective hemodialysis membranes.

Mechanical Strength of Membrane

Table 2. Tensile strength analysis results

Membranes	Strain (%)	Stress (MPa)
PES/NMP 18/82 without 19 cm	32.20	14.93
PES/NMP 18/82 PVP10 19 cm	31.31	1.77
PES/NMP 18/82 PVP10 30 cm	60.19	9.38
PES/NMP 18/82 PVP10 50 cm	40.76	6.40
PES/NMP 18/82 PVP40 19 cm	19.39	9.95
PES/NMP 21/79 PVP10 19 cm	61.35	14.95

The tensile strength results in Table 2 demonstrate the strong dependence of the

mechanical properties of the fabricated hollow fiber membranes on the membrane composition and spinning conditions. The PES membrane without the addition of PVP exhibited the highest tensile strength. The addition of PVP generally decreased tensile strength but improved membrane flexibility. This behavior was attributed to the pore-forming behavior of PVP, which accelerates phase inversion and favors the formation of a more porous structure, thus reducing the load-bearing capacity of the membrane matrix (Yang *et al.*, 2009).

Among the modified membranes, PVP-K10 prepared with a 30 cm air gap exhibited the maximum elongation at break, whereas the increase of air gap to 50 cm decreased both tensile strength and elongation, which might be due to the excessive stretching and wall thinning during the fiber formation (Mansur *et al.*, 2016; Said *et al.*, 2021).

In contrast, increasing the polymer concentration from 18/82 to 21/79 (w/w) improved the tensile performance, resulting in a membrane with high tensile strength and elongation. The enhanced mechanical properties can be attributed to the formation of a denser polymer network and stronger chain entanglement, which improved the structural stability of the membrane (Raharjo *et al.*, 2023).

Similar observations were reported by Ghofrani *et al.* (2023), who found that improved interactions within the membrane matrix enhanced the mechanical resistance of PES-based hollow fiber membranes. Mechanical characterization is particularly important because membrane development requires balancing permeability and structural integrity. Although increased pore formation may enhance the transport performance, excessive porosity can weaken the membrane structure. Therefore, adequate

tensile strength and elongation are required to maintain membrane integrity and ensure reliable operation during hemodialysis (Raharjo *et al.*, 2022; Tewfik *et al.*, 2025).

Performance Analysis

The addition of PVP significantly enhanced pure water permeability owing to its hydrophilic nature and pore-forming effect during phase inversion. As shown in Fig. 10, membranes with PVP (PES/NMP 18/82 (w/w), PVP-K10 and PVP-K40) exhibited higher PWP than the membrane without PVP. The added PVP increased the rate of nonsolvent-solvent exchange, enhanced macrovoids, and increased porosity, which facilitates water transport. In addition, the membrane with PVP-K40 exhibited a higher PWP than PVP-K10. Similar findings were reported by Aryanti *et al.* (2025) and Ong *et al.* (2014), who showed that PVP enhances the hydrophilicity and water flux of PES-based membranes. Membranes with a higher polymer content (PES/NMP 21/79 w/w) exhibited the lowest PWP due to their denser structure and reduced porosity. Higher polymer loading increases dope viscosity, slows down phase inversion, and suppresses macrovoids, as also reported by Alvi *et al.* (2019).

As shown in Fig. 10, the membrane with an air gap of 19 cm showed the lowest PWP at $1.1052 \text{ L.m}^{-2}.\text{h}^{-1}.\text{bar}^{-1}$ and increased to $7.1841 \text{ L.m}^{-2}.\text{h}^{-1}.\text{bar}^{-1}$ at a 50 cm air gap. This increase occurs because the larger finger-like structures formed at the 50 cm air gap allow faster water transport across the membrane pores, as shown in Fig. 8 (Rosid *et al.*, 2021). These results of PWP are classified as low flux membranes, which are consistent with the results of Beek *et al.* (2020), who reported a similar range of $2.25\text{--}7.5 \text{ L.m}^{-2}.\text{h}^{-1}.\text{bar}^{-1}$ for PES/PVP hemodialysis hollow fibers.

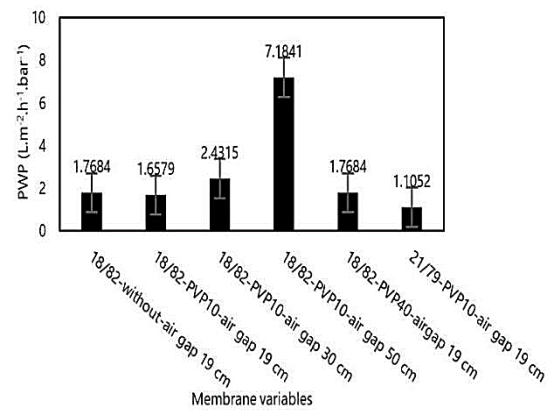


Fig. 10: Pure water permeability analysis results

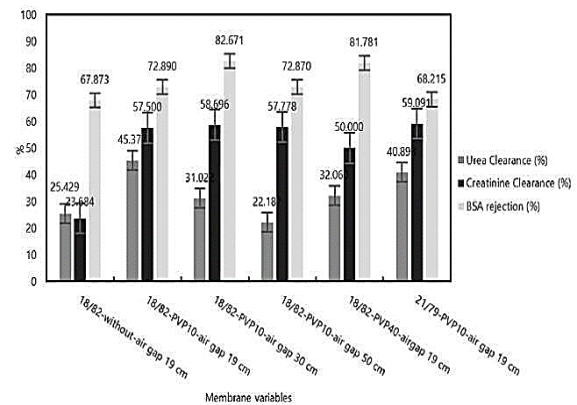


Fig. 11: Performance analysis results

The experimental results showed that the polymer composition and fabrication parameters affected the hemodialysis membrane performance, as shown in Fig. 11. The 18/82 (w/w) PVP-K10 formulation at a 19 cm air gap cleared 45.37% urea, 59.50% creatinine, and 72.89% BSA, exhibiting the best balance. Since solvent dissolution during nonsolvent-induced phase separation (NIPS) severely reduced the effective membrane porosity, solute clearance decreased when the air gap was increased from 19 to 50 cm. However, PVP solved the permeability issues. As a hydrophilic pore-former, PVP enhanced urea clearance from 25.43% (without PVP) to 45.37%; reported by Soundarrajan *et al.* (2023) reported that PVP improves pore

formation and surface wettability during membrane fabrication.

The contrasting trends between Figs. 10 and 11 reflect fundamentally different transport mechanisms. PWP follows the Hagen-Poiseuille relationship, where the hydraulic flux scales exponentially with the pore radius, causing enlarged finger-like macrovoids to produce a disproportionately large increase in water flux (Liao et al., 2005). Conversely, urea and creatinine clearance is governed by diffusion along the concentration gradient between blood and dialysate, making it less responsive to pore size changes (Ghofrani et al., 2023). BSA rejection remained consistently high since albumin (69 kDa) exceeds the membrane pore cutoff under all conditions, sustaining size-exclusion regardless of fabrication parameters (Suryawirawan et al., 2024).

Table 3. Hemodialysis membrane performance comparison with literature

Parameter	This Study	Irfan et al., (2019)	Xu et al., (2023)	(Xiao et al., 2024)
Membrane system	PES/NM P + PVP	PES/O-MWCNT/P VPk25	PES hydrogel + tannic acid	PES/CDs heparinoid hydrogel
Urea clearance	45.37%	34.4%	54.29%	5%
Creatinine clearance	59.09%	31.5%	-	25%
BSA rejection	82.67%	-	92.79%	99%

Table 3 compares the results with those of prior studies. The PES/NMP+PVP membrane exhibited competitive performance. Urea clearance (45.37%) surpassed Irfan et al. (2019) (34.4%) but remained below Xu et al. (2023) (54.29%), attributable to polyphenol-based surface crosslinking via tannic acid. Creatinine clearance (59.09%) was the highest value

among all references, reflecting favorable mid-molecular weight solute transport. BSA rejection (82.67%) was moderate, falling short of Xu et al. (2023) (92.79%) and Xiao et al. (2024) (99%), which employed advanced surface functionalization strategies, hydrogel coating, and heparinoid modification, respectively, to enhance protein retention.

The fabricated membrane demonstrates competitive solute clearance among PES-based systems. However, its BSA rejection of approximately 82.67% remains a limitation, given the established association between dialysis-related albumin loss and mortality risk (Ronco & Clark, 2018). This comparatively lower rejection reflects an inherent permeability-selectivity trade-off characteristic of PES-based membranes without advanced surface functionalization (Park et al., 2017). Morphological control offers an alternative route, as Zhao et al. (2024) improved protein removal through a denser sponge-like structure. Similarly, Cahyaningrum et al. (2026) achieved 97.98% BSA rejection by incorporating a chitosan-Mg(OH)₂ with PVP additive into PES membranes, highlighting composite additives as an alternative strategy to overcome this limitation.

The results in Table 4 indicate that the sieving coefficient (SC) is strongly affected by the presence of additives and fabrication conditions (e.g., air gap length). In contrast, the ultrafiltration coefficient (KUF) consistently remains below 10 mL/h/mmHg, classifying all membranes as low flux. The SC values for BSA, ranging from 0.20 to 0.48, were markedly higher than those reported for clinical dialyzers, where albumin SC is typically maintained below 0.01 to prevent excessive protein loss. These elevated SC values suggest that the fabricated membranes possess relatively large pore

sizes, enabling partial albumin leakage and resembling the behavior of protein-leaking membranes. Although this property can improve the removal of middle-to-large uremic toxins, it raises concerns regarding undesirable albumin loss, which has been clinically associated with malnutrition and poorer outcomes, particularly in super high-flux hemodialysis or hemodiafiltration treatments (Okada *et al.*, 2022).

Table 4. Sieving coefficient and ultrafiltration coefficient

Membranes	Sieving Coefficient	Ultrafiltration Coefficient, K_{UF} (ml/h/mmHg)
18/82-without-air gap 19 cm	0.44	0.0007
18/82-PVP10-air gap 19 cm	0.44	0.0010
18/82-PVP10-air gap 30 cm	0.20	0.0015
18/82-PVP10-air gap 50 cm	0.29	0.0043
18/82-PVP40-airgap 19 cm	0.48	0.0011
21/79-PVP10-air gap 19 cm	0.36	0.0007

The incorporation of PVP had a significant effect on SC. At an air gap of 30 cm, membranes containing PVP-K10 achieved the lowest SC (0.20), indicating improved selectivity for albumin retention compared to other formulations. In contrast, PVP-K40 at a 19 cm air gap produced the highest SC, 0.48, implying that higher molecular weight PVP may increase pore size or broaden pore distribution, thereby facilitating greater albumin passage. Similar trends have been reported in recent studies, where the addition of PVP enhances membrane wettability and water permeability by enlarging pore size and promoting finger-like structures (Ávila *et al.*, 2025). Yet, such pore enlargement may simultaneously elevate albumin loss unless

the pore size distribution is carefully tightened (Van Gelder *et al.*, 2018).

The overall findings indicate that PES/NMP 18/82 (w/w) with PVP10 at a 19 cm air gap provides the best combination of properties for hemodialysis applications, exhibiting high porosity, superior water content, balanced hydrophilicity, and good pure water permeability, resulting in optimized urea clearance, creatinine clearance, and BSA rejection. However, this membrane still falls into the low-flux category, meaning its ultrafiltration rate is relatively limited, which may reduce its efficiency in removing larger amounts of fluid during short dialysis sessions and potentially require longer or more frequent treatments compared to high-flux membranes. Despite this limitation, the configuration achieves an optimal trade-off between permeability, selectivity, and structural integrity, making it a promising candidate for further optimization toward high-flux performance.

CONCLUSIONS

Based on the thorough analysis of the effects of PVP molecular weight, polymer concentration, and air gap distance on the structure, mechanics, and dialysis performance of PES/NMP hollow fiber membranes for hemodialysis, increasing the polymer concentration from 18/82 to 21/79 (w/w) increased the mechanical strength owing to denser chain entanglement. Still, it decreased the porosity and membrane permeability simultaneously. The addition of hydrophilic PVP improved pore formation and surface wettability and reduced the tensile strength. The PVP-K10, PES/NMP membrane 18/82 (w/w) with a 19 cm air gap showed the best composition, with a well-developed finger-like pore structure in the

ultrafiltration range, balanced mechanical properties, and optimum dialysis performance (urea clearance of 45.37%, creatinine clearance of 57.50%, and BSA rejection of 72.89%).

The comparison with the literature validated the competitiveness of this formulation with respect to the PES-based membranes. The ultrafiltration coefficient values of all prepared membranes were low-flux membranes, which could limit the efficacy of fluid removal in short dialysis sessions. In the unmodified PES systems, the permeability-selectivity relationship remains a major obstacle, particularly in the rejection of BSA. The optimized membrane provides a solid base for high-flux hemodialysis performance, necessitating further investigation into improved surface functionalization methods.

ACKNOWLEDGEMENT

This research was carried out with the kind assistance and support of the Department of Chemical Engineering, Institut Teknologi Sepuluh Nopember, and the Ministry of Higher Education, Science, and Technology. We acknowledge the financial and institutional support provided in accordance with the Research Implementation Agreement of the Department Batch 1 Year 2025, under Researcher Contract Number: 2349/PKS/ITS/2025, dated June 3, 2025.

AUTHOR CONTRIBUTION

Z.N. : data collection, formal analysis, writing - original draft.
Y.R. : conceptualization, methodology, supervision, writing - review & editing.
H.A.S.: data collection, visualization.

S. : validation, data evaluation.
A.A. : methodology, supervision.
F.T. : validation, supervision.
S.N. : formal analysis, writing - review & editing.

NOMENCLATURE

ε : Porosity [%]
 W_w : Wet membrane weight [g]
 W_d : Dry membrane weight [g]
 ρ_w : Water density [g/L]
 ρ_p : Polymer density [g/L]
 PWP : Pure Water Permeability [$\text{L m}^{-2} \text{h}^{-1} \text{bar}^{-1}$]
 Q : Rate volume of filtered water [L, mL]
 A : Surface area [m^2]
 ΔP : Pressure difference [bar; mmHg]
 Δt : Filtration time [h]
 C_0 : concentration of solute at the initial time [mg L^{-1}]
 C_t : Concentration at specific time [mg L^{-1}]
 C_p : Permeate concentration [mg L^{-1}]
 C_f : Feed concentration [mg L^{-1}]

REFERENCES

- Alvi, M.A.U.R., Khalid, M.W., Ahmad, N.M., Niazi, M.B.K., Anwar, M.N., Batool, M., Cheema, W., and Rafiq, S., 2019. "Polymer concentration and solvent variation correlation with the morphology and water filtration analysis of polyether sulfone microfiltration membrane." *Adv. Polym. Technol.* 1, 8074626. <https://doi.org/10.1155/2019/8074626>
Aryanti, P.T.P., Dharmayanti, N.L.P.I., Hendarwan, H., Shidiq, A., Khoiruddin, K., and Wenten, I.G., 2025. "Advancements in membrane materials for hemodialysis:

-
- A comprehensive review and future perspectives." *Sep. Purif. Technol.* 375, 133718.
<https://doi.org/10.1016/j.seppur.2025.133718>
- Ávila, E., Sepúlveda, R.A., Retamal, J., and Hachim, D., 2025. "Biocompatibility in hemodialysis: artificial membrane and human blood interactions." *BMC Nephrol.* 26, 482.
<https://doi.org/10.1186/s12882-025-04401-y>
- Bacal, C.J.O., Munro, C.J., Tardy, B., Maina, J.W., Sharp, J.A., Razal, J.M., Greene, G.W., Nandurkar, H.H., Dwyer, K.M., and Dumée, L.F., 2024. "Fouling during hemodialysis – Influence of module design and membrane surface chemistry." *Adv. Membr.* 4, 100100.
<http://doi.org/10.1016/j.advmem.2024.100100>
- Beek, O.E.M., Pavlenko, D., and Stamatialis, D., 2020. "Hollow fiber membranes for long-term hemodialysis based on polyethersulfone-SlipSkin™ polymer blends." *J. Memb. Sci.* 604, 118068.
<https://doi.org/10.1016/j.memsci.2020.118068>
- Bensaadi, S., Arous, O., Kerdjoudj, H., and Amara, M., 2016. "Evaluating molecular weight of PVP on characteristics of CTA membrane dialysis." *J. Environ. Chem. Eng.* 4, 1545–1554.
<https://doi.org/10.1016/j.jece.2016.02.003>
- Bohr, S.J., Wang, F., Metze, M., Vukušić, J.L., Sapalidis, A., Ulbricht, M., Nestler, B., and Barbe, S., 2023. "State-of-the-art review of porous polymer membrane formation characterization—how numerical and experimental approaches dovetail to drive innovation." *Fronti. Sustain.* 4, 1093911. <https://doi.org/10.3389/frsus.2023.1093911>
- Cahyaningrum, S.E., Muhaimin, F.I., Raharjo, Y., Matul, I., Rahmawati, Y., Kinanti, R.G., Witdyantaka, Y., and Wijayanti, A.R., 2026. "Fabrication of PES modified chitosan Mg(OH)₂ membrane for hemodialysis: preparation, characterization and biocompatibility." *Adv. J. Chem. A* 2026, 490–502.
<https://doi.org/10.48309/ajca.2026.547653.1932>
- Canaud, B., Stuard, S., Laukhuf, F., Yan, G., Canabal, M.I.G., Lim, P.S., and Kraus, M.A., 2021. "Choices in hemodialysis therapies: Variants, personalized therapy and application of evidence-based medicine." *Clin. Kidney J.* 14(4), i45–i58.
<https://doi.org/10.1093/ckj/sfab198>
- Chakrabarty, B., Ghoshal, A.K., and Purkait, M.K., 2008. "Preparation, characterization and performance studies of polysulfone membranes using PVP as an additive." *J. Memb. Sci.* 315, 36–47.
<https://doi.org/10.1016/j.memsci.2008.02.027>
- Davenport, A., 2023. "The changing face of dialyzer membranes and dialyzers." *Semin. Dial.* 38(1), 25–34. <https://doi.org/10.1111/sdi.13161>
- Dehghan, R., and Barzin, J., 2021. "High cut-off membrane: evaluation of pore collapse and the synergistic effect of low and high molecular weight polyvinylpyrrolidone." *J. Polym. Res.* 28, 76. <https://doi.org/10.1007/s10965-021-02429-w>
- Francis, A., Harhay, M.N., Ong, A.C.M., Tummalapalli, S.L., Ortiz, A., Fogo, A.B., Fliser, D., Roy-Chaudhury, P., Fontana, M., Nangaku, M., Wanner, C., Malik, C., Hradsky, A., Adu, D., Bavanandan, S., Cusumano, A., Sola, L., Ulasi, I., Jha, V.,
-

- Nephrology, A.S. of, Association, E.R., and Nephrology, I.S. of, 2024. "Chronic kidney disease and the global public health agenda: an international consensus." *Nat. Rev. Nephrol.* 20, 473–485. <https://doi.org/10.1038/s41581-024-00820-6>
- Ghofrani, B., Alizad Oghyanous, F., Karsaz, M., Golkar, M., Etemadi, H., Tayebi Khosroshahi, H., and Yegani, R., 2023. "Fabrication and characterization of novel PES-based nanocomposite hollow fiber membranes for the hemodialysis process." *Sep. Purif. Technol.* 317, 123939. <https://doi.org/10.1016/j.seppur.2023.123939>
- Guillen, G.R., Pan, Y., Li, M., and Hoek, E.M.V., 2011. "Preparation and characterization of membranes formed by nonsolvent induced phase separation: A review." *Ind. Eng. Chem. Res.* 50, 3798–3817. <http://dx.doi.org/10.1021/ie101928r>
- Hasheminasab, S., Barzin, J., and Dehghan, R., 2020. "High-performance hemodialysis membrane: Influence of polyethylene glycol and polyvinylpyrrolidone in the polyethersulfone membrane." *J. Membr. Sci. Res.* 6, 438–448. <https://doi.org/10.22079/JMSR.2020.128323.1391>
- Huang, J., Yang, H., Chen, M., Ji, T., Hou, Z., and Wu, M., 2017. "An infrared spectroscopy study of PES PVP blend and PES-g-PVP copolymer." *Polym. Test.* 59, 212–219. <https://doi.org/10.1016/j.polymertesting.2017.02.005>
- Irfan, M., and Idris, A., 2015. "Overview of PES biocompatible/hemodialysis membranes: PES-blood interactions and modification techniques." *Mater. Sci. Eng. C.* 56, 574–592. <https://doi.org/10.1016/j.msec.2015.06.035>
- Irfan, Muhammad, Irfan, Masooma, Shah, S.M., Baig, N., Saleh, T.A., Ahmed, M., Naz, G., Akhtar, N., Muhammad, N., and Idris, A., 2019. "Hemodialysis performance and anticoagulant activities of PVP-k25 and carboxylic-multiwall nanotube composite blended polyethersulfone membrane." *Mater. Sci. Eng. C.* 103, 109769.
- Kahraman, O.S., Hasanoglu, A., Phoo, M.T., and Kucuk, I., 2022. "Preparation of modified polyethersulfone membranes for hemodialysis." *Bulg. Chem. Comm.* 54, 242–246. <https://doi.org/10.34049/bcc.54.3.f004>
- Kahrs, C., Gühlstorf, T., and Schwellenbach, J., 2020. "Influences of different preparation variables on polymeric membrane formation via nonsolvent induced phase separation." *J. Appl. Polym. Sci.* 137, 48852. <https://doi.org/10.1002/app.48852>
- Kinanti, R.G., Aditya, R.S., Raharjo, Y., Rahmawati, Y., Izza, N., Cahyaningrum, S.E., Wijaya, A.B., Sishartami, L.W., Sumari, S., and Ramadhan, M.H., 2025. "Development of PVP40-based hemodialysis membranes with prospects for mRNA therapeutics delivery." *Salud, Cienc. Tecnol.* 5, 1901. <https://doi.org/10.56294/saludcyt20251901>
- Liao, Z., Klein, E., Poh, C.K., Huang, Z., Lu, J., Hardy, P.A., and Gao, D., 2005. "Measurement of hollow fiber membrane transport properties in hemodialyzers." *J. Membr. Sci.* 256, 176–183. <https://doi.org/10.1016/j.memsci.2005.02.032>
- Lusiana, R.A., Siswanta, D., and Mudasir, 2016. "Preparation of citric acid crosslinked chitosan/poly(vinyl alcohol) blend

-
- membranes for creatinine transport." *Indones. J. Chem.* 2, 144–150. <https://doi.org/10.22146/IJC.21157>
- Maisarah, N.M., Nurkhamidah, S., Altway, A., Susianto, S., Taufany, F., Cahyo, Z.A.I., Sari, D.P., and Rahmawati, Y., 2024. "The comparison of polyethersulfone (PES)/N-methyl 2-pyrrolidone (NMP) on the fabrication of hollow fiber membranes with commercial membranes for applications hemodialysis." *Mater. Sci. Forum* 1114, 43–50. <https://doi.org/10.4028/p-h8YUss>
- Mansur, S., Othman, M.H.D., Ismail, A.F., Sheikh Abdul Kadir, S.H., Kamal, F., Goh, P.S., Hasbullah, H., Ng, B.C., and Abdullah, M.S., 2016. "Investigation on the effect of spinning conditions on the properties of hollow fiber membrane for hemodialysis application." *J. Appl. Polym. Sci.* 133(30), 43633. <https://doi.org/10.1002/app.43633>
- Mntambo, S.A., Mdluli, P.S., Mahlambi, M.M., Onwubu, S.C., and Nxumalo, N.L., 2019. "Synthesis and characterisation of ultrafiltration membranes functionalised with c18 as a modifier for adsorption capabilities of polyaromatic hydrocarbons." *Water SA* 45, 131–140. <https://doi.org/10.4314/wsa.v45i1.15>
- Mulder, M., 1996. *Basic Principles of Membrane Technology*. Kluwer Academic Publisher. Enschede, Netherlands.
- Okada, K., Tashiro, M., Michiwaki, H., Inoue, T., Shima, H., Minakuchi, J., and Kawashima, S., 2022. "Effects of high albumin leakage on survival between online hemodiafiltration and super high-flux hemodialysis: The history study." *Ren. Replace. Ther.* 8, 52. <https://doi.org/10.1186/s41100-022-00440-5>
- Ong, C.S., Lau, W.J., Goh, P.S., Ng, B.C., Matsuura, T., and Ismail, A.F., 2014. "Effect of PVP molecular weights on the properties of PVDF-TiO₂ Composite Membrane for Oily Wastewater Treatment Process." *Sep. Sci. Technol.* 49, 2303–2314. <https://doi.org/10.1080/01496395.2014.928323>
- Park, H.B., Kamcev, J., Robeson, L.M., Elimelech, M., and Freeman, B.D., 2017. "Maximizing the right stuff: The trade-off between membrane permeability and selectivity." *Science* 356(6343), eaab0530. <https://doi.org/10.1126/science.aab0530>
- Raharjo, Y., Ismail, A.F., Dzarfan Othman, M.H., Fahmi, M.Z., Saiful, N., Santoso, D., Nugroho, M.I., Merna, D., Arief, M.D., and Pratama, R.C., 2023. "Selectively mixed matrix hemodialysis membrane for adequate clearance of p-cresol by the incorporation of imprinted zeolite." *RSC Adv.* 13, 2972–2983. <https://doi.org/10.1039/d2ra07557a>
- Raharjo, Y., Zainol Abidin, M.N., Ismail, A.F., Fahmi, M.Z., Saiful, Elma, M., Santoso, D., Haula', H., and Habibi, A.R., 2022. "Dialysis membranes for acute kidney injury." *Membranes* 12(3), 325. <https://doi.org/10.3390/membranes12030325>
- Ronco, C., and Clark, W.R., 2018. "Haemodialysis membranes." *Nat. Rev. Nephrol.* 14, 394–410. <https://doi.org/10.1038/s41581-018-0002-x>
- Rosid, S.M., Hasbullah, H., Raharjo, Y., Ismail, A.F., Othman, M.H.D., Kadir, S.H.S.A., Kamal, F., Abdullah, M.S., and Ng, B.C., 2021. "Effect of air gap distance of PSF/IONPs/ALG hollow fiber membrane on morphology and antifouling
-

- properties." *Mater. Today: Proc.* 46, 1929–1933.
<https://doi.org/10.1016/j.matpr.2021.02.224>
- Said, N., Lau, W.J., Ho, Y.C., Lim, S.K., Zainol Abidin, M.N., and Ismail, A.F., 2021. "A review of commercial developments and recent laboratory research of dialyzers and membranes for hemodialysis application." *Membranes* 11(10), 767.
<https://doi.org/10.3390/membranes11100767>
- Soundarrajan, M., Alibrahim, K.A., Krishnamurthi, J., Maheswari, P., Harikrishnan, A., Alodhayb, A., and Muthumareeswaran, M.R., 2023. "Preparation, enhancement of permeability, and anti-biofouling properties of PEES/nano-silver/PVP mixed-matrix membrane." *Mater. Res. Express* 10, 015301.
<https://doi.org/10.1088/2053-1591/acb1f8>
- Suryawirawan, E., Janssen, A.E.M., Boom, R.M., and van der Padt, A., 2024. "Bovine serum albumin rejection by an open ultrafiltration membrane: Characterization and modeling." *Membranes* 14(1), 26.
<https://doi.org/10.3390/membranes14010026>
- Tewfik, S.R., Sorour, M.H., Shaalan, H.F., Hani, H.A., aboelnour, A.M.G., Eltoukhy, M.A., Mostafa, Y.O., Naguib, A.N., and Awad, M.A.M., 2025. "Assessment of characteristics and performance of fabricated polysulfone and polyethersulfone hollow fiber membranes for hemodialysis." *Egypt. J. Chem.* 68, 129–140.
<https://doi.org/10.21608/ejchem.2025.343407.10958>
- Van Gelder, M.K., Abrahams, A.C., Joles, J.A., Kaysen, G.A., and Gerritsen, K.G.F., 2018. "Albumin handling in different hemodialysis modalities." *Nephrol. Dial. Transplant.* 33(6), 906.
<https://doi.org/10.1093/ndt/gfx191>
- Wang, H., Yu, T., Zhao, C., and Du, Q., 2009. "Improvement of hydrophilicity and blood compatibility on polyethersulfone membrane by adding polyvinylpyrrolidone." *Fibers Polym.* 10, 1–5.
<https://doi.org/10.1007/s12221-009-0001-4>
- Xiao, T., Wang, Y., Wang, H., Zhang, Y., Zhou, J., and Zhao, Q., 2024. "Anticoagulant and antioxidant properties of hemodialysis membranes modified by hydrogels incorporating carbon dots." *J. Memb. Sci.* 692, 122318.
<https://doi.org/10.1016/j.memsci.2023.122318>
- Xu, L., Ji, H., Zhong, R., Cheng, S., Dang, G., Xu, T., Zhao, W., and Zhao, C., 2023. "Antioxidative hydrogel-embedded polyethersulfone membrane with improved hemocompatibility to alleviate oxidative stress." *J. Memb. Sci.* 684, 121866.
<https://doi.org/10.1016/j.memsci.2023.121866>
- Xu, X., Song, H., Xiong, S., and Wang, Y., 2025. "A new route to mixed matrix membranes: Atomic layer deposition of TiO₂ on membrane-forming polymers followed by nonsolvent-induced phase inversion." *Sep. Purif. Technol.* 366, 132737.
<https://doi.org/10.1016/j.seppur.2025.132737>
- Xu, Z.L., and Qusay, F.A., 2004. "Polyethersulfone (PES) hollow fiber ultrafiltration membranes prepared by PES/non-solvent/NMP solution." *Membr.*

Sci. 233, 101–111.

<https://doi.org/10.1016/j.memsci.2004.01.005>

Yang, Q., Chung, T.S., and Weber, M., 2009. "Microscopic behavior of polyvinylpyrrolidone hydrophilizing agents on phase inversion polyethersulfone hollow fiber membranes for hemofiltration." *J. Memb. Sci.* 326, 322–331.
<https://doi.org/10.1016/j.memsci.2008.10.008>

Zhang, L., Zhang, H., Jiang, J., Zhao, D., Shen, C., Zha, S., Qu, S., Lin, R., Wang, Y., and Dai, G., 2022. "Rheological behavior of PES/PVP/DMAc solution and PVP structural regulation for hollow fiber membrane." *J. Appl. Polym. Sci.* 139, 52870.
<https://doi.org/10.1002/app.52870>

Zhao, H., He, T., Yao, S., Tao, L., Zhang, X., Wang, Z., Cui, Z., and Chen, R., 2024. "Improved Protein Removal Performance of PES Hollow-Fiber Ultrafiltration Membrane with Sponge-like Structure." *Polymers* 16(9), 1194.
<https://doi.org/10.3390/polym16091194>
