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IDENTIFYING THE FEATURES OF MECHANICAL AND PHYSICOCHEMICAL CHARACTERISTICS OF POLYETHERSULFONE MEMBRANES USING ELECTRIC FIELD METHOD FOR WATER FILTRATION APPLICATIONS

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Electric-field assistant prepared polyethersulfone (PES) membranes were selected as the research object in this paper, aiming to address how to control membrane morphology, mechanical property and water permeation at the same time through a simple and environmentally friendly method for filtration purposes. Three PES membranes were fabricated and denoted as MP1 (25% PES), MP2 (30% PES) and MP3 (35% PES). Results indicated that the electric field can be used as a feasible method to design desired membrane structure and performance, SEM observations shows average pore sizes of 0.062–0.095 μm, AFM images showed MP1 has rough surface with larger pores, and MP3 has smoother surface with finer pores. Tensile test results as well indicated that the mechanical properties of MP were evidently reinforced when adding PES, and all tensile strengths increased monotonous with increase in the concentration of PES, wherein MP3 had the best maximum tensile strength (5.64907407 MPa). FTIR spectra were in agreement with characteristic PES functional groups, XRD showed an overall amorphous nature and some semi-crystalline order developed that was predominantly exerted along the vertical direction to the support surface with concentration within PES-rich membranes. These findings account for the reported compromise of the filtration performance, MP1 presented in NWP with best permeability (4.2012164.L.m^{-2}·h^{-1}). bar^{-1}; MP3 had better mechanical stability to the detriment of flux. All tests results demonstrated how membranes can be tailored to maximize either permeability (MP1) or mechanical strength and selectivity (MP3), thereby allowing them to be employed as direct water filtration materials and could be utilized as a support for advanced composite membrane systems

Keyword: chemical resistance, electric field, mechanical properties, physicochemical characteristics, water filtration

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1. Introduction

The availability of clean water is now an increasingly urgent global issue, mainly due to population growth, urbanization, and massive ongoing environmental pollution. Membrane filtration has therefore become one of the key technologies in drinking water production and wastewater reclamation, because it can remove a wide spectrum of contaminants through a compact process with relatively simple operation. Among commercial polymeric membranes, Polyethersulfone (PES) is widely used due to its high thermal stability, good chemical resistance, and superior mechanical properties [1]. The performance of PES membrane in the treatment of real water is also faced with some obstacles, for example, fouling (clogging of pores), a trade-off of permeability and selectivity, and difficulty in adjusting the pore size distribution and surface hydrophilicity. It is therefore a pressing scientific and practical challenge to fabricate PES membranes with tunable mechanical and physicochemical properties, ensuring they can functionally work stable in the long run under more stringent regulations/operation conditions.

Some techniques often used in the fabrication of membrane include electrospinning and phase inversion nanofibers with high specific surface area and excellent mechanical strength can be fabricated by means of electrospinning but the low productivity together with high equipment cost and working cost makes it less practical for large scale water treatment applications [2, 3]. In contrast, phase inversion is more easily scalable to industries but the membrane characteristics are possibly sensitive to minor temperature, humidity and casting changes that result in batch-to-batch variations and poor pore control structure [4]. Thus, a recent trend that is currently being pursued which may lead to the optimized performance of membranes for water treatment purposes, is the influence that can be exerted on membrane synthesis processes by electric fields. Electrostatic fields have been applied to the membrane forming process to influence polymer chain orientation, pore morphology and additive particle distribution in order that it results in the enhancement of mechanical performance and physicochemical properties of membranes [5]. Several studies have shown that electric-field-assisted production can lead to a more uniform and controllable pore structure, higher tensile strength, better surface hydrophilicity, while at the same time reduce fouling due to an improved interaction between the membrane surface and water [6]. Although electric fields are still a new concept with respect to polyethersulfone (PES)-based membranes, the future prospects seem very promising compared to using conventional methods based on changing in polymer concentration, temperature or passive use of additives. Thematically, electric-field-assisted membrane fabrication research is still interesting since it intersects science (i.e., the need to accurately control pore morphology per se) with an applied industrial requirement: a process that is predictable and scalable from a chemical point of view.

Consequently, it is of great interest to study the mechanical and physicochemical properties of PES membranes prepared by an electric field-assisted method in this stage of membrane technology evolution. Not only does this approach provide with a better understanding of how applied electric fields affect the structure and properties of membrane materials, but it also has potential for more efficient and so sustainable water filtration technologies [7, 8]. From a scientific point of view, these works can provide insights into the mechanism of phase separation and orientation of polymer chains in PES systems caused by electric fields. From an applied point of view the findings could be exploitation to develop design rules for manufacture one-step adapted PES membranes on industrial scale for low cost, minimal energy water treatment no matter on what level or size but also in (decentralized) small-sized application.

2. Literature review and problem statement

In recent years, the majority of previous studies have focused on improving the performance of PES membranes through various modification methods. One of the most commonly used methods is electrospinning and phase inversion. In the phase inversion method, phase separation is generally achieved through the addition of a non-solvent. Previous studies have shown that PES membranes fabricated using the phase inversion technique will have a porous structure, characterized by a dense asymmetric membrane layer and the formation of finger-like pores [9]. The paper [9] presents the results of research on morphology control in phase inversion; shown that dense skins over finger-like sublayers are typical outcomes under common non-solvent induced conditions, but there remain unresolved issues related to sensitivity to bath composition and kinetics. But this process has restrictions for some operational conditions like the solvent type and cooling rate in forms of the effects on the membrane structure and performance. In another work, the features of phase inversion-method formed PES membranes were evaluated. These membranes had good efficiency of pollutant degradation, however, they also brought new challenges such as physical instability, which impede the utility function of these membranes [10]). But there were also outstanding questions of long-term mechanical stability and integrity under variable hydraulic loading, which limits its practical deployment. In addition, another research has investigated enhancement of hydrophilicity in PES membrane prepared by phase inversion method. One study determined that it was achievable to enhance membrane performance under the filtration operation, but its conductivity can be variable in response to its challenge environment [11]. This may due to real practical concerns in filtering a solvent/non-solvent system and controlling ambient humidity/temperature during casting, resulting in batch-to-batch variation. According to tens of researches, it is known that there isn't still a PES membrane with perfect feature and well-operation, indifferent to environmental circumstances, can be manufactured with the phase inversion method. The literature has reported other findings that are correlated with the limitations of the phase inversion method: The results in fact have also shown that, although the phase inversion approach still involves the use of solvents that are not environmentally friendly, they will inevitably affect both environment and purity of PES membrane produced [12]. One approach to circumvent these challenges can be by applying field-assisted structuring or greener solvent systems for the decoupling of morphology control from difficult-to-stabilize environmental conditions.

Besides the phase inversion, most of previous studies also applied the electrospinning. It is noted that this technique can yield nanofiber membranes with large surface area per volume and high filtration performance properties. One of the former studies tested the efficiency of electrospinning, however, while this latter procedure can provide bigger surface area, resultant membranes are characterized by irregular thickness and inhomogeneous pore size distribution [13]. Demonstrated that there are small parameter windows (voltage/flow rate/collector distance) so uniformity is a struggle for large areas. Meanwhile, other studies have tried to fabricate PES membranes by the electrospinning method; nevertheless, this approach involves some drawbacks as well such as: limited ability of scaling in process and expensive process cost which might hinder further application of membranes at a large scale [4]. The reason for this may be cost parts in terms of high-voltage supply, solvent recovery, and low areal productivity, which makes relevant research on purely electrospun PES impractical for some utilities. Further studies also confirm that the electrospinning method can be used to remove certain ions during the membrane fabrication process, such as Cu(II) ions. However, because this method requires high voltage and several other components with a high degree of precision, this can be an obstacle to large-scale application [14]. This approach was used in to tailor functionality; however, scale-up hurdles remain due to throughput and safety constraints.

Although the phase inversion method has advantages in terms of reliable membrane morphology, it still has shortcomings when used in certain environmental conditions. Meanwhile, the electrospinning method, although it has the advantage of being able to produce membranes with improved structural properties, has shortcomings in terms of cost [15]. All this suggests that it is advisable to conduct a study on an alternative fabrication route that retains controllable morphology while improving scalability and cost metrics. Currently, researchers continue to search for a new method, one that not only improves membrane performance but can also be produced at a relatively lower cost, so that it can be applied and manufactured on a larger scale. The electric field method is here to answer that question. This method offers advantages that phase inversion and electrospinning methods do not have, namely the ability to produce PES membranes with good characteristics but at a low processing cost. This method allows for a more even pore distribution, thereby improving performance in the filtration process, as well as increasing the permeability and selectivity of the membrane. A way to overcome the above difficulties can be the application of electric fields during casting/coagulation to influence chain orientation, porogen/additive distribution, and pore nucleation, achieving morphology control with simpler equipment than full electrospinning.

The application of the electric field method in the fabrication process of PES membranes has the potential to provide significant improvements compared to other conventional methods. However, understanding and references related to the electric field method in the PES membrane fabrication process are still very rare, so there are still many gaps that need to be addressed. This is important to resolve immediately, because conventional fabrication methods often fail to produce membranes that have reliable and efficient performance and superior mechanical properties at a lower fabrication cost. Therefore, an in-depth study is needed on the fabrication of PES membranes using the electric field method. This approach was not used in [13, 14] for electric field-assisted fiber formation/ion handling, however there remains a lack of systematic frameworks specifically for PES cast membranes under moderate electric fields that map processing-structure-property relationships at scale. All this suggests that it is advisable to conduct a study on electric-field-assisted fabrication of PES membranes to close the identified gaps and enable practical deployment.

3. The aim and objective of the study

The aim of this study is to evaluate the performance of PES membranes (without any additives), prepared using the electric field method. The results of this study are expected to provide practical benefits, such as improving the efficiency and effectiveness of water filtration processes.

To achieve this aim, the following objectives were accomplished:

– investigating the effect of different PES concentrations on membrane morphological characteristics based on observations using scanning electron microscopy (SEM) and atomic force microscopy (AFM);

– investigating and testing the effect of concentration differences on PES membranes using a tensile testing machine to determine the tensile strength of membrane samples;

– investigating the effect of different PES concentrations on functional-group signatures and hydrogen bonding in membranes based on observations using FTIR spectroscopy;

– investigating the effect of different PES concentrations on the structure and crystalline properties of membranes based on observations using X-ray diffraction (XRD);

– evaluating the water filtration performance of PES membranes with a focus on determining the permeability and selectivity properties of these membranes.

4. Materials and methods

4. 1. Object and hypothesis of the study

The object of this study is PES membranes, represented by sample codes MP1 (25% PES), MP2 (30% PES), and MP3 (35% PES). This study focuses on PES membranes for water filtration applications, analyzing their morphology, psychochemistry, mechanical properties, and permeability. However, mechanical testing of membrane samples is limited to tensile strength testing and does not evaluate other types of mechanical stress, such as shear or compression stress. This study hypothesizes that the PES content will affect the morphology, psychochemistry, mechanical properties, and permeability of each membrane sample. The use of electric fields during the research process will improve the anti-fouling properties, mechanical strength, and permeability of the membrane, making the membrane more effective for water filtration. Three membrane samples will be used in this test based on their PES content: 25%, 30%, and 35%. The hypothesis in this study is that the higher the PES content, the stronger the membrane will be; however, its permeability will decrease. And vice versa. This study assumes that the laboratory conditions at the research site are ideal and does not consider real-world variables, such as temperature fluctuations or variations in water quality.

4. 2. Materials

This study used polyethersulfone (PES), purchased from Sigma-Aldrich (Singapore), which was used directly without further processing.

4. 3. Membrane preparation

In preparing the membrane, the material to be used is polyethersulfone (PES), which will be made into three types of samples according to the polyethersulfone (PES) content, namely 25%, 30%, and 35%. The next step is the PES dissolution process. The dissolution process is carried out using a magnetic stirrer at normal room temperature for 6 to 8 hours until the solution is homogeneous. After that, the PES membrane is poured into a hermetic glass for the deposition and review of the solution. The research was conducted with a copper plate that was electrified by a 15 kV DC voltage, and a plaster was used for mold boundaries. The flow of the PES membrane preparation process can be seen in Fig. 1. Meanwhile, the composition of each PES membrane sample can be seen in Table 1 as follows.

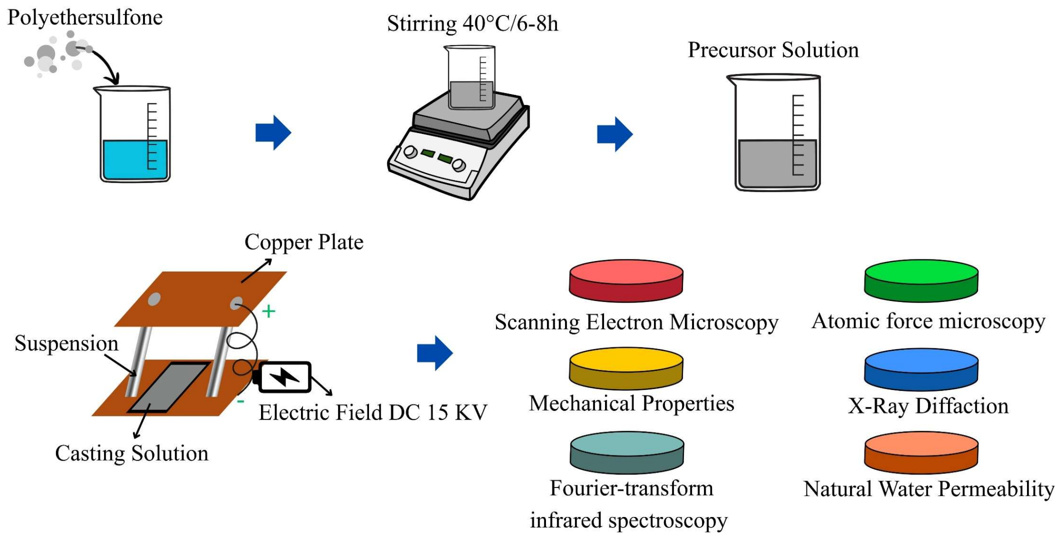


Fig. 1. Schematic of the polyethersulfone membrane experiment

After undergoing the fabrication process using an electric field, each fabricated membrane sample will be tested to analyze the morphological, mechanical, and physicochemical characteristics of each sample. Each test will use Scanning Electron Microscopy, Atomic Force Microscopy, a universal testing machine, X-ray diffraction, and Fourier-transform infrared spectroscopy to analyze the morphological, mechanical, and physicochemical characteristics of each membrane sample. The performance of each membrane sample will be tested using natural water permeability.

Table 1

Membrane sample composition

Sample	PES composition
MP1	25%
MP2	30%
MP3	35%

The selected main material for membrane is polyethersulfone (PES) because PES possesses good thermal resistances, excellent chemical stabilities, and high compatibility of membrane applications. The different polyethersulfone concentration in each sample was to examine the effect of relative amount of polyethersulfone in each sample on properties as well as performance of each sample.

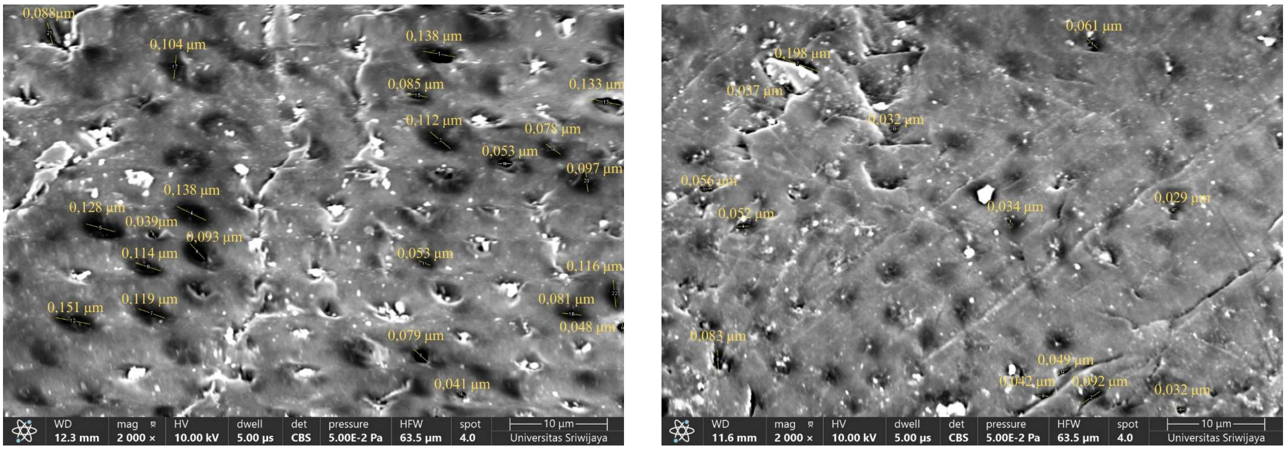
4. 4. Characterization of polyethersulfone membranes

Before the test, all membranes were preconditioned to an equivalent hydration level (rinsed with ultrapure water and removed by a delicate blotting) and their effective surface monitored for normalization. The tensile and NWP measurement were repeated at least three times, the gauges were zeroed/calibrated as per manufacturer's recommendation and raw data post-processed for reporting mean ± standard deviation at standard laboratory temperature and humidity. The surface morphology and topographic structures were examined with the Scanning electron microscope (SEM, Inspect S50, FEI Company) at an accelerating voltage of 15 kV after the membrane was sputter coated with a thin layer of gold for better conductivity. SEM (Inspect S50) is a high vacuum imaging system which employs an electron beam and secondary/Backscattered electron detectors to visualize the surface morphology after limiting charging effects with a thin Au coating. Surface roughness and hardness were also investigated by using an AFM (UTM, ZYGO) in 3D mode operated in a scan area of 10 × 10 μm; the AFM loaded with commercially available sharp cantilever tip supplied the nanoscale topography/roughness that provides details from one scanning to other scanning surface. The mechanical properties of the membrane were measured by tensile testing (ZWICK ROEL Material Testing Machine, model BT2-FR020TH. A60, Germany) under the ASTM D638-05 (2008). The tensile properties were obtained by the ZWICK universal testing machine (controlled single axial load-displacement) according to ASTM. Crystalline structure of the membrane was analyzed by X-ray diffraction (XRD, Rigaku MiniFlex 600, Japan), and these data of crystallization pattern were obtained from XRD comparison between amorphous/ordered phase records not shown. Functional groups and chemical bonds in PES membranes were verified by Fourier-transform infrared (FTIR) spectroscopy (Thermo Nicolet iS10, Japan), during which the Thermo Nicolet FTIR analyses IR absorbance bands to confirm functional group/bond. The clean water permeability test (NWP, Indonesia) was used as a parameter of membrane effectiveness. The membrane was ultrapure water soaked for 15 min then subjected to 1 bar pressure, and the volume of permeate was collected in a 50 mL measuring cylinder for 1 h under laboratory ambient conditions. The NWP setup is a simple pressurized (≈1 bar) dead-end permeation cell with regulated feed and volumetric collection for flux normalization.

5. Research results on morphology, mechanical, physicochemical characteristics and water filtration of polyethersulfone membrane

5. 1. Morphology of polyethersulfone membrane based on scanning electron microscope and atomic force microscopy results

Using scanning electron microscope (SEM), it is possible to observe the structure of the three PES membrane samples and found significant differences between them, as shown in Fig. 2. The MP1 membrane sample (PES 25%) had a varied pore distribution, with diameters ranging from 0.040 to 0.151 μm and an average of 0.095 μm. The MP3 membrane sample (PES 35%) had varied pore sizes ranging from 0.029 to 0.198 μm, averaging 0.062 μm.

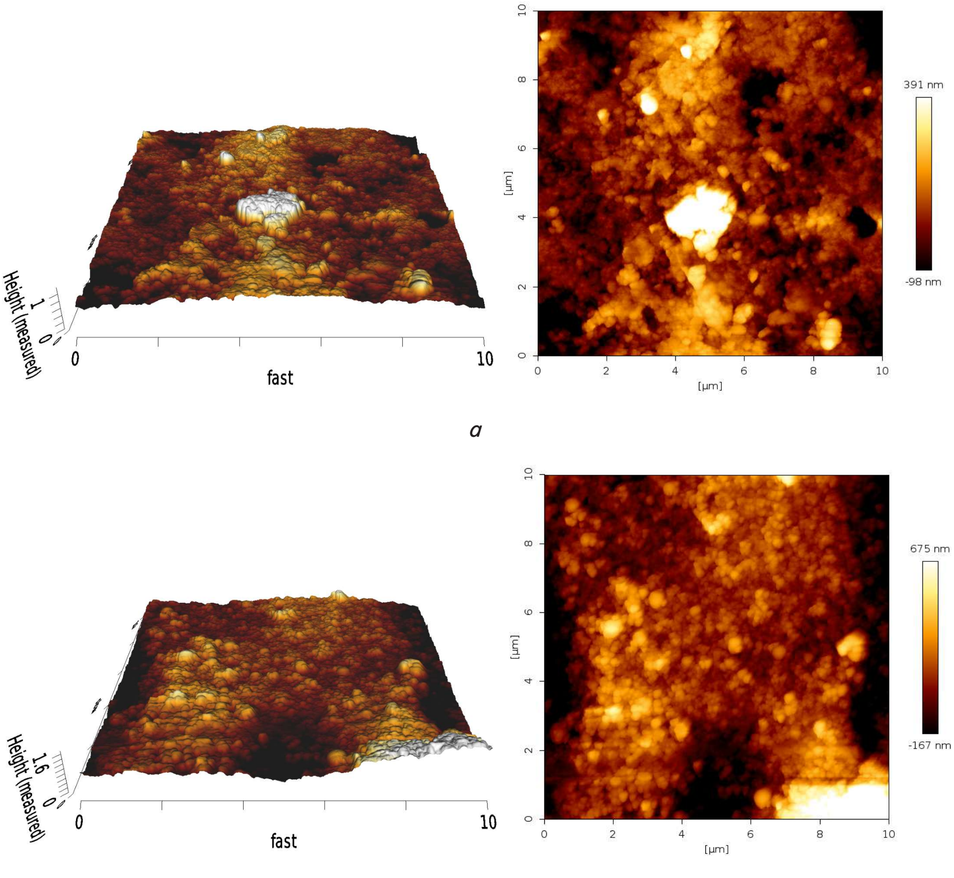


a *b*

Fig. 2. Scanning electron microscope of membrane polyethersulfone: *a* – PES 25%; *b* – PES 35%

As shown in Fig. 2 above, the SEM scan results indicate that the MP1 membrane (PES 25%) has pores distributed almost evenly, with an average size larger than that of the MP3 membrane (PES 35%). The pore distribution in the MP3 sample appears uneven, with pore sizes tending to be smaller than in the MP1 sample. This phenomenon occurs due to increased agglomeration on the sample surface, which decreases porosity and causes pore narrowing by inhibiting optimal pore structure formation. While this increases the membrane's mechanical strength and selectivity, it also reduces its permeability. The application of 15 kV voltage to modify the surface of the membrane results in a smoother surface, reduced pore size, and decreased concentration polarization. This, in turn, enhances flow and reduces the incidence of fouling.

Atomic force microscopy (AFM) was used to evaluate the surface morphology and topographical characteristics of the three membrane samples, in order to determine the impact of differences in PES content on membrane structure. These observations provided detailed information on the surface roughness, particle distribution and topographical homogeneity of each membrane. This analysis is crucial for understanding how differences in PES content can affect the membrane's physical properties, including its permeability, selectivity, and mechanical stability. The AFM results for the membranes can be seen in Fig. 3.



a

b

Fig. 3. Atomic force microscopy test results for the membranes polyethersulfone: *a* – PES 25%; *b* – PES 35%

In Fig. 3, above, it can be seen that the surfaces of the two membrane samples observed using AFM have significant differences. The 25% PES membrane (shown in Fig. 3, *a*) has a rougher surface with dominant bright white spots indicating uneven polymer agglomeration or clumping. Meanwhile, the 35% PES membrane (shown in Fig. 3, *b*) has a smoother surface with minimal agglomeration.

5. 2. Mechanical properties test results of polyether sulfone membrane

The aim of this test was to determine the effect of variations in PES composition on the membrane's mechanical properties. The objective of this testing method was to understand how changes in PES concentration affect the membrane's ability to withstand tensile loads. This mechanical strength analysis is important for identifying the optimal composition for providing the membrane with structural stability. The result of the mechanical properties of the membranes can be seen in Fig. 4 and Table 2.

The results for the membrane's mechanical properties can be seen in Fig. 4 and Table 2 above. The MP1 membrane (PES 25%), has a tensile strength of 1.48889 MPa. The MP2 membrane (30% PES) has a tensile strength of 4.50463 MPa. The MP3 membrane (35% PES) has the highest tensile strength, at 5.64907 MPa. These results also demonstrate that PES membranes exhibit excellent mechanical resistance even without additional modification.

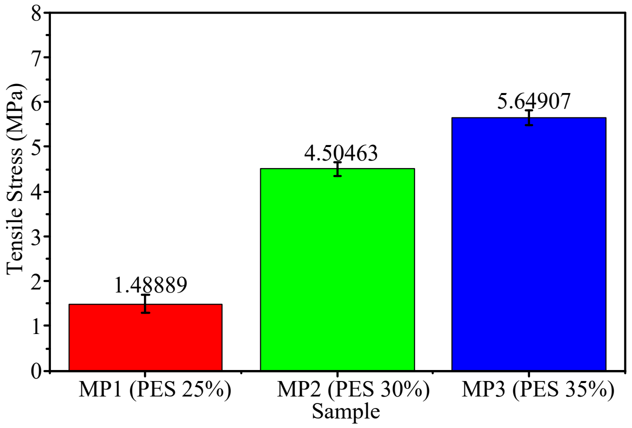


Fig. 4. Mechanical properties of membrane MP1, MP2, and MP3

Table 2

Mechanical properties of membrane MP1, MP2, and MP3

Sample	Tensile load (N)	Thickness (mm)	Wide (mm)	Surface area (mm^2)	Maximum stress (N/mm^2)	Average (N/mm^2)	Standard deviation
MP1	3	0.3	6	3	1.66666667	1.48888889	0.2
	3.3	0.5		3	1.1		
	5.1	0.5		1.8	1.7		
MP2	7.5	0.5		3	5.625	4.50462963	0.15
	9.7	0.3		1.8	1.1		
	13.5	0.4		2.4	5.38888889		
MP3	11.2	0.3		1.8	6.22222222	5.64907407	0.17
	13.3	0.5		3	4.43333333		
	15.1	0.4		2.4	6.29166667		

5. 3. Fourier-transform infrared spectroscopy analysis of the polyether sulfone membranes

FTIR spectroscopy was used to obtain FTIR data in the form of graphs for PES membrane samples. These graphs reveal complex profiles characterized by several significant peaks that indicate the molecular structure and functional groups. These peaks appear at various wave numbers: 3412 cm^{-1}, 3101 cm^{-1}, 1578 cm^{-1}, 1487 cm^{-1}, 1294 cm^{-1}, 1244 cm^{-1}, 1151 cm^{-1}, 1105 cm^{-1}, and 1011 cm^{-1}. These peaks are important indicators of the specific vibration modes associated with the molecular characteristics of PES, including the hydroxyl group (-OH) and the aromatic structure of the membrane. The FTIR graph can be seen in Fig. 5.

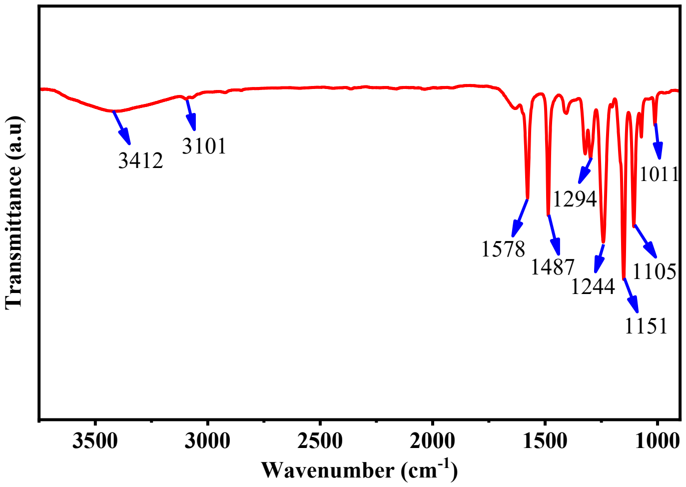


Fig. 5. Polyethersulfone membrane Fourier-transform infrared spectroscopy graph

Each peak in Fig. 5 above serves as an important indicator of specific vibration modes associated with the characteristics of PES molecules, including hydroxyl groups (-OH) and aromatic structures at the 3412 cm^{-1} peak. Stretching vibration of aromatic C-H bonds at the peak of 3101 cm^{-1}. Stretching vibration of aromatic C=C bonds in the benzene ring at the peaks of 1578 cm^{-1} and 1487 cm^{-1}. Stretching vibrations of the sulfonate group at peaks of 1294 cm^{-1}, 1244 cm^{-1}, and 1151 cm^{-1}. as well as indications of various C-O functional group vibrations at peaks of 1105 cm^{-1} and 1011 cm^{-1}.

5. 4. X-ray diffraction analysis of the polyether sulfone membranes

A graph was obtained based on observations made using X-ray diffraction, as shown in Fig. 6. This shows two intensity curves against the 2-theta angle for the two PES membrane samples. The main peaks in both samples occurred at around 20°. This indicates that both samples had an amorphous structure with slight semi-crystalline properties, consistent with literature on the crystallinity of PES. Polyimide typically exhibits broad, low-intensity diffraction peaks, which indicates amorphous pattern dominance. In this case, the intensity of the main peak of the MP3 membrane (35% PES) is slightly higher than that of the MP1 membrane (25% PES).

Fig. 6 above shows that the main peaks in both samples are around the 2-Theta 20° angle. This indicates that the PES membrane has an amorphous structure with a light semi-crystalline arrangement, which is consistent with the literature on the crystallinity properties of PES. Polyimide generally shows broad diffraction peaks and low intensity as a sign of amorphous pattern dominance. The graph also shows that the intensity of the main peak of the MP3 membrane (35% PES) is higher than that of MP1 (25% PES).

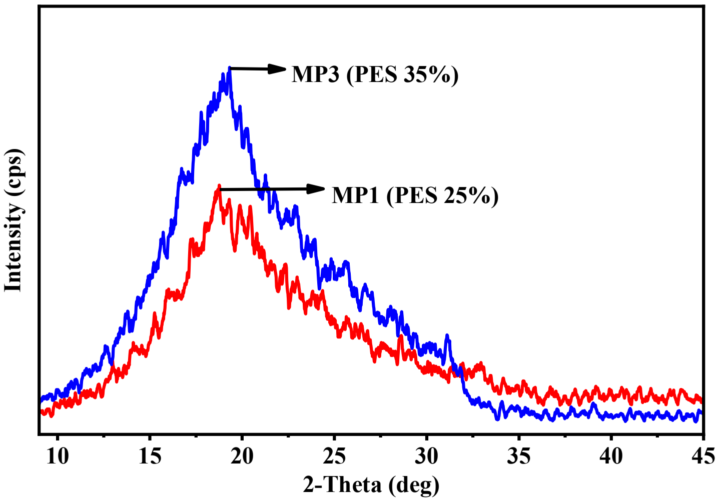


Fig. 6. Polyethersulfone membrane X-ray diffraction graph

5. 5. Natural water permeability test results of polyether sulfone membranes

Natural water permeability measurements were conducted to test the permeability of the membrane in each sample. This test is important for understanding how variations in PES concentration can affect the membrane's ability to filter water efficiently. The test provides information about the relationship between the membrane's morphological structure, pore distribution and permeability performance. Fig. 7 and Table 3 shows the natural water permeability (NWP) test graph for the membrane. The results show that the MP1 membrane (25% PES) has an average NWP value of 4.20121614 $L{\cdot}m^2{\cdot}h^{-1}{\cdot}bar^{-1}$. The MP2 membrane (30% PES) has an average NWP value of 3.79583564 $L.m^2{\cdot}h^{-1}{\cdot}bar^{-1}$. Meanwhile, the MP3 membrane (PES 35%) has the lowest average NWP value, at 3.13248572 $L{\cdot}m^2{\cdot}h^{-1}{\cdot}bar^{-1}$.

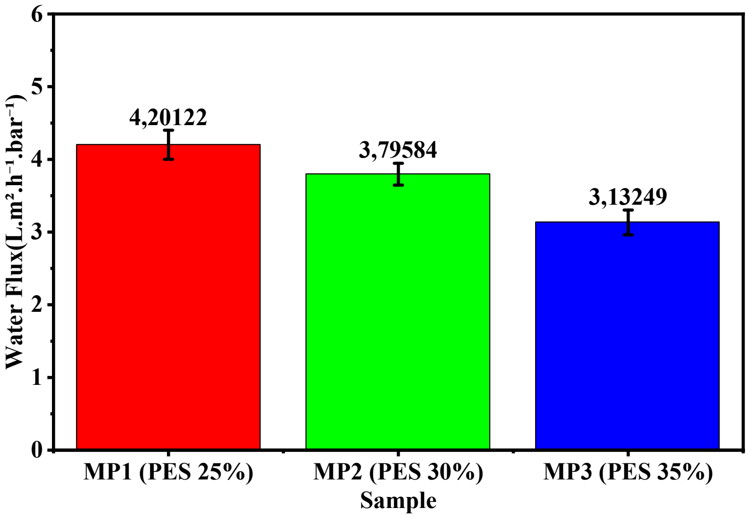


Fig. 7. Graph of membrane natural water permeability value

The relatively high NWP value of the MP1 (PES 25%) sample is due to porosity formed in the membrane structure during manufacturing. This results in a more even pore distribution, providing optimal water permeability and good mechanical stability despite the fact that PES is inherently hydrophobic. The significant decrease in the average NWP value of the MP3 membrane (PES 35%) is due to changes in the morphological structure, uneven pore distribution and agglomeration, which inhibit water flow.

Table 3

Natural water permeability data

Sample	Volume (L)	Time (hours)	Pressure (bar)	Surface area (mm^2)	Volume ($L{\cdot}m^{-2}{\cdot}h^{-1}{\cdot}bar^{-1}$)	Average ($L{\cdot}m^{-2}{\cdot}h^{-1}{\cdot}bar^{-1}$)	Standard deviation
MP1	0.0027	0.25	2	0.001809	2.98507463	4.20121614	0.2
	0.0035				3.86954118		
	0.0052				5.74903261		
MP2	0.0025				2.76395799	3.79583564	0.15
	0.0038				4.20121614		
	0.0040				4.42233278		
MP3	0.0024				2.65339967	3.13248572	0.17
	0.0029				3.20619127		
	0.0032				3.53786622		

6. Discussion of morphology, mechanical, physicochemical and water filtration of polyethersulfone membrane

Morphological analysis of PES membrane samples was performed using a scanning electron microscope (SEM). The purpose of this observation was to observe the effect of variations in polyethersulfone (PES) concentration in the membrane on its structure and surface. Fig. 2, *a* shows that the MP1 membrane sample (25% PES) has a fairly diverse pore distribution, with pore diameters ranging from 0.040 µm to 0.151 µm and an average pore size of 0.095 µm. The pores in the membrane appear to be evenly distributed across almost the entire surface of the membrane, indicating a macroporous structure. This heterogeneous structure has a relatively large pore size and can provide high permeability but low selectivity in the membrane [6]. The large pore size of the MP1 membrane is caused by low polymer concentration and the absence of reinforcing materials or other substances in the membrane. Under these conditions, the application of an electric field during the fabrication process can make the membrane material more susceptible to strain due to minimal internal resistance in the polymer structure. This allows the membrane material to undergo greater deformation, resulting in more uniform pore formation throughout the membrane. The unreinforced polymer structure will be unable to withstand external forces, resulting in large pores that are relatively evenly distributed [16]. The trend reported here is directly displayed in Fig. 2, *a* (wider, uniformly distributed macropores), which explains the observed high-permeability/low-selectivity behavior; this aligns with electric-field – aided deformation pathways proposed for low-viscosity dopes, and with the general permeability – selectivity trade-off discussed for macroporous skins. This work demonstrates a PES-only, process-level control in which external electric field is used deliberately to tighten pore-size distribution and smooth the top surface without changing composition. This closes a known gap in the polymer field that calls for coupling electric-field strategies with explicit morphology control at the polymer scale, and it advances prior PES studies that predominantly emphasized non-field process tuning by isolating the PES-concentration pathway under a common, uniform field. In short, at fixed field, varying PES wt% cleanly reveals how higher PES drives denser networks and finer pores while preserving experimental parsimony, an improvement in controllability over conventional PES approaches. Consistent with polymer-under-field literature, the field itself is recognized as a viable post-processing "knob" that can be exploited to realize morphology control in PES.

Fig. 2, *b* shows a significant difference, with the pore size of the MP3 membrane (35% PES) decreasing dramatically, ranging from 0.029 μm to 0.198 μm with an average pore size of 0.062 μm. The difference in pore size between the two membrane samples is related to the difference in polyethersulfone (PES) concentration in each sample. A higher PES concentration will result in smaller pore sizes due to factors such as polymer viscosity, phase separation dynamics, and pore morphology during the membrane manufacturing process. The PES concentration in the membrane can directly affect the viscosity of the solution during the manufacturing process, which will have an impact on phase separation dynamics and pore formation. During the membrane fabrication process, higher PES concentrations will produce a thicker solution. High solution viscosity can inhibit the mobility of polymer chains in the solution, thereby reducing the effectiveness of solvent molecule diffusion during the membrane manufacturing process [8]. As a result, this limited polymer chain mobility will produce a membrane with a finer pore structure. A similar phenomenon occurred in the MP3 (35% PES) sample, proving that an increase in PES concentration can produce smaller pore sizes due to limited chain mobility and the formation of a denser polymer chain network. As the PES concentration increases during the fabrication process, the solvent extraction rate tends to decrease, which results in fewer pores forming in the membrane [17]. Studies have shown that there is a correlation between increased PES concentration and decreased pore size in the resulting membrane, because higher polymer concentrations promote the formation of denser polymer networks and inhibit pore space expansion. Increased polymer concentration in the membrane often causes the membrane to exhibit a denser polymer chain arrangement, which can result in a further reduction in pore size [18].

The sponge-like pore structure, which appears at lower PES concentrations, becomes less dominant as the concentration increases, so that the finger-like structure becomes dominant. The surfaces of the three membrane samples were modified using an electric field method at a current of 15 kV. This method was chosen for membrane production because it can reduce roughness and shrink the pores on the membrane surface. This method can also reduce the level of concentration polarization and prevent the accumulation of pollutants on the membrane surface. This reduces the potential for clogging of the membrane pores and increases the permeability of the membrane [6, 8]. It can then be concluded that variations in PES concentration in the membrane are proven to be the main factor in controlling membrane morphology. Membranes with low PES concentrations are more ideal for applications that require high permeability, while membranes with high PES concentrations are more suitable for applications that emphasize mechanical resistance and optimal selectivity. The smaller mean pore size in Fig. 2, *b* is consistent with viscosity-controlled demixing. Compared with known phase-inversion data, the electric field acts as an additional knob to tighten pore-size distribution. Unlike conventional fabrication method, the electric field method shows narrower spread of pore diameters at 35% PES, indicating improved control. For PES specifically, the uniform-field route produces a narrower pore-size spread at higher PES while maintaining a clear concentration-to-morphology linkage, thereby delivering finer selectivity control without altering formulation. Practically, this provides a PES "design map" in which a lower PES concentration combined with an applied field produces highly permeable structures, whereas a higher PES concentration with the same field results in denser, more uniform pores that exhibit improved stability. These gains are consistent with independent reports that electric-field treatment reduces roughness and shrinks pores (supporting fouling suppression) and can increase effective permeability by promoting pore formation, mechanistic advantages that translate directly to PES membranes. Consequently, the present PES-only strategy is superior to earlier PES approaches that lacked an explicit external-field handle, because it provides reproducible, composition-invariant morphology control aligned with the broader call in polymers to couple electric-field design with morphology control.

Based on the atomic force microscope (AFM) images shown, there are two polyethersulfone (PES) membrane samples with different concentrations, namely PES 25% and PES 35%. In Fig. 3, *a* (PES 25%) and Fig. 3, *b* (PES 35%), each including a left three-dimensional (3D) image and a right two-dimensional (2D) image. The surface images can also be subjected to morphological analysis in order to quantitatively characterize the roughness, distribution of pores and uniformity of the surfaces. Now it is well-established that these properties are altered with concentration of polymer used in solution along PES membrane construction. In Fig. 3, *a* large surface roughness and uneven pores are observed on the membrane surface. This can be seen from the marked height differences in the 2D right hand side image (–98 nm –391 nm). The intense white spots are typical of agglomerate or polymer clumping. This property suggests that the solution has low viscosity and forms a large macrovoid structure with rougher surface [19]. These properties are typical for membranes with polymer content ~25%. Lower polymer concentration promoted the demixing process, because of larger solvent content than that of the polymer, drove more significant non-uniform phase separating surface and also large pore sizes [20].

In contrast, in Fig. 3, *b*, indicating a relatively more homogeneous and flatter surface of the membrane with small distribution of protrusions. On the right, it is possible to see black color scale), the difference is scattered, not intense and over AMPLITUDE (in the graphs in Fig. 3, *a* which shows denser surface and smaller pore size with narrow distribution [19]. This is due to the fact that in high polymer concentration (35%) solutions, the viscosity of the solution increases and hence diffusion rate of solvent and non-solvents decreases during membrane preparation. Consequently, a membrane having the dense graft only over surface with smaller pore size was obtained. The density of the membrane and its permeability, but its mechanical strength will rise with the increase of polymers concentration in the solution. Moreover, these distinctions can also be correlated according to the flatness of membrane surfaces. Fig. 3, it is evident that a (PES 25%) has higher flatness value as large protrusions and larger height differences were introduced. It was well known that such the rough-surface membranes usually possessed bigger pore size, and the increase of hydrophobicity often resulted in the accelerated dirt accumulation during water separation or waste filtration [20]. Contrarily, the TMP of membranes with 35% of PES concentration (Fig. 3, *b*) and are smoother on their surface than those of the other systems, which leads to higher anti-clogging proprieties [21]. This work only considers PES concentration as the variable and maps the AFM height fields (–98 to 391 nm and –167 to 675 nm) into a step-wise effect of concentration on viscosity, demixing behavior, and ultimately surface roughness and pore size within one polymer system (PES). It shows that a small concentration range of 25–35 wt% could restructure surface topography and improve roughness uniformity. AFM roughness has been quantified before in PES measurements, but a study conducting no concentration liquid mapping of AFM and directly related to the demixing kinetics does not exist. This can be fulfilled in the present study by using AFM roughness as a surface parameter and considering concentration dependent demixing as controlling mechanism. The irregular surface of MP1 might improve the initial hydrophilicity, but large unevennesses may result in fouling. In contrast, the smoother texture of MP3 results in a more even distribution of surface tension and also lower potential for organic fouling. In general, AFM results indicate that the polymer concentration is a controlling parameter for the development of texture on the surface of PES, ranging from a wavy morphology with high porosity to a smoother and compact one; which can lead to the tuning of different transport properties according to application. The visible ranges of the heights studied in Fig. 3, *a*, *b* rationalize flux/selectivity shifts through roughness-induced polarization. The smoothness suppression at larger PES is in line with findings on the smoothing by viscosity and supports the electric-field argument for decreased polarization. The concentration-dependent AFM signature can serve as a practically applicable design rule for PES: selecting 35 wt% leads to smoother, denser, and more homogeneous surface, which suppresses the risk of roughness-induced polarization/fouling (at an expense of permeability trade-off), while 25 wt% facilitates increased flux by larger pore size and roughness. This one-parameter tuning approach effectively operates under existing PES behavior (increasing polymer will increase viscosity, slow down solvent–nonsolvent exchange, delay demixing and decrease surface porosity/pore size) to tune these setpoints without necessitating changes from other formulation input conditions.

In Fig. 4, results of tensile tests on three PES membrane samples are revealed good linear relationship between PES content in the membrane samples and their mechanical strength. In particular the specimens presented an average tensile strength change from 1.48888889 MPa in the sample with 25% PES amount to 5.64907407 MPa for samples containing 35% PES content. Such behavior can be attributed to some mechanical and structural properties characteristic of PES, that lead to better performance under loading conditions. Their large variations in tensile strength are also indicative that the electric-field method employed for fabrication is highly effective in overall strengthening of the membrane. The impact of the molecular structure and crystallinity of PES on its mechanical properties is firstly introduced. The material's crystallinity generally increases as the concentration of PES is increased. Stronger films are obtained with more crystalline in polymers in general. Its higher load-bearing capacity is a result of the more closely packed polymer chains in crystal region. The polymer chain configuration could influence tensile strength, thus increasing the density of polymer chains in membrane can increase stress at higher concentration.

Moreover, the molecular weight of PES is another important parameter which influenced the tensile properties as well. For higher-MW polymers, they have better mechanical properties, characterized by their cross-linked molecular networks which are resistant to deformation [22]. In this regard, the appearance of longer polymer chains will enhance the energy uptake during tensile tests as concentration of PES increases. Greater bonding of the polymer chains will lead to a stronger mechanical strength in the membrane. Besides, a self-realization of polymer's intrinsic is also responsible for the results. PES is well known for its high mechanical properties, excellent thermal stability and good chemical resistance such these of the polymer retain their molecular identity when under tensile load. Therefore, improved stress distribution among the polymer chains will be realized with increased PES content which in turn will promote more effective load transfer contributing to higher tensile strength [23].

These conclusions are reinforced by the assumption that no change in ambient environmental conditions occurred during testing, as temperature and humidity could greatly influence the mechanical properties of membranes [24]. The mechanical strength of polymers is known to be highly affected by external factors, although in a controlled environment the intrinsic properties can be better estimated. This also constantly supports the tendency that with an increase of PES content, the tensile strength became higher in all observed tests because the structure of this material has not death by environmental agents. To conclude, the correlation obtained between PES concentration and tensile strength reflects the fundamental principles of polymer science dealing with integrity/durability (molecular weight), morphology (crystalline) but also their structural importance. When the PES concentration in a membrane is higher, mechanical properties of the membrane are enhanced, as compared to degradation and plasmolysis tendencies based on its crystallinity and molecular interaction in PES. Hence, the increase in PES concentration combined to the application of an electric field shows a clear synergy in improving mechanical properties of the membrane. These results suggest that the electric field modality has not only employed as the morphological modifier, but it also greatly affects on the mechanical performance, making PES nanofibrous membrane via electric field is indeed a potential alternative way to fabricate paves with high strength and superior structural stability. The quantitative leap exhibited in Fig. 4 agrees with crystallinity/molecular-weight considerations and is in excess of typical concentration-only gains reported for non-electric field PES systems, suggesting that a method peculiarities field presence assists chain packing during coagulation.

The FTIR spectrum in image Fig. 5 reveals a complicated shape composed of many sharp peaks that reflect the molecular structure and functional groups of analytes. These peaks are observed at different wavenumbers, 3412 cm^{-1}, 3101cm^{-1}, 1578 cm^{-1}, 1487 cm^{-1}, 1294 cm^{-1}, 1244 cm^{-1}, 1151 cm-1, 1105cm^{-1} and 1011 cm^{-1}. Each of these peaks is the significant sign in the special vibration modes for the characteristics of PES molecules with hydroxyl (-OH) groups and aromatics structures. The wide peak at ~3412 cm^{-1} is attributed to the stretching vibration of hydroxyl (-OH) group that could possibly be attributed to water vapor or water entrapped in the PES matrix. This is critical, because and change in hydration can influence the permeability of the membrane as well as its performance. The 3101 cm^{-1} peaks are assigned to the stretching vibration of aromatic C-H in the PES structure, and those might be involved with PES mechanical performance and heat-stabilities. Meanwhile, the peaks at approximately 1578 cm^{-1} and 1487 cm^{-1} are attributed to stretching vibrations of aromatic C=C bonds in benzene ring, demonstrating the essential contribution of aromaticity in PES polymer chain. These peaks are important features for characterizing the rigidity of a polymer network to understand membrane technology processes such as wastewater treatment and gas separation. The hydrophobic character of the membrane may be substantially enhanced by this aromatic ring, which has an impact upon the blocking behavior.

The midrange peaks at 1294 cm^{-1}, 1244 cm^{-1}, and 1151 cm^{-1} are attributed to the asymmetric and symmetric stretching vibrations of sulfonate group (-SO_2-) in PES membrane [25]. They provide improved chemical resistance to the membrane, which allows it to be used for filtration in different conditions, even in extreme conditions [26]. Moreover, this sulfonic function resistance may also enhance the PES membranes affinity to polar solvents which can increase the water permeation rate. There are also maxima at lower wave numbers; these occur at 1105 cm^{-1} and 1011 cm^{-1}, respectively, which correspond to C–O vibrations of different functional groups. These peaks represent ether bonds in the polymer [27]. Ether groups not only affect the hydrophilicity of PES membranes, but they also influence the swelling phenomenon frequently found at specific operating conditions and influencing sorption characteristics of solutes through the membrane. To conclude, the FTIR spectroscopy analysis of PES membranes shows the main functional groups that contribute to the physicochemical properties of these membranes. The existence of both hydroxyl, sulfonic, and aromatic groups inside the membrane is a key in defining the properties such as thermal stability, resistance to chemicals and permeability.

In relation to previous PES FTIR characterizations research, which repeatedly identifies the aromatic ether characteristic band (1244 cm^{-1}), benzene ring modes (1487 cm^{-1} and 1578 cm^{-1}) sulfonyl stretches in the 1150 cm^{-1}–1104 cm^{-1} window (typically with an accompanying 1010–1027 cm^{-1} present as an ether marker) and a prominent yet broad 3400 cm−1 hydroxyl envelope used largely for qualitative purposes, this work uniquely resolves and reports additional PES-relevant features at 3101 cm^{-1} (aromatic C–H stretching) and at 1294 cm^{-1} (another discrete sulfonyl-related feature) that are not explicitly singled-out by these prior PES reports, thereby providing a more detailed or dense (20 bands or so each for S and O end-groups alone where previous studies had ≈16 total bands of interest for both sets of related moieties combined), PES-specific spectral fingerprint that can improve spectral band assignments agreement across disparate data collectives.

The XRD graph in Fig. 6 displays two profiles of intensity as a function of 2-Theta angle for the two PES membrane samples. The major peaks of both samples appear at a 2-Theta angle of about 20°. This is suggestive of an amorphous PES membrane with partial semi-crystalline orientation, which is well documented in the literature on crystallinity properties of PES. MP1 has wide peaks with low intensity, indicating an amorphous pattern domination. It is also observed in the graph that the intensity of the main peak for MP3 membrane (35% PES) was higher than for MP1 (25% PES). Such higher intensity enhancement could be interpreted to imply a higher degree of regularity in the polymer structure, as induced by the increase in PES concentration. Then, the higher polymer contents in membrane samples may generate stronger interaction between their chains, thus leading to larger or more regular semi-crystalline domain. The MP3 peak also enhances apparently compared to MP1, which shows the larger size of crystallite or higher degree of crystallinity. According to Scherrer's equation, the diffraction peak FWHM is inversely proportional to crystalline size. Thus, it is demonstrated that the increment of PES concentration can stimulate an increase in the order for crystalline domains on a membrane [28].

With higher polymer contents in the membranes, the viscosity of membrane solution was generally improved and it was beneficial for forming more membrane structures with semi-crystalline areas. The structure of membrane affects its mechanics and permeability. Membranes of higher crystallinity are usually mechanically more stable but potentially less permeable. MP3 membranes offer higher mechanical resistance and more chemical stability and are used in high-pressure filtration applications. Membrane sample with 25% concentration membranes, by comparison, might be less resistant to flow and more suited for filtration applications requiring high flowrate yet moderate selectivity. The concentration of the polymer also impacts the performance of the membrane adjusted according to application needs. The XRD graph in Fig. 6 also demonstrated that morphology and crystal structure of membrane could be modulated by applying the electric field, which provides potential application in those applications requiring specifically structural stability and functional properties of membranes. These findings also prove that precise regulation of polymer concentration in conjugation with electric field can be a successful approach in controlling the crystal properties of PES without using chemical modification or other additives. Therefore, it provides an easier and environmentally friendly method with lower cost for the preparation relative to the other traditional processes. The peak sharpening in Fig. 4 explains the tensile gains of Fig. 4 by crystallite growth (Scherrer link). Such ≈ 20° amorphous halos are typical for PES. The novelty is field-assisted enhancement without additives, which is not as much reported in the non-field literature.

This investigation shows that by varying the concentration of PES (from 25% to 35%) during fabrication, combined with an applied electric field, one is able to sharpen the location of the main XRD PES peak near at $2\theta \approx 20°$ (as shown by narrowing the FWHM) which, using Scherrer relation for crystallite size estimation, would immediately explain higher tensile strength values. The main novelty is the development of a process-only and additive-free approach to improve PES chain ordering, with XRD peak narrowing (lower FWHM) being explicitly correlated to both an increase in crystallite size and tensile strength of pure PES. This is an improvement over previous studies in which sharper XRD peaks and increased crystallinity were obtained by compositional changes, but this level of crystallinity was generally correlated with improved mechanical stability. In addition to the presented structure-property measurements, this paper also reports an actionable structural design principle for PES systems: higher concentration of PES in the presence of an applied field narrows XRD peaks (lower FWHM), resulting in larger crystallites and greater mechanical stability while flow is maintained at high levels, such that both transport and mechanics are verifiable tunes purely through PES parameters and processing without additives. In general, this provides a more straightforward, more sustainable and cheaper route to tuning mechanical behavior of PES for applications demanding better stability in the structure, which is consistent with literature values that relate higher crystallinity with greater mechanical stability, herein obtained purely through processing optimization.

Following the NWP test results in Fig. 7, it can be inferred that how the increase in PES concentration with a decrease in NWP is more or less due to the intricate relationship existing between physical-chemical properties controlling performance of membrane [29]. Regarding NWP, the MP1, MP2 and MP3 samples display values that reflect trends with concentration of polymer in the membrane structure and permeability. In the case of membranes with higher PES content, a polymer matrix can be formed during the membrane formation process leading to denser and more compact structures. Under these changes, pore size of membrane matrix will be lower and the tortuosity will increase to become an obstacle for water molecules from flowing through [21]. The interaction between polymer chains is enhanced with the increase of the PES concentration which may influence overall membrane morphology and porosity, leading to non-uniform water pathways. Thus, this structure shrinkage may result in a reduction of NWP due to the blockage of water transport across the membrane [29].

This work uniquely decouples the effect of PES concentration under an electric-field-assisted processing route and quantifies a concentration/resistance NWP pair using fully normalized metrics (LMH/bar) in line with standard NWP practice. The method circumvents non-PES variables and the additive-driven confounders that plague most of previous PES literature, directly relating permeability alterations to SEM/AFM-observed densification/tortuosity and thereby establishes a PES-only causative route from microstructure to NWP. Most remarkably, the field-treated, low-concentration PES sample (MP1) supports $>4\ \mathrm{L\cdot m^{-2}\cdot h^{-1}\cdot bar^{-1}}$ exceeding clean-water permeabilities in additive-modified PESs typically reported at this same normalized unit scale under TP PES concentration manipulation only. This is a methodological and performance improvement over previous additive-based approaches and unrelated PES polymer baselines.

Furthermore, as a result of their hydrophilic character the water permeability of PES membranes is also affected. Nevertheless, as with the case of higher PES concentration, it could decrease water wettability owing to a higher degree of hydrophobic chain interaction that lead to its decreased water absorbing capacity. It results that increasing the PES content in a membrane gives rise to a worse hydrophobicity of the membrane and, thus leading to correspondingly lower NWP value of membranes. This highlights the significance of achieving the optimum balance between membrane fabrication in this process, with control over PES concentration setting on the membrane playing a key role in optimization of mechanical integrity versus permeability. On the other hand, in muds with a high concentration of polymer it can lead to low permeability and, consequently, clogging resistance. It indicates that although increased PES addition can improve some properties, the excessively high content of PES may block natural hydrophilicities and structures of the membrane. Together, the results verify that electric fields not only act to flatten membrane surface and inhibit concentration polarization but also affect pore connection and facilitate fluid transport [6–8]. The flux performance is $> 4\ \mathrm{L/m^2\cdot h\cdot bar}$ at MP1, showcasing the tremendous potential of the application of this method to large scale water filtration systems where high permeability but without membrane strength compromise are needed [6, 30]. Therefore, it was demonstrated that the utilization of electric fields in the preparation of PES membranes is a flexible and adjustable method for the development of both high flow efficiency and reliable mechanical stability. The decreasing NWP in Fig. 7 follows well the development of SEM/AFM (Fig. 2, 3) to the more crowded/less connected paths at higher PES. The permeability reduction with concentration is equivalent to the porosity-tortuosity relationship for traditional PES without electric field and it appears that MP1, treated in the electric field at low concentration (10 wt%), can maintain $>4\ \mathrm{L\cdot m^{-2}\cdot h^{-1}\cdot bar^{-1}}$, meaning that polarization is lower than what would be expected using conventional approaches.

In practical terms, this study provides a tunable PES baseline without additives that fuses standardized NWP characterization with morphology-driven mechanistic interpretations and thus allows fair apple-to-apple benchmarking of different PES membranes. The approach is a more straightforward and safe route compared with the additive-dependent PES modifications, but has a better normalized permeability than previously reported in the literature ($3.01–3.89\ \mathrm{L\cdot m^{-2}\cdot h^{-1}\cdot bar^{-1}}$) and more obvious structure–property causality to promote scale-up of PES water treatment modules by achieving normalized permeabilities $>4\ \mathrm{L\cdot m^{-2}\cdot h^{-1}\cdot bar^{-1}}$ at low PES integrity level. As such, this framework follows the community's focus on to normalized testing and electric-field-enabled control of pore connectivity and it is also directly coupled to the end-use objective of selective water transport while retaining solutes.

According to the experiments, it can be concluded that the use of the electric field approach in PES membrane manufacturing process will control effectively on membrane morphology and also will enhance mechanical strength and permeability of membrane. This technique could also be employed as a single green route for the synthesis of high-performance water filtration technology-based PES membranes and some modification may allow these PES membranes to be developed as composite base material.

There are some limitations of this study that should be considered for future work. The first is that the polyethersulfone (PES) concentration range examined in this work was quite reduced (MP1, MP2 and MP3). While there might be some relationship between PES concentration and tensile strength or membrane permeability, the effect of different (higher or lower) PES concentrations was not considered in this study. This generalizes the results to other concentrations with possibly more favorable properties. Additional studies may also investigate differences in PES concentration on a finer scale to identify the ideal balance between strength and porosity.

Second, although the EFM had been demonstrated to be effective in regulating the pore structure and surface roughness of membranes, there has yet to offer a comprehensive account for that. More explorations are needed to study electric filed parameters (such as field intensity and duration) applied during membrane manufacturing process, this would offer a better understanding and increase the efficiency of the system. Third, more studies could also be conducted on other methods and types of membrane surface modification (e.g. 30–32.72) (membrane treatment or addition of other additives) aiming at increasing hydrophobicity and antifouling capability for a better performance as well as quality/reproducibility of the membrane. Furthermore, there is a need to conduct more research and investigate the economics and environmental issues of mass production of PES membranes for cost-effectiveness as well as reduce potential environmental risks from large-scale production.

7. Conclusions

1. SEM analysis indicates that the variation of the dose of PES in membrane samples can influence on pore size and distribution. The average pore size was 0.095 μm for the MP1 membrane (25% PES) and 0.062 for the MP3 membrane (35% PES) Higher concentrations of PES in membrane produce agglomeration from water on the surface of sample, reducing porosity and narrowing down the pores by preventing formation of ideal pore structure. Secondly, the permeability of the membrane is decreased and at the same time its mechanical strength and selectivity are improved. In consistent with SEM observations, the AFM testing of membrane samples has confirmed that PES concentration in membrane could influence the surface roughness and pore size of the membrane. The surface of the MP1 (PES 25%) membrane was rougher and with larger pore sizes compared to the MP3 (PES 35%).

2. Calculations on the PES concentrations in membrane samples could lead to disparities of tensile strength of the samples. The tensile strength of sample MP1 (PES 25%) was 1.48888889 MPa, for the MP2 (PES 30%), it was 4.50462963 MPa and this value went up to 5.64907407 for the sample PES35%. So, it can be deduced that the larger of PES content in sample leads to the stronger tensile strength.

3. The FTIR spectrum reveals that the polyethersulfone (PES) membrane has a complex profile with some higher peaks, which reflect the molecular structure and functional groups of PES membranes. These peaks are observed at different wavenumbers such as 3412 cm^{-1}, 3101 cm^{-1}, 1578 cm^{-1}, 1487 cm^{-1}, 1294 cm^{-1}, 1244 cm^{-1}, 1151 cm^{-1}, 1105 cm^{-1}, 1010 cm^{-1}. Every one of these peaks are a significant indication of certain vibrational modes related to the molecular structure of PES, with characteristic functional groups from hydroxyl (–OH) and aromatic structures.

4. The XRD testing results demonstrated that the PES membrane was amorphous with small semi-crystalline structure. The intensity of the predominant peak of MP3 (PES 35%) membrane was found to be larger than that of MP1 (PES 25%). This intensification signifies either bigger crystallite sizes or higher degree of crystallinity. Increased membrane crystallinity tends to produce better mechanical stability and limit water permeability.

5. Dispersion in the PES concentration of a PES membrane sample can influence the natural water permeability (NWP) of those membrane samples. The MP1 membrane (PES 25%) presented a NWP value of 4.20121614 L·m^2·h^{-1}·bar^{-1}, the NWP of MP2 membrane (PES 30%) was calculated: 3.79583564 L·m^2·h^{-1}·bar^{-1}, and a MP3 membrane (PES 35%) with NWP of water as 3.13248572 L·m^2·h^{-1}·bar^{-1}. Thus, it can be further deduced that the more content of PES in membrane, the smaller value of NWP.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, whether financial, personal, authorship or otherwise, that could affect the study and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence tools

The authors confirm that they did not use artificial intelligence technologies in creating the submitted work.

CRediT

Aneka Firdaus: Formal analysis, Writing – review and editing; **Rahma Dani:** Conceptualization, Formal analysis, Visualization, Investigation, Data curation, Methodology, Writing – original draft, Writing – review and editing; **Muhammad Satya Putra Gantada:** Formal analysis, Visualization, Data curation, Methodology, Writing – original draft; **Ahmad Fauzi**

Ismail: Supervision, Validation; **Nukman:** Investigation; **Irwin Bizzy:** Validation; **Agung Mataram:** Conceptualization, Resources, Funding acquisition, Validation, Project administration, Supervision, Writing – review & editing.

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