Influence of Bamboo Cellulose Coating on the Flux Performance of Polyvinylidene Fluoride Hollow Fiber Membrane

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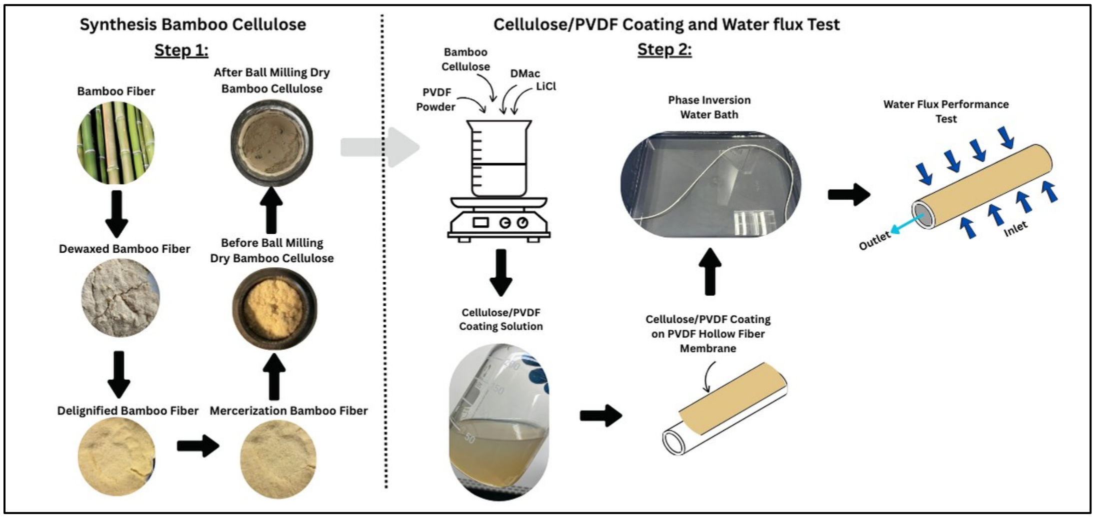
GRAPHICAL ABSTRACT



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This study showcases the characterization of a surface modified polyvinylidene fluoride (PVDF) hollow fiber membrane *via* Cellulose/PVDF coating. Scanning electron microscopy shows evidence of Cellulose/PVDF coating where surface roughness and coating lines with cracking is visible. The rough surface correlates with an improved pure water flux. However, the presence of surface cracks and higher cellulose loading results in decreased flux. Fourier transform infrared spectroscopy shows evidence of cellulose on the coated membrane. X-Ray diffraction revealed amorphous phase on the surface of the coated membrane, indicating that coated membrane has improved hydrophilic properties. The coated membrane samples have improved pure water flux performance up to 3 times the value from control (157.8864 L/m^2/h/bar) for samples P01 (432.9142 L/m^2/h/bar) and P02 (483.8453 L/m^2/h/bar) which is the best performing membrane. The porosity and mean pore size correlate with the pure water flux as increase in porosity with increased mean pore size enables better permeability. However, the increased porosity with decreased mean pore size causes a clogging effect which may be attributed to the swelling of the membrane when in contact with the pure water. Overall, the cellulose/PVDF coating modifies the surface properties by developing a rough and porous hydrophilic layer. It enables better performance for the hydrophobic PVDF hollow fiber membrane.

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Keywords: Bamboo Cellulose; PVDF; Water Flux; Membrane

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INTRODUCTION

The use of polyvinylidene fluoride (PVDF) polymer is well known in the water treatment industry. The development of membrane technology using PVDF polymer shows excellent chemical resistance, thermal stability, mechanical strength, and ease in processing. However, PVDF membrane is known to be more hydrophobic in nature due to its low surface energy. Researchers have observed that the protein adsorption and other impurities during water treatment, in addition to the hydrophobic nature of PVDF membrane. The presence of -CF_2 groups in PVDF leads to a significant decrease in pure water flux, thus limiting its efficiency during application (Wang *et al*. 2012; Fathanah *et al*. 2023; Lee *et al*. 2023). One of the simple and immediate methods to improve pure water flux without surface modification is to use more membranes during water treatment. The utilization of PVDF hollow fiber membranes is advantageous due to ease in scaling up for applications (Zou *et al*. 2022). With the large number of hollow fiber membrane fabricated in a membrane unit, the surface area for water contact is increased significantly in the membrane unit, hence increasing the pure water flux without surface modification.

However, the simple and immediate method is not always a good thing, as the cost and maintenance of adding more membrane units to achieve the desired pure water flux performance will increase considerably. Hence, the option of surface modifications is still a good alternative solution to overcome these challenges. Surface modification techniques *via* membrane coating have been a popular topic for researchers in water treatment industries. The goal of many researchers is to successfully incorporate hydrophilic materials as a coating onto the PVDF hollow fiber membrane, improving the pure water flux performance as well as reducing fouling (Shi *et al*. 2009; Kusuma *et al*. 2021; Kamaludin *et al*. 2022). An example of a hydrophilic material which could be used as a surface modification technique *via* membrane coating is cellulose. Cellulose is a biopolymer with good hydrophilic properties due to its hydrogen bonds (Wang *et al*. 2021). It is also known that micro-nano size cellulose has good chemical, mechanical, and physical properties, which opened a wide range of applications in multiple industries (Lv *et al*. 2018; Wang *et al*. 2021).

Bamboo-derived cellulose, BC was selected herein over conventional sources such as wood pulp, cotton due to its higher crystallinity (James *et al.* 2024; Namakka *et al.* 2025), which promotes membrane stability. PVDF on the other hand is hydrophobic with limited water interaction, the incorporation of BC, which inherently possessed aligned microfibrils, and enhances hydrophilicity (Rahman *et al.* 2025). Additionally, bamboo's rapid renewability and low processing costs make it a sustainable alternative, while preliminary data suggest BC outperforms other cellulosics in fouling mitigation (Rahman *et al.* 2025).

The incorporation of cellulose as a membrane coating has a modifying effect by adding the hydroxyl groups from cellulose onto the PVDF membrane surface, thus improving wettability, at the same time increasing the surface roughness, and porosity, hence improving pure water flux performance. Some researchers have investigated that the arrangement of cellulose as a coating is important in regard to the direct contact of more hydroxyl groups of water molecules. This will inevitably affect the porosity and pore size of the cellulose coating. Therefore, the aggregation or disorder of cellulose has its limitation as a surface modification technique for PVDF hollow fiber membrane (Li *et al*. 2012; Medronho and Lindman 2014; Wang *et al*. 2021). The use of PVDF polymer as a binder for the cellulose coating could overcome this limitation. This provides good adhesion between the cellulose and the neat PVDF surface as binder. This will also ensure good coating stability for the cellulose due to binder chemical compatibility to the neat PVDF membrane. This concept of incorporating PVDF polymer as binder for cellulose coating applications stems from the development of Cellulose and PVDF composite membranes.

In a previous review paper, the evidence of incorporating various hydrophilic polymers and di-block amphiphilic copolymers as additives with PVDF polymer demonstrated great improvements in pure water flux performances and mechanical stability (Nyuk Khui *et al*. 2024). The incorporation of directly blending PVDF and cellulose together shows a rough and heterogenous surface characteristics. These agglomerate sites and larger pores that develop forms channels for better pure water permeability (Nyuk Khui *et al*. 2024). Numerous studies have shown good pure water flux performances of such composite membranes.

Coating application *via* phase inversion bath method is a simple but effective way to incorporate the cellulose hydrophilic properties onto the PVDF hollow fiber membrane (Varanasi *et al*. 2015; Nainar *et al*. 2020; Malucelli *et al*. 2021; Wang *et al*. 2021; Joshi *et al*. 2023; Bai *et al*. 2025).

While cellulose modification of PVDF membranes has been achieved through bulk blending and casting (phase inversion) methods, the dip-coating approach remains comparatively underexplored despite its unique advantages for surface-selective modification. Critical knowledge gaps persist regarding: (a) how coating-derived surface characteristics compare to bulk modification in terms of the flux-stability trade-off, particularly the transition from beneficial roughness to crack formation; (b) whether surface-localized cellulose can provide sufficient fouling resistance while preserving the PVDF matrix's mechanical integrity; and (c) the optimal coating parameters for performance optimization.

This work systematically addresses these questions this research is focused on the study and characterization of the pure water flux performance of Cellulose/PVDF coated membrane in comparison to the neat PVDF hollow fiber membrane sample.

EXPERIMENTAL

Materials

Bamboo fiber was collected from the Forest Research Institute, Sarawak, Malaysia. Hydrogen peroxide, Acetic acid, Titanium (IV) oxide, Sodium hydroxide, Toluene, Ethanol, PVDF hollow fiber membrane, PVDF powder, Lithium Chloride, N, N-Dimethylacetamide (DMAc) were obtained from Sigma Aldrich USA.

Methodology

Bamboo cellulose extraction for coating solution development

The extraction of bamboo cellulose was performed following the procedures according to Liew *et al*. (2015).

Dewaxing of Bamboo Fiber

About 400 mL of toluene and 200 mL of ethanol were mixed to obtain a toluene-ethanol ratio of 2:1. A Soxhlet extractor connected with a Liebig condenser was used for dewaxing purpose. Approximately 10 g of Green Bamboo Fiber (GBF) was scooped into a membrane tube and then placed into the extraction thimble. The toluene-ethanol solution was heated until it was visibly boiling above 110 °C. After 10 to 12 cycles of extraction *via* Soxhlet extractor, the resulting fiber was oven dried at 35 °C for 24 h. The dried sample is identified as Dewaxed Bamboo Fiber (DBF) Liew *et al.* (2015).

Delignification of Bamboo Fiber

Delignification solution consists of 82.3 g of 35 wt% hydrogen peroxide and 106.2 g of 99.8 wt% acetic acid with a small amount of titanium (IV) oxide as catalyst. This solution was used for the delignification of 30 g of DBF by heating at 130 °C. After 2 h, the solution was cooled to room temperature. The treated fiber was filtered and rinsed with deionized (DI) water until pH 7, followed by drying at 35 °C for 24 h. The dried sample was placed into a bottle and kept in a dark and cool place for alkaline treatment. The sample is identified as Delignified Bamboo Fiber (DLBF) Liew *et al.* (2015).

Fig. 1. Illustration of the extraction of bamboo cellulose from bamboo fiber.

Mercerization

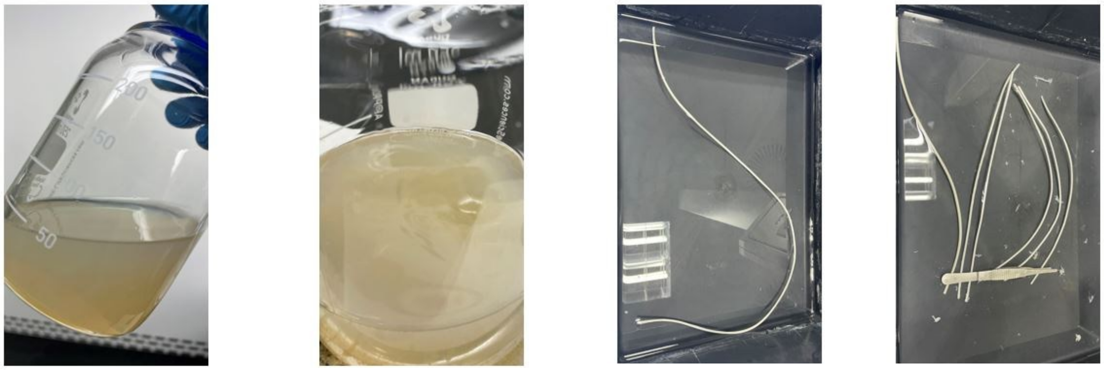
DLBF was mixed with a 6 wt% sodium hydroxide solution. The mixture is consistently stirred with a magnetic stirrer and heated to 80 °C for 2 h. After 2 h, the heating was stopped, and the mixture was allowed to cool to room temperature with stirring. The mixture was rinsed continuously with DI water until the product reached pH 7. The treated product was then filtered using a Buchner flask, rinsed with DI water until the pH level reached 7, and oven dried at 30 °C (Liew *et al.* 2015). The cellulose underwent ball milling for a total of 1.0 h until a fine powder was formed. The purpose was to assist the weighing and dissolution of cellulose during the development of the coating solution.

Cellulose/PVDF Coating Solution

Cellulose/PVDF dissolution for coating followed the same parameters according to Sadeghifar *et al*. (2019) using N,N-dimethylacetamide/lithium chloride (DMAc/LiCl). Firstly, (0.25 g) PVDF powder was dissolved in 42 g DMAc, making a PVDF/DMAc solution. Second, the desired amount of cellulose (0.25 g, 0.5 g, 0.625 g, 0.725 g, 1.0 g) and 3 g LiCl were added into the PVDF/DMAc solution. The mixture was heated up to 130 °C and stirred with a magnet bar. The temperature was maintained at 130 °C for 20 to 30 min until there was a visible dissolution. The mixture was allowed to cool down slowly and continuously stirred for 12 h at room temperature. The end product was the Cellulose/PVDF coating solution.

Coating of PVDF Hollow Fiber Membrane

The PVDF hollow fiber membrane coating follows the principle of dip coating time/process according to Wenten *et al.* (2020), where the membrane was dipped for 2 s and withdrawn from the solution for 10 s. A glass rod was used to remove excess coating solution to yield a thin layer coating. The coating membrane was immersed in a deionized water bath to allow the remaining solvent (DMAc) migration to water. The coated membrane was then taken out from the water bath and dried at room temperature. Once dried, the coated hollow fiber membrane can be used for application.



Synthesized Coating Solution of Cellulose/PVDF

Phase Inversion water bath technique for all Coated PVDF hollow fiber membrane

Fig. 2. Illustration of coating solution and coated PVDF membrane using synthesized Cellulose/PVDF coating solution

Pure Water Flux Performance Analysis

The pure water flux performance analysis was firstly conducted for 15 to 20 min at a functioning pressure 1.0 bar to achieve a stable pure water flux prior to the actual readings to be recorded. This allows the membrane sample to properly swell and drive the pure water to start permeating through the membrane sample. The actual pure water flux readings are recorded for a total of 1.0 h at the functioning pressure of 1.0 bar. The pure water flux is calculated according to the equation below:

$$Pure\ water\ flux, J_W = \frac{V}{(A \times \mathrm{T} \times \mathrm{P})} \tag{1}$$

where J_W denote Pure water flux (L/m^2/h/bar);

A: Effective area of membrane (m^2)
V: Pure water permeated volume (L)
T: Filtration time (h)
P: Functioning pressure (bar)

Fourier Transform Infrared Analysis

Fourier transform infrared (FTIR) spectroscopy was conducted (‘IRAffinity-1’ spectroscopy, Shimadzu, Kyoto, Japan) according to the ASTM E168-16 (2016) and ASTM E1252-98 (2013) standards for qualitative and quantitative analyses. The spectrum scanning was conducted in the wavenumber range of 4000 to 400 cm^{-1} for each sample.

Scanning Electron Microscopy of Membrane Samples

Scanning electron microscopy (SEM) for the samples was conducted (M-3030 Hitachi High-Technologies Europe GmbH, Krefeld, Germany) according to ASTM E2015-04 (2014) testing procedure. Magnifications of 500× and 1000× were utilized to observe the surface of the samples. A total of 6 samples were tested using SEM.

X-ray Diffraction Analysis

X-ray diffraction analysis (XRD) is used to verify the range of crystalline phases of the samples and to observe the availability of either a crystalline or amorphous phase. The membrane samples were analyzed at room temperature using a Rigaku Smart Lab Powder X-ray diffractometer (Rigaku Smart Lab, Tokyo, Japan) with CμKα radiation (λ= 1.5418 Å). The XRD analysis for the control and coated samples were recorded within a scattering angle (2θ) ranging from 5° to 90° at a scanning rate of 2 min^{-1}. This procedure was carried out in accordance with the ASTM F3419-22 (2022) standard.

Porosity and Mean Pore Size Analysis

The membrane samples porosity was determined using the gravimetric method based on equations below (Yuliwati *et al.* 2011; Rahman *et al.* 2024):

$$\boldsymbol{Porosity, \varepsilon} = \frac{\left(\frac{W_{wm} - W_{dm}}{\rho_{water}}\right)}{\left(\frac{W_{wm} - W_{dm}}{\rho_{water}}\right) + \left(\frac{W_{dm}}{\rho_{PVDF}}\right)} \qquad (2)$$

$$\boldsymbol{Porosity\ Percentage, \varepsilon}\ (\%) = \frac{\left(\frac{W_{wm} - W_{dm}}{\rho_{water}}\right)}{\left(\frac{W_{wm} - W_{dm}}{\rho_{water}}\right) + \left(\frac{W_{dm}}{\rho_{PVDF}}\right)} \times \mathbf{100} \qquad (\mathbf{3})$$

where W_{wm}: Weight of wet membrane (g); W_{dm}: Weight of dry membrane (g); ρ_{water}: Density of water (0.998 g/cm^3); ρ_{PVDF}: Density of PVDF polymer (1.740 g/cm^3)

The mean pore size of both control and coated sample was calculated following the Guerout-Elford-Ferry equation. The mean pore radius was obtained from equation (4), and the mean pore diameter was determined by multiplying the value of the mean pore radius by two,

$$\boldsymbol{Mean\ Pore\ Radius\ (m)} = \sqrt{\frac{(2.9 - 1.75\varepsilon) \times 8\eta LQ}{\varepsilon A(\Delta P)}} \qquad (4)$$

where ε is membrane porosity, η is water viscosity (0.00089 Pa·s), L is membrane thickness (m), Q is volume of water permeation per unit time (m^3/s), A is effective area of membrane (m^2), and ΔP is pressure applied (Pa).

$$\boldsymbol{Mean\ Pore\ Size\ (m)} = \mathbf{2} \times (\boldsymbol{Mean\ Pore\ Radius}) \qquad (5)$$

The equations used for porosity, mean pore radius and mean pore size analysis is based on pore volume or bulk measurement of pore available. In this research, the PVDF hollow fiber membrane porosity analysis is to identify the bulk measurement of pore available before and after coating.

RESULTS AND DISCUSSION

Table 1 showcases the sample name and their weights for developing the coating solution with the purpose of coating the control PVDF hollow fiber membrane A0. Coating development parameters and cellulose weights are generally based on the study by Sadeghifar *et al*. (2019), with a 3% lowest weight ratio done by the author. However, in this study, the weightage is reduced, as the coating solution shows a thickening effect at the highest cellulose content (1.0 g). Additionally, according to the study, the lowest weight ratio yields better membrane performance, hence conducting a study at even lower weightage may also yield better membrane performance (Sadeghifar *et al*. 2019).

Table 1. Sample Name and Weights Used for Developing the Coating Solution

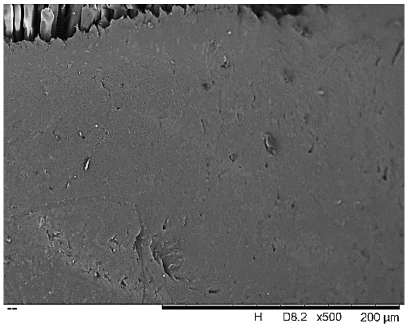
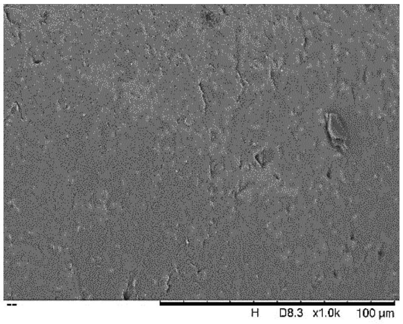
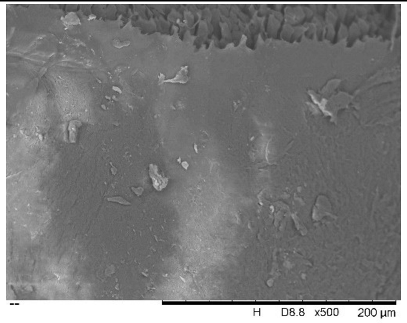
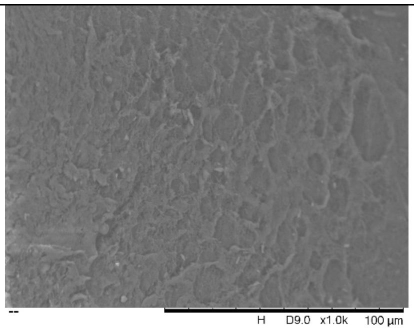
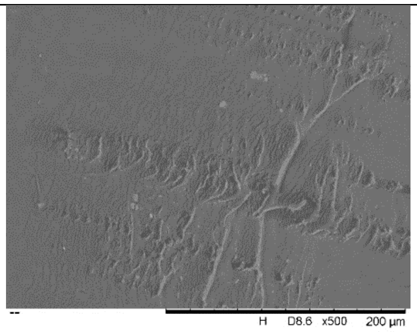
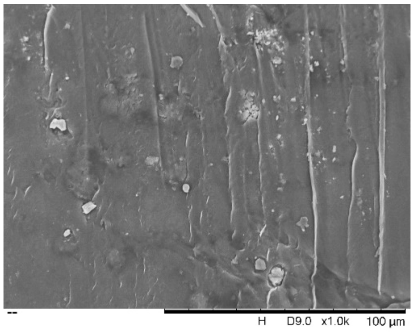
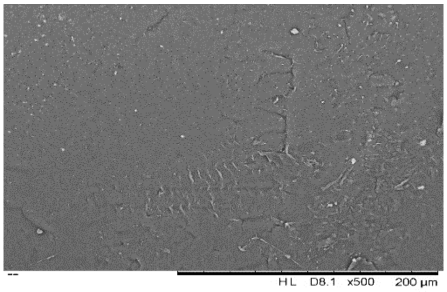
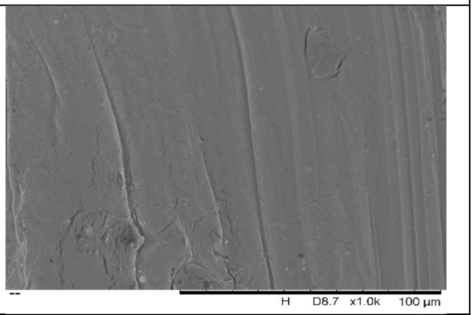
Sample Name	Cellulose Weight	PVDF Weight	DMAc Weight	LiCl Weight
A0 (control)	-	-	-	-
P01	0.250 g	0.25 g	42 g	3 g
P02	0.500 g	0.25 g	42 g	3 g
P03	0.625 g	0.25 g	42 g	3 g
P04	0.725 g	0.25 g	42 g	3 g
P05	1.000 g	0.25 g	42 g	3 g

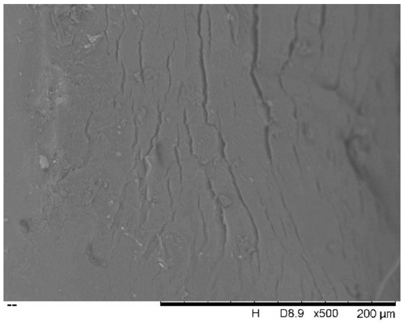
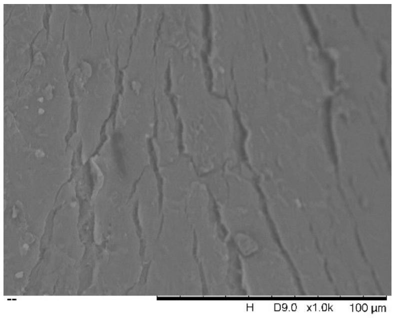
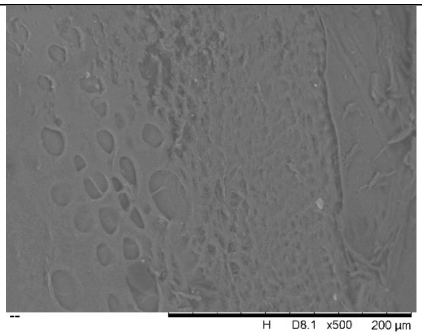
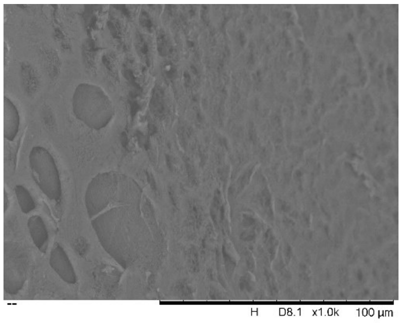
Scanning Electron Microscopy

Table 2 showcases the SEM at 500× and 1000× magnifications for the control PVDF hollow fiber membrane A0 and Cellulose/PVDF coated samples P01, P02, P03, P04, and P05. It could be observed that A0 has a surface structure which is generally smooth and compact with minimal visible pores. This result matches few studies in regard to neat PVDF, where water flux or permeability of the membrane is lower as compared to modified PVDF membrane (Bai *et al*. 2012; Ma *et al*. 2017). P01 and P05 surface structures may share some similarity with rough and non-uniformity with visible pores and voids, however in respect to the pure water flux performance, P01 has the higher pure water flux in comparison to P05. Hence, P05 surface structure may be the result of a thicker coating because of the higher cellulose content of 1.0 g (Ma *et al*. 2017). It is also possible that the 0.25 g PVDF weight in the coating solution may not be able to be a suitable binder when cellulose weight is above 100% of PVDF binder content. P02 surface structure shows more rougher surface structure with visible coating lines, it could be indicative that the rougher surface may bring better pure water flux performance, as P02 has the best pure water flux performance among all coated samples (Ma *et al*. 2017; Koriem *et al*. 2022).

P03 and P04 show signs of cracking with P04 being the sample with mostly cracking surface structure, no visible pores or voids are observed as compared to the rest of the samples. P03 and P04 have similar coating lines at P02 which could be indicative that cellulose above 0.25 g may yield cleaner coating layer. In relation to pure water flux performance, P03 and P04 are the first to show signs of reduced pure water flux, followed by P05 being the lowest among the coated samples (Ma *et al*. 2017; Koriem *et al*. 2022).

Table 2. SEM of Cellulose/PVDF coated PVDF Hollow Fiber Membrane and Control Sample

Sample	500x Magnification	1000x Magnification
A0		
P01		
P02		
P03		

P04		
P05		

FTIR Analysis

According to the FTIR analysis for Cellulose/PVDF coated fiber membrane and control sample, it could be observed that there is a visible difference in peak intensity between coated samples and the control. Peaks labelled as control is truly a neat sample of PVDF hollow fiber membrane. The control sample shows an identifiable at C-H stretching region with bands located at 3371.56 and 2931.80 cm^{-1}, this is indicative of $–CH_2$ groups for PVDF. Another characteristic region at the C-F stretching region with band located at 1174.65 and 1107.14 cm^{-1}, the intense stretching and peaks at the C-F stretching region is one of the key areas to identify the existence of PVDF in the PVDF hollow fiber membrane sample tested.

Regarding the Cellulose/PVDF coating on PVDF hollow fiber membrane, the characteristic peaks were the board and gradual bands of O-H stretching at 3700 to 3000 cm^{-1}, which are indicative of hydroxyl groups addition of cellulose on the sample. As more cellulose is incorporated, some samples indicated increased in intensity and the higher weights seem to have a masking effect to the PVDF. In the C-O and C-F stretching regions, the Cellulose/PVDF coated samples showed board peaks indicative of PVDF between the 1170 to 840 cm^{-1} region, and cellulose at the 1124 to 1087 cm^{-1} region (Kang *et al*. 2016). A study on PVDF composite membranes blended with nano-crystalline cellulose showcase similar FTIR results for cellulose availability at the 1124 to 1087 cm^{-1} region and as well as the 3700–3000 cm^{-1} O–H stretching region (Mohammadpour *et al*. 2024). Overall, it is shown that, there is evidence of cellulose addition in the samples tested, which demonstrates the successful Cellulose/PVDF coating on neat PVDF hollow fiber membrane.

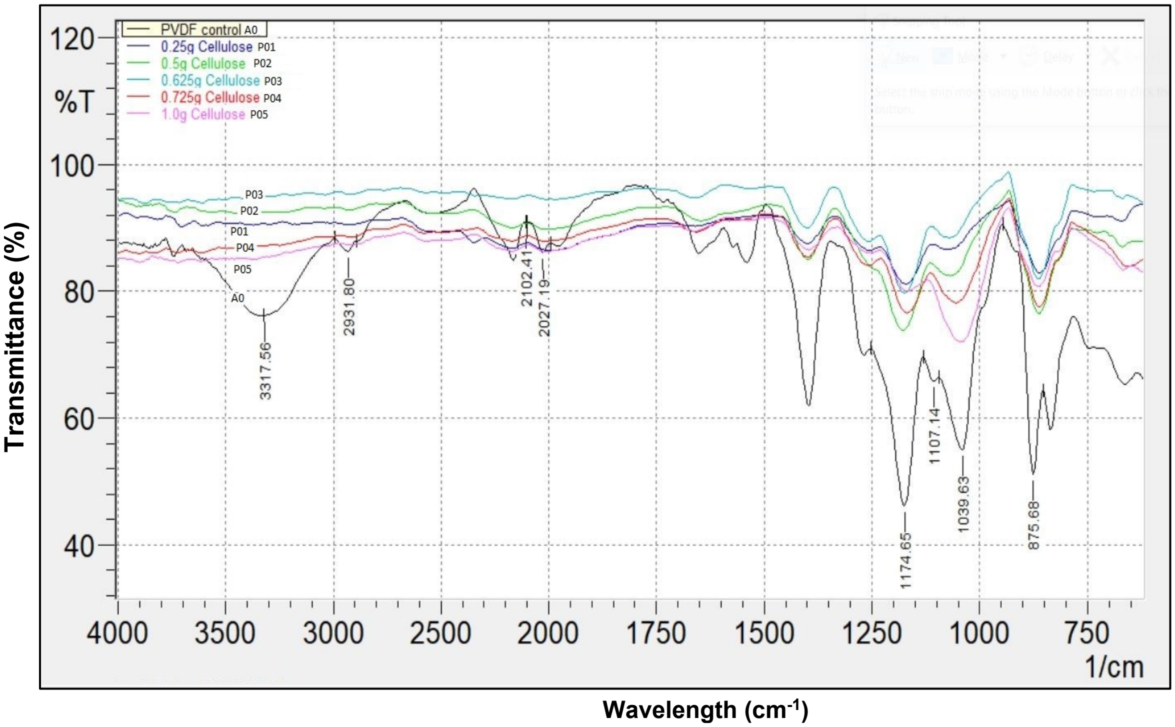


Fig. 3. FTIR for Cellulose/PVDF coated PVDF hollow fiber membrane and Control samples

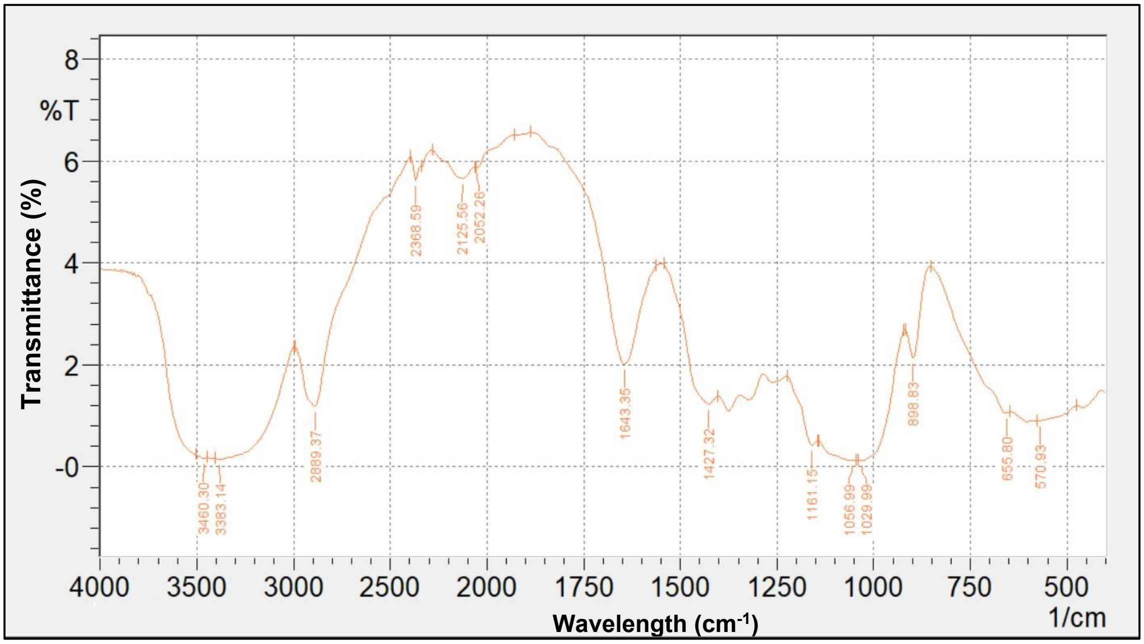


Fig. 4. FTIR for Extracted Cellulose from Bamboo Fiber

The FTIR results shown in Fig. 4 show the extracted cellulose with similar graph patterns and functional groups of a successfully extracted cellulose. According to Liew *et al*. (2015), the functional group at 1514 cm^{-1} is attributed to the C=C stretching vibration in the aromatic ring of lignin. The extracted cellulose in Fig. 4 did not show this stretching, which indicates that lignin was removed during the extraction process (Liew *et al*. 2015). The broad and intense peaks observed at 3460 and 3383 cm^{-1} resemble the O–H stretching vibrations indicating the presence of hydroxyl groups. The peak at 2889 cm^{-1} is attributed to C–H stretching, while the band at 1427 cm^{-1} is associated with $–CH_2$ bending vibrations. The intense peak at 1643 cm^{-1} corresponds to the H–O–H bending vibration of adsorbed water in carbohydrates, and the peak at 1029 cm^{-1} is related to C1–H deformation vibrations characteristic of cellulose. These results for the extracted cellulose from bamboo fiber match the results according to Liew *et al*. (2015). Other studies also match these results in regard to available functional groups for a successfully extracted cellulose (Abderrahim *et al.* 2015; O'Brian *et al.* 2022; Weng *et al.* 2015).

Pure Water Flux

The pure water flux test was conducted using pure deionized water for all developed Cellulose/PVDF coated fiber membranes comparing with the neat PVDF hollow fiber membrane as control. The pure water flux test was conducted at 1.0 bar functioning pressure for the total time of 1.0 h/sample. It could observe that all the Cellulose/PVDF coated fiber membranes have increased flux performance in comparison to the control pure water flux of 157.8864 L/m^2/h/bar. P02 achieved the highest pure water flux at 483.8453 L/m^2/h/bar followed by P01 at 432.9142 L/m^2/h/bar and then drops in performance starting from P03, P04, and P05, respectively. It could be stated that the optimal weight of cellulose content is 0.5 g for P02 as the highest pure water flux was achieved at this weight. The pure water flux performance for the best performing coated membrane sample P01 and P02 is comparable to other studies which uses also PVDF and Cellulose. The addition of cellulose at 1% weight increases the pure water flux of the PVDF/Cellulose membrane from 17.08 to 31.07 m^2/L/h almost 2 times in comparison to the control PVDF (Trisnawati *et al*. 2024).

In this study P01 and P02 exhibited pure water flux increases up to 3 times in value compared to the control sample. Another study also has similar results with the use of cellulose acetate and cellulose nanocrystals doped onto PVDF. The researcher found the incorporation of cellulose doped onto PVDF has improved water flux performance up to 2-3 times in comparison to the control. It was the increased porosity, pore size, and hydrophilic behavior attributed to the cellulose that help modify and improve the PVDF water flux performance (Bai *et al*. 2025).

Table 3. Pure Water Flux Performance Data for Control and Coated Samples

	Sample (0.25 g PVDF Powder)	Pure water flux (L/m^2/h/bar)
A0	PVDF (Control)	157.8864
P01	Cellulose 0.25 g	432.9142
P02	Cellulose 0.5 g	483.8453
P03	Cellulose 0.625 g	388.6042
P04	Cellulose 0.725 g	249.5623
P05	Cellulose 1.0 g	180.8053

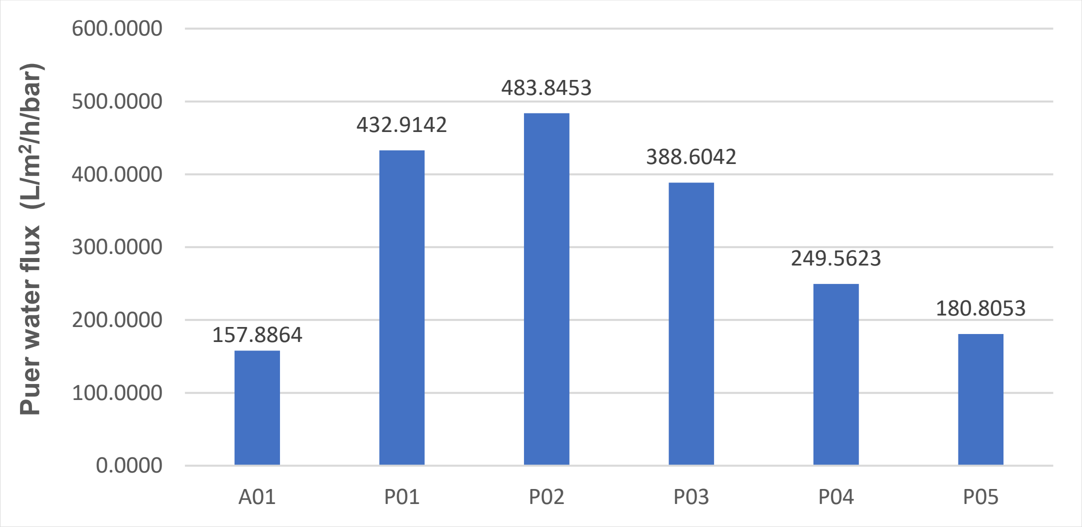


Fig. 5. Graph visualizations of pure water flux performances for control and coated samples.

Porosity Analysis

Table 4 shows the porosity and means pore size analysis for the control PVDF and Cellulose/PVDF coated fiber membrane samples. It was observed that all coated samples exhibited an increase in porosity and mean pore size values. The porosity has increased from 69.38% to 72.33% for P01 and 70.93% for P02 for the two best pure water flux performance membranes which are coated with Cellulose/PVDF. It was also observed that the mean pore size increased from 0.0203 to 0.0376 and 0.0378 for P01 and P02 respectively. The increased mean pore size improves the pure water to permeate through membrane, as evidently shown in Tables 3 and 4 regarding the results for P01 and P02.

Reducing the mean pore size may contribute to the reduced pure water flux performance for samples P03 to P05. As the membrane swells, in combination with a smaller mean pore size, a clogging effect takes place and reduces the available spaces for the pure water to permeate (Trisnawati *et al*. 2024). It seems that the higher the porosity, it is likely the swelling takes place and hinder the pure water flux performances. One study also demonstrates a similar scenario with Polyvinylpyrrolidone (PVP), cellulose nanocrystals with PVDF samples having high porosity and reduced pore size that indicate a correlation towards reduction in pure water flux performance. Some researchers HAVE managed to develop the PVDF membrane with 54.57% porosity and was able to increase the porosity to 67.78% with the incorporation of 0.5 wt% cellulose nanocrystals with PVDF and PVP as membranes (Acarer Arat *et al*. 2025).

Table 4. Characteristic Porosity and Mean Pore Size of Control and Coated Samples *via* Gravimetric Method

Sample (0.25g PVDF Powder)		Porosity (%)	Mean Pore Size (μm)
A0	PVDF (control)	69.38	0.0203
P01	cellulose 0.25g	72.33	0.0376
P02	cellulose 0.5g	70.93	0.0378
P03	cellulose 0.625g	75.83	0.0304
P04	cellulose 0.725g	74.77	0.0279
P05	cellulose 1.0g	79.32	0.0275

XRD Analysis

Figures 6 and 7 shows that the XRD graphs for Cellulose/PVDF coated PVDF hollow fiber membrane and control sample shows a difference in intensity illustrating the addition and availability of cellulose on the coated PVDF hollow fiber membrane.

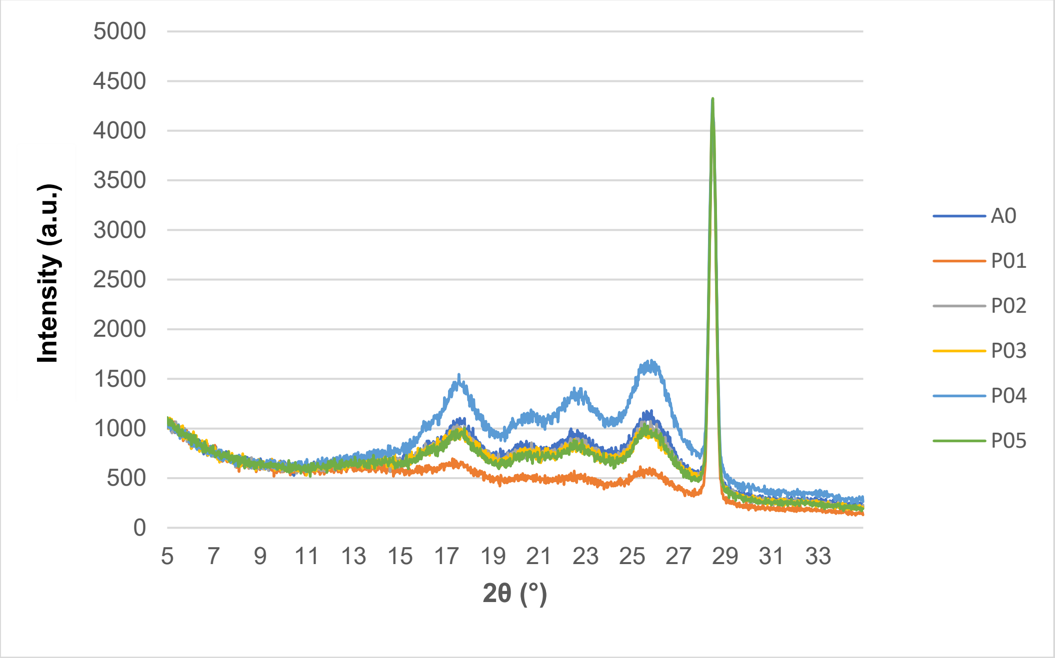


Fig. 6. The combines XRD graph for Cellulose/PVDF coated PVDF hollow fiber membrane and control sample

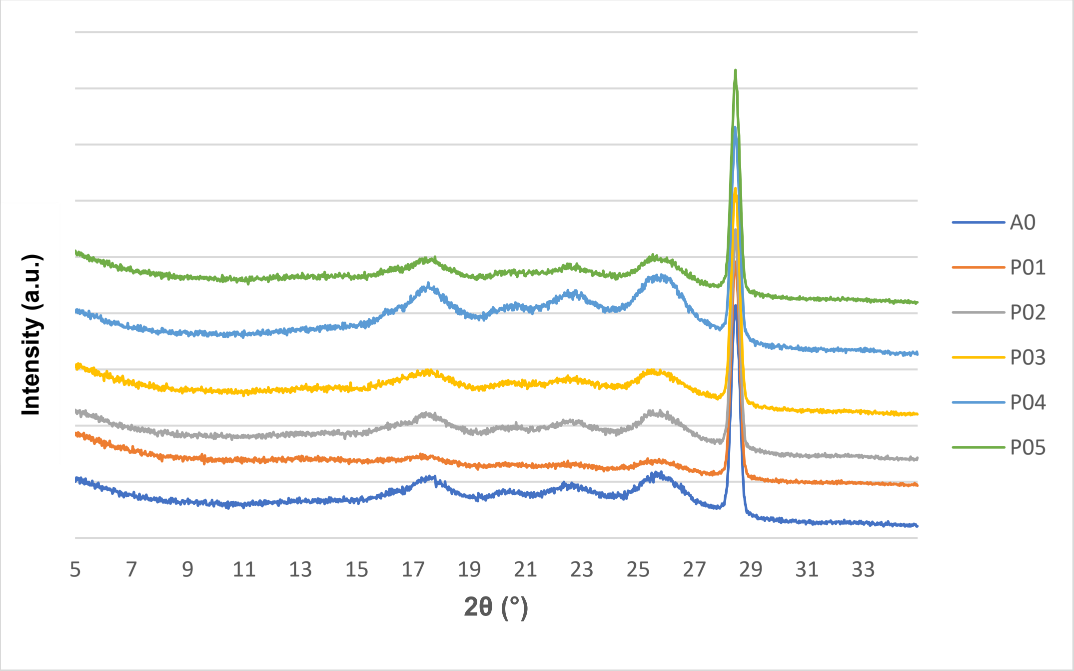


Fig. 7. The stacking XRD graph for Cellulose/PVDF coated PVDF hollow fiber membrane and control sample

Membrane analysis using XRD helps to identify the range of phases between amorphous and crystallinity regions of the membrane. This will showcase the evidence of improved pure water flux performance, as amorphous phase for water filter membranes is related to improved pure water flux performance because of hydrophilic behaviors, and more crystalline phase is related to lower pure water flux performance and hydrophobic behaviors (Yuan *et al*. 2020; Acarer-Arat *et al*. 2024). In the combined XRD graph, it could be observed that the control sample shows peaks indicative of a semi-crystalline neat PVDF membrane material similar to other studies with neat PVDF as a control (Ma *et al*. 2017; Yuan *et al*. 2020; Acarer-Arat *et al*. 2024). The main peaks at "2*θ* (°)" of PVDF control sample are within the 18º, 20º, 26º, and 28° marks. Sharper and intense peaks observed are signs of the membrane crystallinity phase (Bai *et al*. 2012; Ma *et al*. 2017; Yuan *et al*. 2020; Acarer-Arat *et al*. 2024).

The XRD graphs reveal that the addition of cellulose showcases peaks at similar regions as the main material PVDF hollow fiber membrane. All the coated samples indicated lower intensity in comparison to the control. The peaks are noticeably broader with moderate peaks, which show evidence of the coating on the membrane has modified to an amorphous phase (Ma *et al*. 2017; Yuan *et al*. 2020; Acarer-Arat *et al*. 2024). The pure water flux results obtained with coated samples show a modification from a semi-crystalline phase to an amorphous phase that brings improved pure water flux performance.

CONCLUSIONS

1. The use of a surface modification technique using cellulose/poly(vinylidene fluoride) (PVDF) as a phase inversion coating on neat PVDF hollow fiber membrane was successful, as revealed in the scanning electron microscope (SEM), Fourier transform infrared (FTIR), and X-ray diffraction (XRD) analyses.
2. In comparison to the control, the coated samples increased the pure water flux performance by up to 3 times the value for samples P01 and P02, which were the best performing membranes.
3. The correlation between cellulose weight, porosity, mean pore size, and pure water flux was apparent where the increased porosity with smaller mean pore size influences the permeability of the coated membrane samples. Hence, there was a gradual reduction in pure water flux performance with increased cellulose content.

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