

Research Paper

Preparation and Characterization of Microfiltration membrane by Utilization Non-Solvent Induced Phase Separation Technique

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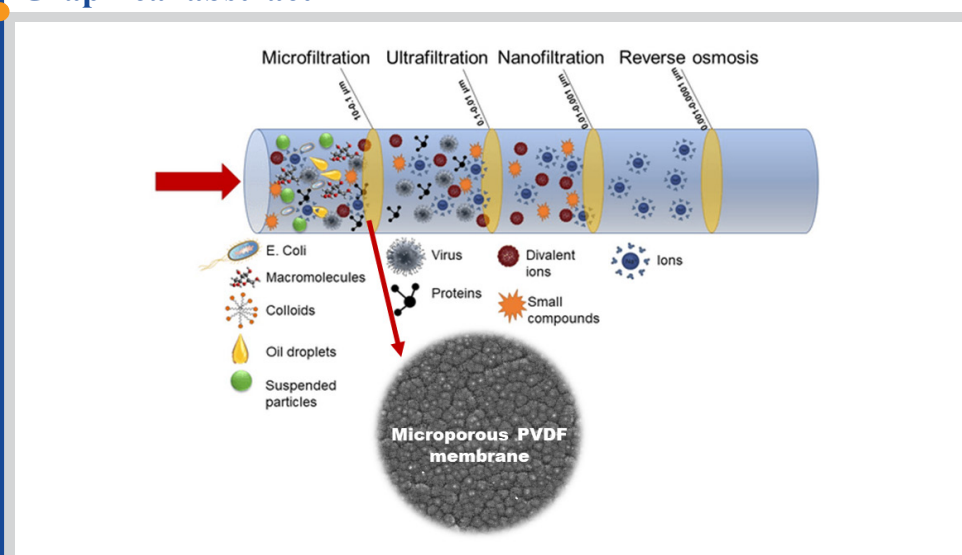
PVDF

PEG

Highlights

- Membranes were fabricated by the non-solvent induced phase separation (NIPS) method.
- The SEM images showed thick skin on the upper and macro-voids in the lower layer.
- The expected performance could not be reached because the PEG leaked from the membrane.

Graphical abstract



Abstract

The Non-solvent induced phase separation (NIPS) method is often performed for manufacturing flat sheet polymeric membranes. Several studies have shown how effective the NIPS approach is in creating microfiltration membranes. Because of its unique technical properties, polyvinylidene fluoride (PVDF) is frequently employed in microfiltration membranes. One issue that must be solved is improving the PVDF membrane's performance, and the usual approach is to add a polymeric addition to the PVDF solution. The resulting PVDF membrane's porosity, hydrophilicity, and filtering ability may all be enhanced by adding polyethylene glycol (PEG) to the PVDF solution. This study aims to examine the impact of a PVDF polymer blending ratio with PEG additive on the filtration ability of the manufactured membrane by using NIPS production. The impact of varied PEG ratios employed in the PVDF membrane polymer mixture during synthesis as well as the morphology, hydrophilicity, and permeability of the produced membrane is subsequently studied. Results indicated that increasing additives concentration enhanced the viscosity, which might prevent the microvoid formation and reduce the pore size and the membrane permeability. According to the findings, the maximum flux was obtained when the polymer ratio was 10%, and the additive was 5 wt % as 383.80 L/m²h. Although the membrane produced with this composition has a maximum contact angle of 61.6 ° compared to other membranes, it is also one of the thinnest. Because of the complicated interplay between membrane thickness, contact angle, and flux, this ratio in which the most optimum flux was attained.

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1. Introduction

Rapid population growth and industrialization are placing a significant strain on global water resources. As the population continues to grow and

urbanization accelerates, the demand for water for drinking, sanitation, and industrial purposes is increasing, leading to water scarcity and contamination.

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Industrial activities, such as manufacturing, mining, and agriculture, generate significant amounts of wastewater that often contain harmful pollutants, including heavy metals, chemicals, and pathogens. This contamination can make water sources unsafe for human use and pose significant health risks to communities that rely on these resources. The rise in contaminated water sources has led to an increase in waterborne diseases, such as cholera, dysentery, and typhoid fever. These diseases can have severe health impacts, particularly in developing countries with inadequate sanitation and hygiene infrastructure. Furthermore, the economic cost of treating waterborne illnesses is substantial, and the burden of these costs falls disproportionately on low-income households and communities. The water-related problems highlight the urgent need for sustainable water management practices to ensure access to safe and clean water for all. Membrane technology is an innovative and fast-expanding field that has become an essential tool in modern water treatment and cleaning processes. In recent years, membrane technology is leading to a significant market expansion. The membrane market is expected to increase from 6.4 billion USD in 2022 to 10.1 billion USD by 2027 [1]. Microfiltration (MF) is considered to be the birth of the membrane industry, which uses mechanical mechanisms to filter polluted components from a liquid stream effectively. Microfiltration is known to collect particles bigger than 0.1 μm in size, providing colloids and bacteria to be removed from the stream with pore sizes ranging from 0.05 to 10 μm and the thickness ranging from 10 to 150 μm . The main drawback of membranes is fouling, which can result in low permeability and increased operating costs due to frequent maintenance and replacement of the membranes. Multiple strategies can prevent and reduce membrane fouling. Increasing surface hydrophilicity is commonly suggested to reduce membrane fouling [2]. It is widely assumed that hydrophilic membranes have a lower fouling potential than hydrophobic membranes, although no substantial theoretical evidence supports this belief [3–5]. Boributh et al. studied on modification of hydrophobic PVDF membrane into the hydrophilic structure for reducing protein fouling. Results indicated that modified membranes showed antifouling properties, reducing irreversible membrane fouling [6]. In another work, the thin-film composite (TFC) membrane's surface hydrophilicity was increased using plasma treatment by the introduction of nitrogen-containing functional groups. Modified membranes demonstrate the best performance in terms of pure water permeate flux, salt rejection, and antifouling properties [7]. Chen et al. modified the PVDF microfiltration membrane through ZnO–Ag nanocomposites. The resultant membrane showed high surface hydrophilicity and organic/bio-fouling resistance [8]. Similarly, incorporating nanoparticles into the PVDF membrane increased membrane hydrophilicity and enhanced membrane fouling resistance [9–11]. On the other hand, Zhang et al. demonstrated that membrane surface hydrophilicity/hydrophobicity was not directly important to the interfacial interactions with sludge particles, although a high zeta potential and a particular roughness greatly reduced membrane fouling. [12]. Choo et al. that the most hydrophobic PVDF membrane had the least fouling tendency to anaerobic digestion broth compared to more hydrophilic ones [13].

Hydrophilic additives offer cost-effective pathways to alter filtration membranes and fouling among all available techniques. Using additives is a popular and effective way of membrane modification, and it may afterward be adjusted to change the structure and characteristics of the membrane to produce high performance. Macromolecular and micromolecular polymeric chemicals, organic acids, inorganic acids or salts, strong non-solvent additives, and blended additives are only a variety of additions that have been recommended [14]. In this study, polyethylene glycol (PEG) is used as a hydrophilic additive for the PVDF membrane. Adding PEG to the PVDF solution allows the active OH group to penetrate the PVDF backbone chain, resulting in improved non-solvent diffusion within the membrane. As a consequence, it was demonstrated that incorporating PEG into a polymer system might improve the porosity, hydrophilicity, and filtering performance of the resultant PVDF membrane [15,16].

Based on the given works of literature above, it is crucial to understand the role of additives on PVDF membranes. There is still a big gap in understanding the relationship between hydrophilic membrane treatment and membrane permeability. The objective of this work is to investigate the effects of two different parameters, namely the concentration of PEG additives and the concentration of PVDF solution, on the properties of polymeric membranes made of PVDF by non-solvent induced phase separation method (NIPS). It is known that the concentration of PEG additives affects membrane parameters such as porosity, water permeability, and mechanical strength. Thus, the aim is to comprehend the effect of PEG additives concentration on the performance of PVDF membranes by examining the changes in their properties while the PEG additives concentration is adjusted. The concentration of the PVDF solution is a crucial factor in creating polymeric membranes. The concentration of the polymer solution influences the membrane's shape and pore size distribution. By

examining the influence of PVDF solution concentration on non-solvent-induced polymeric membranes, we determine the ideal conditions for fabricating PVDF membranes with desirable qualities.

The effect of different PEG ratios used in the polymer mixture on the membrane production stages and the effect of morphology, hydrophilicity, and permeability of the obtained membrane is investigated. In summary, this work aims to contribute to the understanding of the relationship between the concentration of PEG additives and PVDF solution concentration on the properties of PVDF membranes and to provide insights into the design and optimization of polymeric membranes for various applications such as water filtration, heavy metal industry, gas separation, biomedical application, energy storage, fuel cells, microbial fuel cells, and sensors

2. Materials and Methods

2.1. Chemicals

In this study, membranes with varied concentrations of PVDF (PVDF from Kynar Flex®, France) were produced to explore microporous PVDF membranes' features with PEG additives.

Polyvinylidene fluoride (PVDF) as the polymer material, N,N-dimethylacetamide (DMAc from Penta s.r.o without any purification)) as the solvent in membrane preparation, polyethylene glycol (PEG, with an average molecular weight of 400 g/mol from Sigma) non-solvent additive, sodium chloride (NaCl from Penta s.r.o) for the coagulation bath, and glycerol anhydrous (Glycerin from Penta s.r.o) for maintaining membrane pore size was utilized for the experimental procedure in this study.

2.2. Preparation of polymeric solution

PVDF powder was combined with DMAc solvent at two different concentrations, 10 wt% and 15 wt%, to create the polymeric solution. Next, the PEG additive would be added at different quantities (2, 5, and 8 wt %) to polymer-solvent combinations. The polymer ratios used in the study are given in Table 1.

Table 1
Composition of the polymeric solution

Sample Code	Polymeric concentration (w/v %)	Polymeric solution
PVDF - 10	PVDF 10%	10g PVDF in 100ml DMAc
PVDF - 10 / PEG 2	PEG 2% / PVDF 10%	2g PEG in 100ml PVDF 10 wt%
PVDF - 10 / PEG 5	PEG 5% / PVDF 10%	5g PEG in 100ml PVDF 10 wt%
PVDF - 10 / PEG 8	PEG 8% / PVDF 10%	8g PEG in 100ml PVDF 10 wt%
PVDF - 15	PVDF 15%	15g PVDF in 100ml DMAc
PVDF - 15 / PEG 2	PEG 2% / PVDF 15%	2g PEG in 100ml PVDF 15 wt%
PVDF - 15 / PEG 5	PEG 5% / PVDF 15%	5g PEG in 100ml PVDF 15 wt%
PVDF - 15 / PEG 8	PEG 8% / PVDF 15%	8g PEG in 100ml PVDF 15 wt%

The combination of polymer-additive-solvent was heated to around 60°C and mixed with the help of a magnetic stirrer (Heidolph Co., Germany) at 400 rpm till the polymer and chemicals were fully dissolved. The end product was viscous and homogenous polymeric solutions. This solution, also known as the casting solution or sometimes called dope solution, conducted an overnight degassing procedure to eliminate any apparent bubbles. Afterward, a thin film could be cast from this formed solution by the NIPS technique.

2.3. Membrane preparation by NIPS technique

The dope solution was placed onto the glass surface and manually cast in a specified thickness of 200 μm using a casting knife. The glass had a thin coating of the dope solution. It was instantly submerged in CB containing 5% NaCl-water (non-solvent) for phase inversion at ambient temperature for 5 minutes to allow the solvent and non-solvent to completely exchange, resulting in asymmetric microstructure membranes. Using NaCl in a coagulation bath is beneficial. It was found that the NaCl in CB was utilized to generate ion-dipole interactions between Na⁺ and PVDF molecule chains and to facilitate the creation of the polar β -PVDF phase during the phase inversion procedure [17]. The presence of NaCl in the coagulation bath can alter the membrane's morphology and pore structure. NaCl functions as a

pore-forming agent, which can increase the membrane's porosity and surface area. Adding NaCl can also alter the size and distribution of membrane pores, resulting in a more uniform and clearly defined pore structure [18]. In addition, adding NaCl to the coagulation bath can increase the hydrophilicity of the membrane, hence enhancing its permeability and fouling resistance. This is because NaCl can increase the membrane's water uptake and decrease the water contact angle.

As the thin polymeric layer formed and separated from the glass, it was removed from CB and thoroughly rinsed with DI water to eliminate solvent residues. Before membrane characterization, a glycerin post-treatment was used to fill the membrane pores and prevent them from shrinking or collapse of the pore structure during storage. For this, membranes were impregnated in a 40% glycerin solution. Membranes were then dried in an oven at 60°C for 2 hours to eliminate excess non-solvent from the membrane matrix. Before further membrane characterization, all samples were maintained in plastic zip bags. The membranes were cleaned with distilled water before characterization to remove glycerin.

2.4. Membrane characterization

To evaluate membrane features such as water contact angle and membrane filtration performance, various characterization methods were used.

Images of membranes taken using a scanning electron microscope (SEM, Tescan Vega3) were examined using ImageJ software to evaluate their microstructure, including average membrane pore diameter and thickness.

The chemical compositions of membranes were also characterized by Fourier transform infrared spectroscopy (FTIR -Nicolet iZ10) study.

The water contact angle of the membrane was measured by the sessile drop method. For the measurement, a deionized water droplet was dripped to a dry membrane surface through a fine tip by using Drop Shape Analyzer DSA30E from KRÜSS GmbH for the liquid dispensed controller. The droplet image was visualized by DSA4 –Drop Shape Analysis software to analyze the water contact angle (4 μ L of drop volume).

The water flux of the membranes was calculated by Eq. 1

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

where, J is the permeate flux ($L/(m^2h)$), Q is the volume of permeate (L), A is the active filtration area (m^2), and t is the time interval, respectively. Membrane permeability was calculated by dividing membrane flux by applied pressure.

Filtration studies utilized by Amicon dead-end filtration (Amicon stirred cell model 8050, 50ml, UFSC05001). Before installing Amicon dead-end filtration, the circular membranes were cleaned with DI water. As a filtering solution, 40 ml DI water was poured into the Amicon cell. The applied pressure was set to 0.25 bar and gradually raised to 5 bar if the permeability measurements could not be completed after every 3 minutes of waiting. The filtration was done via a 13.4 cm^2 filtration active area of circular membranes, and the time to collect 10, 20, 30, and 35 mL permeate solution in the container was recorded. A schematic representation of Amicon dead-end filtration is shown in Fig. 1.

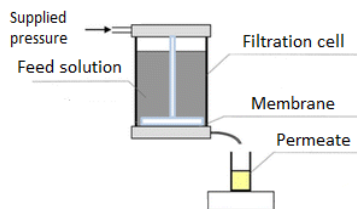


Fig. 1. Schematic diagram of dead-end filtration cell.

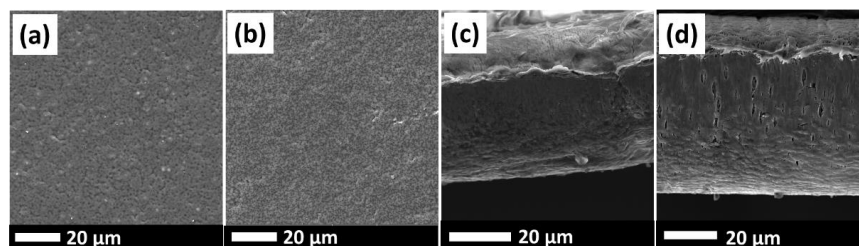


Fig. 2. (a) top-view image of 10 wt% PVDF membrane, (b) top-view image of 15 wt% PVDF membrane, (c) cross-section image of 10 wt% of PVDF membrane, and (d) cross-section image of 15 wt% PVDF membrane.

3. Results and discussion

In the NIPS method for membrane fabrication, the cast polymer solution is immersed in a nonsolvent-filled coagulation bath to produce phase separation and phase inversion. The content and concentration of the dope solution play a crucial role in influencing membrane shape and performance by regulating phase separation behavior.

3.1. Effects of initial polymer concentration in membrane preparation

Fig. 2 shows the morphology of the top surface and the cross-section of the PVDF membranes prepared with different concentrations (10 and 15 wt. %). Regardless of polymer content, all PVDF membranes displayed a typical asymmetric NIPS structure consisting of a top layer with small pores and a macro void sub-layer. SEM pictures of the manufactured membranes revealed a dense top surface. It is obvious that surface compactness increased with the concentration of the solution.

The pore size and thickness of membranes are given in Table 2. The polymer concentration and viscosity are important parameters of membrane pore size [19]. Here, an increased polymer concentration causes an increased solution viscosity due to entanglement between macromolecules. As a result, the dense and strong top layer will of membranes will prevent them from shrinking.

Table 2
Pore size, thickness, and contact angle of PVDF and PVDF-PEG membranes.

Sample Code	Average pore size (nm)	Average thickness (μ m)	Contact angle ($^\circ$)
PVDF - 10	356.62 \pm 41.94	27 \pm 2.50	45.0 $^\circ$ \pm 0.57
PVDF - 10 / PEG 2	181.92 \pm 4.24	49.8 \pm 6.90	53.4 $^\circ$ \pm 1.10
PVDF - 10 / PEG 5	110.05 \pm 28.10	38.4 \pm 2.50	61.6 $^\circ$ \pm 0.04
PVDF - 10 / PEG 8	367.00 \pm 22.50	64.3 \pm 3.30	58.7 $^\circ$ \pm 1.10
PVDF - 15	113.80 \pm 31.65	64.6 \pm 2.10	48.4 $^\circ$ \pm 2.28
PVDF - 15 / PEG 2	61.54 \pm 28.08	32.8 \pm 1.30	46.3 $^\circ$ \pm 0.32
PVDF - 15 / PEG 5	199.65 \pm 61.59	55.3 \pm 1.80	55.6 $^\circ$ \pm 0.40
PVDF - 15 / PEG 8	133.44 \pm 30.70	58 \pm 2.30	54.7 $^\circ$ \pm 2.00

Herein, the pore size of PVDF-10 was reduced by almost 68% when the concentration increased from 10 to 15 wt% (PVDF-15). On the other side, the membrane thickness increased with increased polymer solution concentration. Even though the casting thickness was the same for both PVDF-10 and PVDF-15, after the solvent-nonsolvent exchange procedure and drying, the thickness varied depending on concentration due to the amount of used polymer. When the additive ratio grew, it appeared that this material escaped during manufacture and did not contribute to the final product's structure as theoretically intended. This resulted in the haphazard development of properties like membrane thickness and pore width, which may be modified using additives.

Increased polymer concentration raises the viscosity of the polymer solution, resulting in increased resistance during the solvent-nonsolvent exchange procedure. Hence, the membrane's porosity and pore size is reduced, resulting in lower pure water flux.

The water contact angle value of the pristine PVDF membrane was supposed to be higher than 85° [20], illustrating the membrane's hydrophobic character because of PVDF's chemical properties [21]. In this study, the contact angle of pristine PVDF in 10wt% and 15wt% was 45° and 48.4° , respectively. The contact angle is a typical measurement to evaluate the hydrophilicity of the membrane surface [22,23]. However, the surface hydrophilicity was linked to contact angle and dependent on membrane surface morphology, surface smoothness, surface homogeneity, and pore dimension [24]. Post-treatment with glycerin can influence the membrane's pore size, resulting in changes in membrane surface morphology and hydrophilicity. It could be the main reason for the mobilized water contact angle value of pristine PVDF membranes and blended PVDF membranes in this study. Another reason for the increased hydrophilicity is the treatment of membranes with glycerin. The purpose of glycerin post-treatment is to prevent the membrane pores from contracting or collapsing during storage. When glycerin is added to the PVDF membrane, it can increase the membrane's water content and reduce its contact angle, which indicates an increase in hydrophilicity. Glycerin post-treatment of the PVDF membrane can further increase its hydrophilicity. Because glycerin can permeate the membrane matrix and generate new hydrophilic sites by breaking the hydrogen bonds between polymer chains, thereby enhancing the membrane's capacity to retain water. The post-treatment process involved immersing the PVDF membrane in 40% glycerin solution over the night, followed by washing with water to remove any excess glycerin. The degree of hydrophilicity augmentation can be affected by the glycerin treatment's concentration and duration.

3.2. Effects of additives in membrane preparation

Fig. 3 shows the morphology of the top surface and the cross-section of the additive-included PVDF membranes prepared with different concentrations. It seems like the interactions between polymer, additive, and solvent; the additive may not act as a pore-forming agent. As expected, the use of additives enhanced viscosity. In contrast, when PEG was added to the PVDF dope solution, macrovoidic structures were produced, indicating rapid water penetration into the polymer matrix following phase inversion. In addition, the presence of additives enhanced surface porosity, as shown in Fig. 3.

When the polymer concentration in the top layer remains high during the exchange of solvent and non-solvent, an asymmetric structure consisting of a dense skin layer and a porous substructure is typically generated. Owing to the hydrophilic nature of the additive, the pore width of PVDF/PEG mix membranes expands when the additive concentration in the dope solution rises. Yet, the pore size of pristine PVDF membranes was greater than that of the others. This may be a result of the increased viscosity of the casting solution. The higher viscosity of the polymeric solution, which impedes the exchange of solvent and nonsolvent in NIPS, would delay the formation of macrovoids while increasing the interconnectivity of the pore matrix. Concurrently, the complexity of the porous sublayer could result in a smaller pore size on the dense skin layer of the membrane [25]. Due to the addition of an additive to the polymeric solution, the PVDF/PEG blend membranes exhibited a thermodynamic impact that predominated over a kinetic effect, resulting in a larger porosity and narrower pore size [26]. Given the dense nature of the membranes, it was practically difficult to verify the exact pore size; consequently, the filtration property of the membrane must be determined by permeability tests.

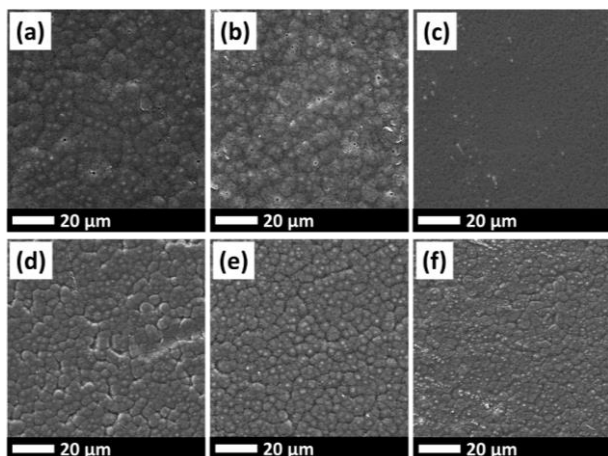


Fig. 3. (a) PVDF-10/ PEG 2 (b) PVDF-10/ PEG 5, (c) PVDF-10/ PEG 8, (d) PVDF-15/ PEG 2 (e) PVDF-15/ PEG 5, and (f) PVDF-15/ PEG 8 membranes.

Fig. 4 shows the results of FTIR for whole membrane samples from only PVDF and PVDF with various compositions of PEG additives. As is expected from FTIR results, there are no differences between the pristine PVDF10, and PVDF15 (Fig. 4). The absorption bands at 3020 cm^{-1} and 2980 cm^{-1} corresponded to the $-\text{CH}_2$ asymmetric and symmetric vibration of PVDF [27]. The bands located at 1266 cm^{-1} and 1400 cm^{-1} were attributed to $-\text{CH}_2$ wagging vibration [27,28]. The absorption band at 840 cm^{-1} shows $-\text{CF}_2$ stretching [29]. The peak at 876 cm^{-1} corresponded to C-F groups of PVDF [27]. Stretching bands at 1170 cm^{-1} show the $-\text{CF}_2$ groups [27]. The band is located at 1273 cm^{-1} and is attributed to the vibration of C-F bonds [30]. In some papers, absorption bands around 880 , 1071 , 1176 , and 1400 cm^{-1} with high intensity were used to characterize the crystal phases of PVDF [31]. The symmetrical stretching bands of the $-\text{CF}_2$ group are indicated at 1071 cm^{-1} [32].

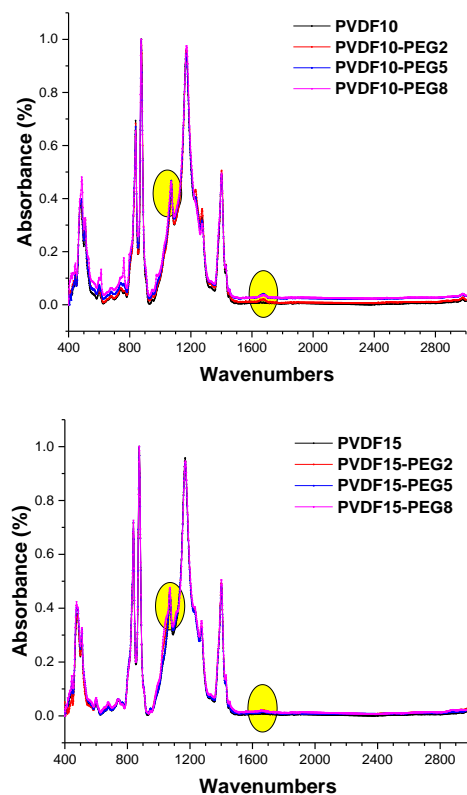


Fig. 4. FTIR results of PVDF-10 and PVDF-15 membranes.

FTIR images of PVDF – PEG membranes are shown in Fig. 4. As can be seen, the characteristic peaks of PVDF membranes appear at 1400 , 1273 , 1170 , 840 , and 876 cm^{-1} . It was found that PEG hydrophilic additive can leach out from the casted film to the water nonsolvent during phase inversion [33]. 10 and 15 wt % PVDF concentration did not show PEG characteristic peaks around 2915 and 2848 cm^{-1} . PEG (400Mn) has a small molecular structure. It probably has a smaller molecular structure than the solvent (the molar mass of DMAc is 87.12 g/mol) [34]. The rate at which the PEG molecule diffuses from the polymer-rich phase to the polymer-poor phase is much higher than that of the DMAc solvent. As a result, PEG molecules can be easily washed out when immersion in water-nonsolvent due to the high diffusion rate during the phase inversion process. In summary, the symmetrical stretching bands of the $-\text{CF}_2$ group are indicated at 1071 cm^{-1} and shifted towards 1040 cm^{-1} obviously after PEG grafting modification (Fig. 4) [35]. The C-O stretching band (associated with PEG) at 1040 cm^{-1} is visible for the higher amount of PEG modification (5 and 8 wt. %), and this proved that PEG remained in the membrane (Fig. 4).

The pure water permeabilities of membranes manufactured with various polymer concentrations were evaluated to explore their characteristics as shown in Table 3. The flux measurements for pure water indicate that the constructed membrane should be microfiltration.

Table 3

Pure water flux and permeability of the membranes.

Sample Code	Pure Water Flux (L/(m ² h))	Permeability (L/(m ² hbar))
PVDF - 10	62.20	248.80
PVDF - 10 / PEG 2	54.20	216.80
PVDF - 10 / PEG 5	479.70	1917.60
PVDF - 10 / PEG 8	383.80	1535.20
PVDF - 15	113.80	455.20
PVDF - 15 / PEG 2	16.30	65.20
PVDF - 15 / PEG 5	13.50	54.00
PVDF - 15 / PEG 8	209.90	839.60

The increased hydrophilicity of membranes was immediately mirrored in the efficacy of the transport medium. In several investigations, increasing the hydrophilic groups in a membrane by adding additives led to a proportionate increase in its hydrophilicity and improved permeability [36,37]. While average pore size, membrane thickness, membrane porosity, and contact angle also contributed favorably to membrane permeability performance. The water permeability performance is expected to increase as the additive concentration in the polymeric solution increased for most membranes. Nevertheless, when PEG was added, the opposite tendency was observed.

Table 3 shows that the water permeability value varied with increasing PVDF concentration in pure PVDF membranes and additive content in blended PVDF membranes. When the PVDF concentration rose, the water flux initially increased (PVDF10 at 62.2 L/(m²h) and PVDF15 at 113.8 L/(m²h)). The water contact angle of PVDF10 and PVDF15 is nearly the same. In this instance, pore size and porosity can significantly impact water permeability.

Increasing the PEG additives concentration apparently enhanced the polymeric solution's viscosity. The higher viscosity prevented the development of macrovoids, reduced the pore size on the top thick skin layer during membrane production, and reduced the permeability. So that adding hydrophilicity agents like PEG would increase the membrane permeability until a certain content was reached. The inclusion of PEG may either increase viscosity, resulting in decreased flow or decrease surface tension, resulting in increased flux. This study discovered a competition impact between rising and decreasing water flux [38]. In the case of PVDF-10, 5 and 8 wt % of PEG addition might increase the membrane porosity, resulting in high flux and permeability.

To increase water flux and permeability significantly, the PEG concentration added should be higher than 2 wt% in PVDF-10 and 5 wt% in PVDF-15 membranes. Moreover, the applied pressure in this work is quite low. In general, increased pressure increases membrane flux and accelerates filtration rates. It is essential to balance membrane flux and applied pressure to optimize water filtration performance. Moreover, it must be considered that the adjusted pressure during the filtration process must help maintain a constant flow rate without damaging the membrane.

4. Conclusion

In this work, a commonly used hydrophilic additive PEG was employed to PVDF dope solution using the NIPS technique at various concentrations. The concentration of the PEG additive and the PVDF was investigated. The membranes were characterized using SEM, pore size, FTIR, contact angle, and water permeability. Due to the NIPS approach, the SEM pictures revealed that the manufactured membranes had dense skin on the top layer and macrovoids in the sublayer, creating a rather good route for media transport. The exchange of solvents and non-solvents led to the formation of asymmetric membrane structures. As a result of the asymmetry of the structure, a portion of the top skin served as an actively filtering layer, while the cross-sectional portions served as mechanical supports. Adding PEG additive could not bring in a clear effect on membrane property, it could be because PEG in blended PVDF/PEG membranes was leached out or trapped in dope solution and increased the dense structure. When the membrane was utilized to filter, the subsequent compaction effect occurred. It induced the instability of the membrane structure, resulting in the collapse of the pore system and a drop in permeability performance.

A complex interaction between membrane characteristics and the performance values obtained may not always be foreseen. The results show that when the polymer ratio was 10% and the PEG additive quantity was 5%, the flux and permeability of the membrane were 383.80 L/m²h and 1535.20 L/m²hbar, respectively. In comparison to other membranes, this membrane has the highest contact angle, measuring 61.6 °, but it is also one of the thinnest. Due to the intricate correlations between membrane thickness,

contact angle, and flux, this blend ratio was found to be the one where the flux was most optimal.

It can be concluded that increasing the concentration of the dope solution in the NIPS process could have an effect on membrane development, but only when the optimal concentration and conditions were identified. This was approved for both the primary polymer and the additive in the dope solution.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Credit authorship contribution statement

T. D. T. Nguyen: Data curation; - Formal analysis, Investigation; Methodology
E. Altuok: Writing – original draft; Conceptualization; Validation; Visualization.
A. Siekierka: Writing – original draft; Conceptualization; Validation; Visualization.
A. Pietrelli: Funding acquisition; Project administration; Resources; Software.
F. Yalcinkaya: Writing – review & editing; Supervision.

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