Bamboo-Derived Cellulose Polyvinylidene Fluoride Nanocomposite Membranes for Enhanced Hydrophilicity and Dye Removal Performance

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The increasing global demand for freshwater and the growing issue of water pollution, particularly from industrial sources, motivates efforts to develop more effective wastewater treatment technologies. This research focuses on developing polyvinylidene fluoride (PVDF) membranes enhanced with bamboo-derived cellulose nanocomposites for dye removal. The study aimed to overcome the hydrophobic limitations of PVDF membranes by incorporating cellulose, which is known for its hydrophilic and dye adsorption properties. The membranes were fabricated using different cellulose contents (2% to 6%) and characterized using Field Emission Scanning Electron Microscopy (FESEM) and Fourier-Transform Infrared Spectroscopy (FTIR). The membranes' performance was assessed through water contact angle (WCA), water permeation flux and dye rejection tests. Results indicated that increasing cellulose concentration improved membrane porosity, water permeability, and dye rejection capabilities. The 6% cellulose membrane demonstrated low water contact angle value with highest water flux with 317.95 L/m²h and dye rejection of 51% after 10 min, stabilizing at 41% after 70 min. This enhancement was attributed to cellulose's hydrophilic nature and ability to form hydrogen bonds with dye molecules, thereby improving dye removal efficiency. This study demonstrates the potential of cellulose-enhanced PVDF membranes for industrial wastewater treatment, offering a scalable, sustainable solution to mitigate water pollution and promote environmental sustainability.

DOI: 10.15376/biores.21.4.10149-10165

Keywords: Emission scanning electron microscopy; Fourier-transform infrared spectroscopy; Water permeation flux; Dye rejection; Hydrophilic; Dye adsorption

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INTRODUCTION

Freshwater demand is increasing annually. Global freshwater withdrawal was 3,790 km^3/year in 1995, which increased to 4,430 km^3/year in 2000. Researchers anticipated that the demand would rise to 5,240 km^3/year by 2025. The rise in water demand is attributable to heightened consumption resulting from the lifestyle of communities, including agricultural, residential, and industrial needs. Additionally, water demand is influenced by economic development, wealth, cultural values, and local climate (Kuok *et al*. 2024a). Of all the water on Earth's surface, only three percent (3%) constitutes fresh water, and only 0.06% is readily accessible (Kuok *et al*. 2018; Musie and Gonfa 2023).

The growth of the human population has resulted in an escalation of human activities, some of which may adversely affect the environment, especially the contamination of water resources (Schwarzenbach 2006; Kuok *et al*. 2024b). Water pollution significantly impacts all organisms, including humans, as all living things depend on water for survival (Inamuddin 2019; Mersal *et al*. 2024). Annually, it is estimated that around 14,000 human lives are lost owing to fatalities and illnesses associated with water pollution (Chaudhry and Malik 2017; Kuok *et al*. 2022).

Industrial wastewater is the primary cause of direct water contamination (Kanu *et al*. 2011; Kuok *et al*. 2018). The textile industry is one of the sectors that negatively affects the environment (Ahmed *et al*. 2020). The textile sector is thriving in Bangladesh (Maiko Sakamoto *et al*. 2019) and in Türkiye (Neşe Tüfekçi *et al*. 2007). The untreated effluent from textile industries contains heavy metals and dyes, posing a considerable environmental risk. The untreated industrial effluent would significantly harm the ecosystem and the health of individuals residing near the contaminated river and those reliant on the river for their livelihoods (Sakamoto *et al*. 2019). Therefore, an appropriate treatment system is essential to purify the contaminated water prior to its discharge into the environment.

Recently, membrane technology has garnered the attention of researchers, who have been particularly fascinated by its capacity to eliminate dye from water (Ahmad *et al*. 2002; Moradihamedani 2021). Membrane technology is effective in dye removal, exhibits low operational costs, consumes minimal energy, offers straightforward operation, eliminates the need for additional chemicals, and necessitates less space for wastewater treatment compared to conventional systems. One of the materials that could be used to produce membranes is polyvinylidene fluoride (PVDF). PVDF has a semi-crystalline structure. It possesses substantial mechanical strength, superior thermal and chemical stability, and remarkable resistance to aging (Mat Nawi *et al*. 2020; Tian *et al*. 2020). Despite the numerous advantages of PVDF membrane, it has a notable drawback. PVDF is inherently hydrophobic, hence limiting dye absorption and overall efficacy in dye removal.

The hydrophilicity and dye adsorption capabilities of PVDF membranes can be significantly enhanced by including cellulose. The hydroxyl groups in cellulose can establish hydrogen bonds with dye molecules, aiding in their extraction from aqueous solutions. Cellulose is extracted from plant cell walls and is renowned for its natural biodegradability, renewability, and hydrophilicity. Nanocellulose has become more popular as a membrane material because it enhances filtering properties such as pore size, porosity, and wettability (Tan *et al*. 2020).

While cellulose/PVDF composite membranes have been reported (James *et al*. 2024; Khui *et al.* 2025; Namakka *et al.* 2023; Rahman *et al.* 2025; Sueraya *et al.* 2025), this study employs cellulose extracted from bamboo species indigenous to Borneo Island, a renewable biomass source high potential physicochemical properties and membrane-forming characteristics. The study further establishes mechanistic correlations between cellulose-induced morphological changes such as surface roughness, pore formation, and interconnectivity with membrane performance metrics including hydrophilicity, water flux and dye rejection, providing a structure-property framework for rational membrane design.

The use of Borneo bamboo addresses the growing interest in utilizing under-exploited biomass resources for sustainable membrane technology development providing sustainable alternative to conventional cellulose sources.

METHODOLOGY

PVDF and NMP solvent were purchased from Sigma Aldrich, while cellulose was extracted in the laboratory. Bamboo samples (species *Bambusa vulgaris*) were collected from local plantations in Sarawak, Borneo Island. The extraction procedure followed a modified alkaline and bleaching process. Dried bamboo culms were ground into fine powder (particle size < 250 µm) using a planetary ball mill. The powdered biomass was treated with 4 wt% sodium hydroxide (NaOH) solution at 80 °C for 2 hours under continuous stirring at 300 rpm to remove lignin and hemicellulose. The residue was washed with distilled water until neutral pH was achieved. The resulting holocellulose was bleached using a 1:1 (v/v) mixture of sodium chlorite ($NaClO_2$, 1.7 wt%) and acetic acid buffer (pH 4.8) at 70 °C for 1 hour. The bleaching cycle was repeated three times to obtain purified cellulose. The final cellulose product was filtered, washed extensively with distilled water, and dried for 24 hours. The extracted cellulose was stored in a desiccator prior to membrane fabrication.

Bamboo Cellulose Polyvinylidene Fluoride Membrane Preparation

About 34 g of NMP solvent was measured and transferred into a laboratory glass container. As indicated in Table 1, a specified percentage of cellulose (1% to 6%) was added to the laboratory glass bottle containing 100 mL NMP solution. The solution was stirred for 24 h at 200 rpm at a temperature of 100 °C following the procedure described in (Namakka *et al.* 2026a,b; Rahman *et al.* 2026) with the following modifications. Briefly, the nanocomposite solution, approximately 10 mL, was cast onto a clean glass plate using a manual casting rod to achieve a membrane thickness ranging from 150 to 180 µm after drying. The casting was performed at 25 ± 2 °C. The membrane films were immediately immersed in a coagulation bath containing ultra-pure water at 25 °C for 24 h to induce phase inversion and complete solvent exchange. The membranes were subsequently rinsed with ultra-pure water to eliminate residual NMP solvent and stored for further characterization.

Table 1. Composition of PVDF and Cellulose for Different Membranes

Membrane Sample	PVDF (g)	Percentage of Cellulose (%)	Mass of Cellulose (g)
1	6	2	0.12
2	6	3	0.18
3	6	4	0.24
4	6	5	0.30
5	6	6	0.36
Pristine	6	0	0.00

Bamboo Cellulose PVDF Membrane Characterization

The developed bamboo cellulose PVDF membrane was characterized using field emission scanning electron microscopy (FESEM) and Fourier-transform infrared spectroscopy (FTIR). The membranes' functionality and efficacy were tested through a water permeation flux test and dye rejection analysis.

FESEM analysis

Field emission scanning electron microscopy (FESEM) was utilized to examine the structure of the nanocomposite membrane in terms of surface and cross-section. The study was done utilizing the Jeol FESEM equipment with a magnification of 2,000 for the surface of the membrane and two magnifications of 5,000 and 10,000 for the membrane cross-section. The membrane was sliced into tiny rectangular fragments for surface morphology and covered with gold to facilitate sample imaging. Additionally, the cross-section of the membrane sheet was gold-coated to improve the picture quality.

Fourier transform infrared spectroscopy

FTIR 'IRAffinity-1' spectroscopy manufactured by Shimadzu, Japan, was used to determine the functional groups and structures by examining IR spectra bands ranging from 4000 to 400 cm^{-1}. For ATR-FTIR, a 1 × 1 cm solid membrane sample was cut and placed on the crystal holder. The rotating wedge was used to push the specimen and crystals down, verifying that they had made contact. The qualitative and quantitative components of the spectrum of FTIR were evaluated using the ASTM E1252-98 (2021) and ASTM E168-16 (2016) standards.

Membrane hydrophilicity analysis

The surface hydrophilicity of the bamboo cellulose membranes was performed via static water contact angle (WCA) utilizing the sessile-drop methodology on an Ossila contact angle goniometer with ultrapure water serving as the probing liquid (Namakka *et al.* 2026c). To account for inherent surface heterogeneity, independent measurements were randomly acquired from three discrete locations on each specimen. The temporal dependence of the WCA was also systematically monitored. The contact angles reported herein correspond to the arithmetical mean derived from these replicated readings, thereby ensuring a rigorous characterization of the macroscopic wetting behaviour.

Membrane water permeation flux test

The membrane permeation test was done by using a methylene blue dye solution. Inflow was pumped to the membrane filtration system. The bamboo cellulose PVDF membrane sheets prepared previously were placed into a membrane filtration system to filter the inflow. Once filtered through the membrane, the treated water flowed out as permeate.

The water flux analysis of the membrane was conducted by pumping ultra-pure water into the membrane system with a pressure of 2 bar for 30 min to stabilize the membrane filtration system. Then, the test was continued by changing the pressure from 2 bar to 1 bar for another 30 min, and the results were recorded at intervals of 10 minutes. This procedure was repeated five times for an accurate reading, and the results were analyzed. The water permeation flux caused by the treated membrane implantation was determined by measuring the proportion of permeate volume to permeation time using Eq. 1 (Khansanami and Esfandiar 2021). Every membrane material was subjected to 5 permeability flux tests to establish an average and standard deviation,

$$J_W = \frac{V}{A \text{ X } \Delta T} \tag{1}$$

where J_W is the pure water permeation flux (L/m^{2}h), V is permeate volume (m^3), A is the effective area of membrane (m^2), and ΔT is the filtration time (h).

Membrane Dye Rejection Analysis

This study used two ppm MB dye as a specimen for the membrane's rejection test. The starting level of dye was measured using a UV-160 UV-Vis-NIR spectrophotometer developed by Shimadzu Scientific Instruments, Inc., Tokyo, Japan. About 1000 mL of 2.0 ppm MB dye solution was added into the solution's tank, and the pressure on the membrane was set to 1 bar at ambient temperature. The permeate (JMB) was gathered, and the amount was measured every 10 min for a period of 70 min. The dye rejection ratio (R) was determined using Eq. 2 (Pramono *et al*. 2023). Every membrane sample was subjected to 5 dye rejection tests to determine its average and standard deviation,

$$R\% = (1 - \frac{C_f}{C_i}) \times 100 \tag{2}$$

where R is the dye rejection ratio (%), C_f is the final MB dye concentration (mg/L), and C_i is the initial MB dye concentration (mg/L).

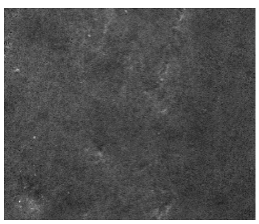
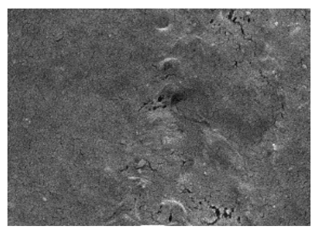
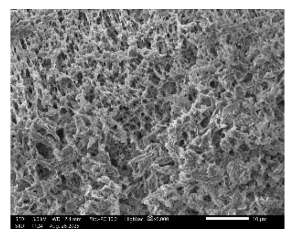
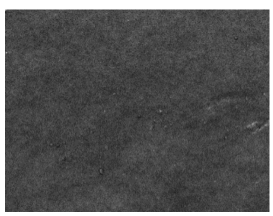
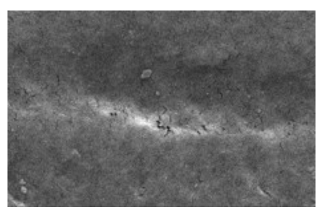
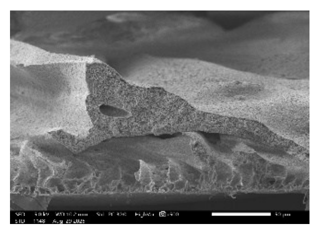
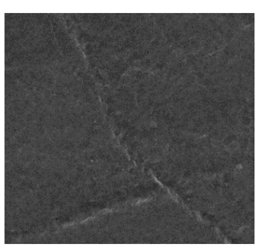
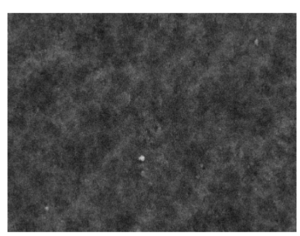
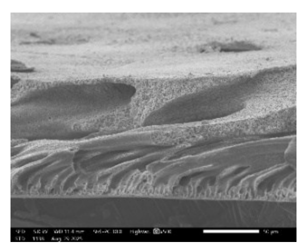
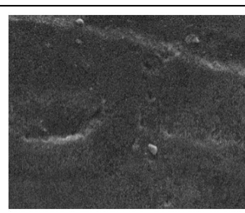
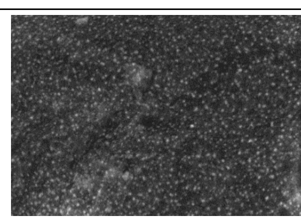
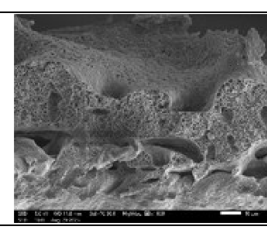
RESULTS AND DISCUSSION

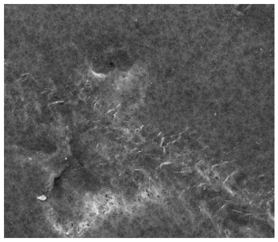
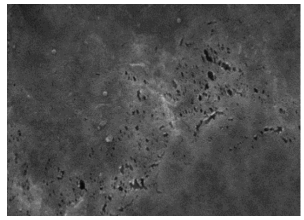
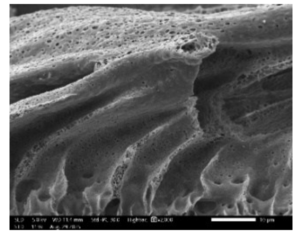
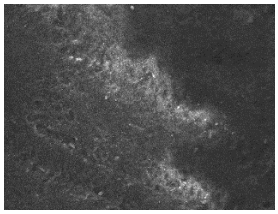
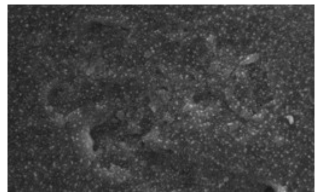
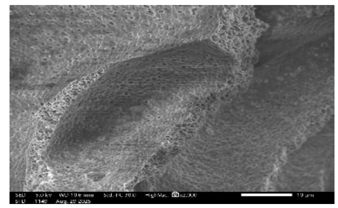
FESEM Analysis of the Membrane

Table 2 shows the FESEM analysis results for the pristine and bamboo cellulose PVDF membranes with 2%, 3%, 4%, 5%, and 6% cellulose. Based on the surface morphology of the membranes, no cracks were observed on 2% cellulose, while 3% and 4% cellulose gave rise to minimal cracks on the membrane surface. According to Bortot Coelho *et al*. (2021) and Robert *et al*. (2020), a combination of chemical and mechanical stress can increase membrane degradation, which leads to cracking. It is also possible that the membrane surface cracking is due to the drying process of the membrane or the vacuum environment in the FESEM machine (Rudolph *et al*. 2021).

The cross sections of the membrane were conducted at two magnifications of ×5,000 and ×10,000 for analysing the membrane pores and the agglomeration in the pores. Based on membranes with increasing cellulose concentration from 2%, 3%, 4%, 5%, to 6%, cellulose exhibits a progressive shift in internal structure (refer to Table 2). The membranes appeared to be more porous as the cellulose concentration increased, implying that cellulose addition affects pore development and total porosity of the PVDF membrane. Some aggregation or dispersion patterns of cellulose inside the PVDF matrix was visible. Membranes with a greater cellulose concentration (*e.g.*, 5% and 6%) showed a more uniform or dense cellulose distribution, resulting in brighter spots or distinct phases than the pristine membrane. Higher cellulose content led to increased surface roughness and larger pore sizes, which created voids or channels within the membrane. Higher cellulose concentration resulted in more well-defined and linked pores, contributing to the membrane's increased permeability and adsorption capabilities and generating a more hydrophilic surface to remove methyl blue dye more effectively. In this study, membranes containing up to 6% cellulose operated optimally, balancing dye removal efficiency and mechanical robustness.

Table *2.* FESEM Analysis Surface and Cross-sections of the Membrane Materials

Cellulose content	Surface 5000x magnification	Surface (10000x magnification)	Cross Section
Pristine			
2%			
3%			
4%			

5%			
6%			

Fourier Transform Infrared Spectroscopy (FTIR) Analysis

Figure 1 shows the FTIR spectra of the primary materials that were used in fabricating Pristine and bamboo cellulose PVDF membranes. Based on the analysis in Fig. 1(a), the peaks detected at the wavenumbers 875.7 cm^{-1} and 1180.4 cm^{-1} revealed the stretching vibration of C-C and CF_2 of PVDF (Kartohardjono *et al*. 2023). The appearance of the peak at 1396.5 cm^{-1} signified the bending vibration of CH_2 in the PVDF polymer (Omar *et al*. 2023). The peaks became more pronounced in Figs. 1b to 1f when incorporating both PVDF and cellulose into the PVDF matrix, resulting in enhanced interaction and improved structural integrity.

All nanocomposite membranes exhibited distinct bands at 875.7 cm^{-1}. These peaks corresponded to the robust vibrational bands characterizing the β phase of PVDF. Figures 1(a) and 1(b) exhibit a broad peak spanning from 3772 to 3417 cm^{-1} in an FTIR spectrum, which is likely associated with O-H stretching vibrations (Ng *et al*. 2021; James *et al*. 2023; James *et al*. 2024). This broad peak is characteristic of hydrogen-bonded hydroxyl groups, which can be found in cellulose and potentially in the PVDF if any moisture or other functional groups are present.

A peak around 2164 cm^{-1} in an FTIR spectrum is commonly associated with the stretching vibration of a C≡C or C≡N triple bond. In the bamboo cellulose PVDF membrane context, this peak indicates the presence of cyano groups (C≡N) if they are part of the cellulose or any other component in the membrane. It could also indicate the presence of acetylene (C≡C-H) groups. Alternatively, this peak might represent potential contaminants or residues from the synthesis or processing of the membrane.

In the FTIR result shown in Figs. 1(b) to 1(f), a peak around 1396 cm^{-1} in an FTIR spectrum is shown. It is typically associated with the bending vibrations of C-H bonds, but it also can be attributed to deformation or scissoring vibrations. This peak indicates the presence of cellulose, as it is often linked to C-H bending vibrations within the glucose units of the cellulose polymer.

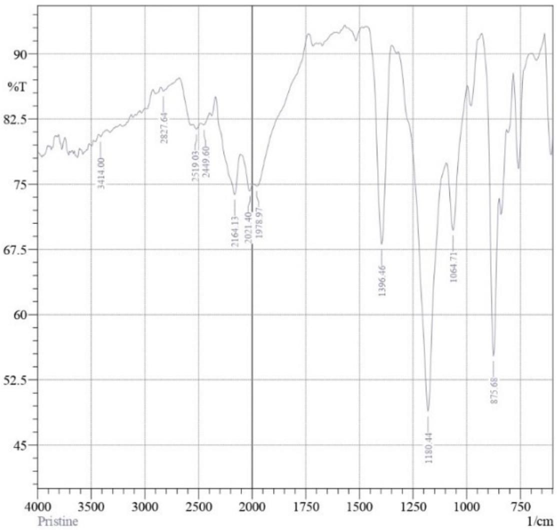


Fig. 1a. FTIR spectra of Pristine membrane

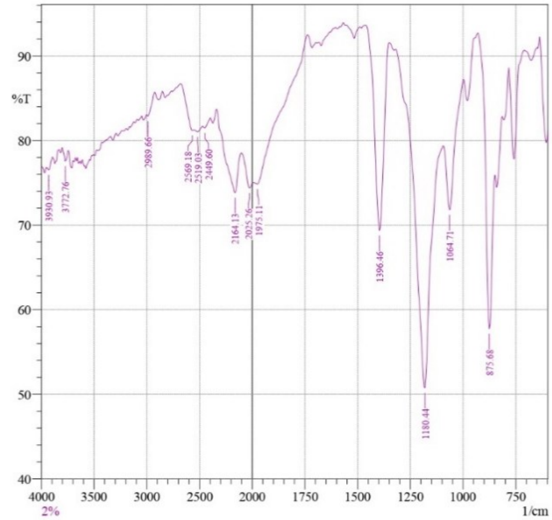


Fig. 1b. FTIR spectra of 2% bamboo-cellulose PVDF membrane

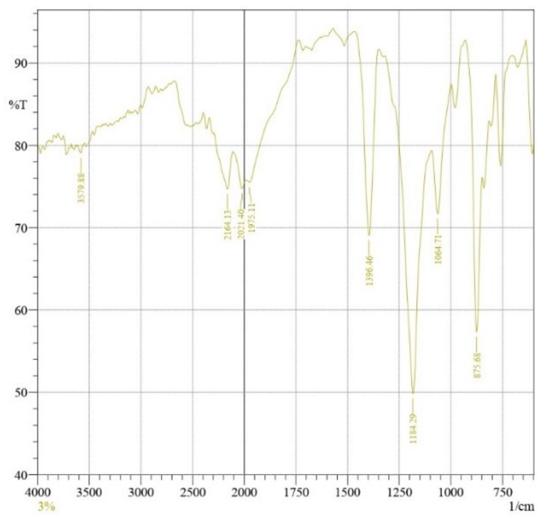


Fig. 1c. FTIR spectra of 3% bamboo-cellulose PVDF membrane

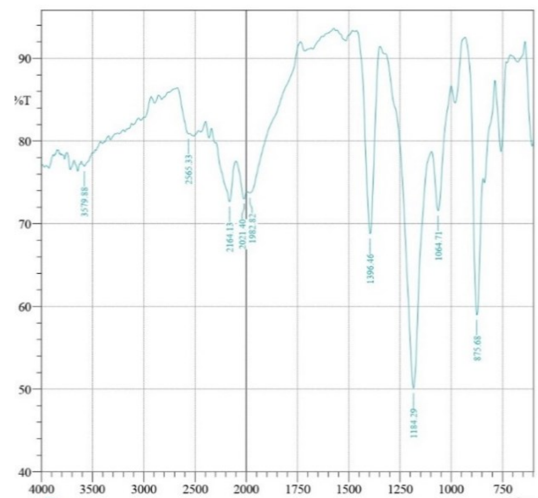


Fig. 1d. FTIR spectra of 4% bamboo-cellulose PVDF membrane

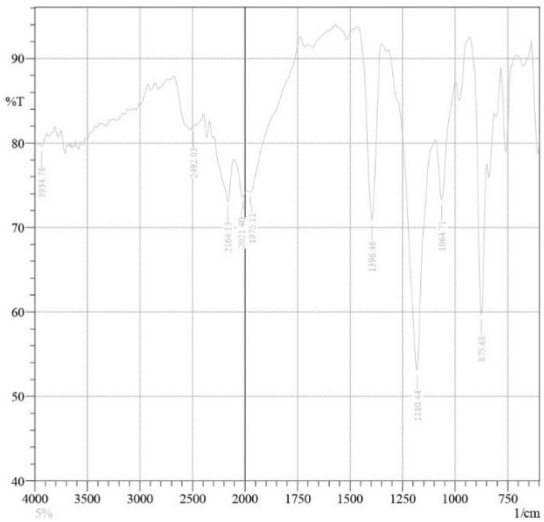


Fig. 1e. FTIR spectra of 5% bamboo-cellulose PVDF membrane

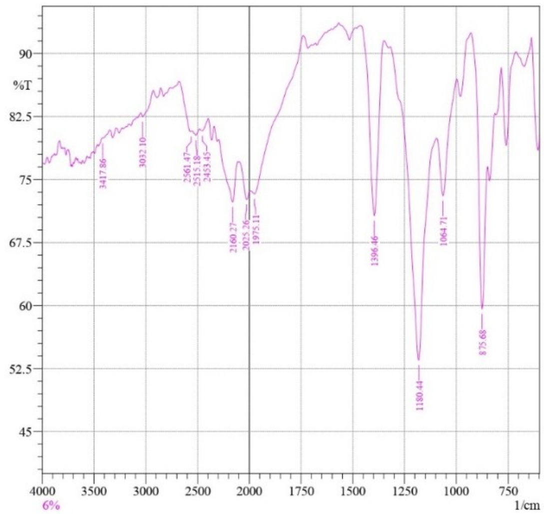


Fig. 1f. FTIR spectra of 6% bamboo-cellulose PVDF membrane

Hydrophilicity Analysis

Polyvinylidene fluoride (PVDF) is a widely employed membrane material owing to its exceptional chemical resistance, thermal stability, and mechanical robustness (Namakka *et al.* 2026). However, its intrinsic hydrophobicity substantially compromises membrane permeability and renders it susceptible to fouling (Bin Bakri *et al.* 2026; Namakka *et al.* 2025a; Rahman *et al.* 2024). Cellulose, a biopolymer abundant in polar hydroxyl (-OH) groups, is used to modify the polymer matrix (Kuok *et al.* 2024; Rahman *et al.* 2024).

The influence of cellulose at various percent contents, *viz.* 0, 1, 2, 3, 4, 5, and 6%, on hydrophilic properties of the fabricated membranes was investigated *via* water contact analysis (WCA), following the procedure described in Namakka *et al*. (2025a). The pristine (0% cellulose) PVDF membrane exhibited a WCA of 86.3° (refer to Fig. 2a), which is consistent with literature reports for unmodified PVDF materials (Namakka *et al.* 2026). As cellulose loading increased incrementally from 0 to 6 wt%, the WCA demonstrated a monotonic decrease, terminating at 50.5° at the highest cellulose concentration. This systematic reduction establishes how cellulose incorporation progressively enhanced membrane hydrophilicity. An observed WCA decrease of approximately 35.8° across the compositional range signifies a substantial transformation in surface chemistry, transitioning the membrane from a hydrophobic state into the hydrophilic regime (James *et al.* 2025).

The initial addition of 2 wt% cellulose produced a sharp reduction of 13.1° from the pristine values, indicating surface enrichment of cellulose chains during membrane formation *via* the non-solvent-induced phase separation (NIPS) process. Between 2 and 5 wt%, the decreases were more gradual and linear, suggesting relatively well-dispersed cellulose materials within the PVDF matrix (Binti Mohd Sufian *et al.* 2026; Namakka *et al.* 2024). However, a dramatic decline of 15.6° was observed between 5 and 6 wt%, dropping the WCA from 66.1° to 50.5°. This non-linear drop suggests the attainment of a percolation threshold, beyond which excess hydrophilic segments are expelled to the membrane–air interface, resulting in exponentially improved surface wettability (Mun *et al*. 2018; Namakka *et al.* 2026; Rahman *et al.* 2024). The subsequent reduction in WCA to

50.5° at 6 wt% cellulose concentration supports the antifouling propensity, as hydrophilic surfaces resist hydrophobic adsorption.

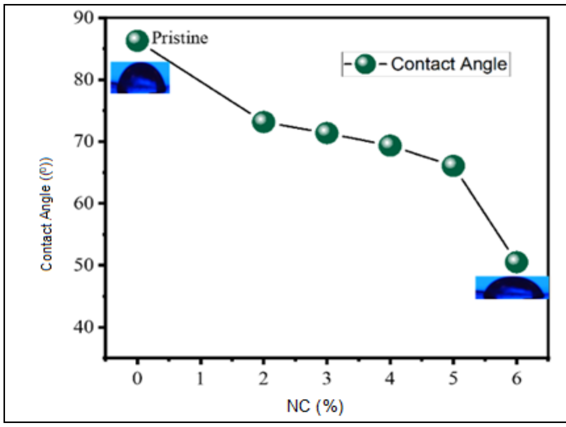


Fig. 2a. WCA of the membrane materials

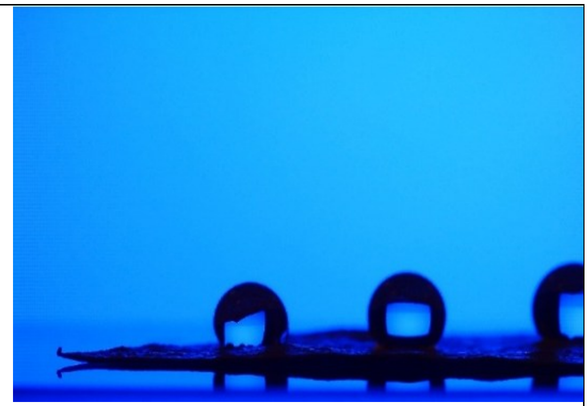


Fig. 2b. Water droplets on membrane surface via sessile goniometer

Membrane Water Permeation Flux Test

The bamboo cellulose PVDF membrane sheets prepared were placed into a laboratory-scale filtration system (Sterlitech HP4750). The effective membrane area for filtration was 14.6 cm. The water permeation flux test examined the permeability rate through novel fabricated nanocomposite membranes by measuring the amount of permeate collected per membrane surface area over time at 1 bar while observing the effect of varying the TiO_2 nanoparticle loadings in the membrane system. Results in Table 3 show that incorporating cellulose into the nanocomposite membrane system markedly increased water permeation compared to the pristine, PVDF-only membrane. The analysis revealed a proportional relationship between 2% to 6% of bamboo-cellulose loadings incorporated into the PVDF membrane through a water permeation flux test. Results revealed that the addition of cellulose into PVDF had contributed to forming a homogeneous nanocomposite membrane structure with enhanced properties and productivity.

The water permeation flux for pristine was 54.7 L/m^2h for 70 min water permeation test. With the addition of 2% bamboo-cellulose to the PVDF membrane, the water permeation flux increased to 78.4 L/m^2h within the same time frame. This enhancement was due to the development of a more composed structure within the 2% bamboo-cellulose PVDF membrane, allowing more water to permeate.

The water permeation flux increased with the addition of cellulose, reaching 91.9 L/m^2h for 3%, 156.7 L/m^2h for 4%, 253.7 L/m^2h for 5%, and 318.0 L/m^2h for 6% bamboo-cellulose PVDF membranes, respectively. Multiple studies have corroborated the current conclusion that the inclusion of various hydrophilic additives elicited a synergistic effect in the virgin PVDF membrane, augmenting its hydrophilicity and hence raising flux rates (Ahmad *et al*. 2020; Azad *et al*. 2022; Batool *et al*. 2021).

Table 3. The Water Flux of Cellulose PVDF Membrane

Membrane Sample	Water Flux (L/m^2.h)
6% Cellulose	317.95
5% Cellulose	253.69
4% Cellulose	156.72
3% Cellulose	91.89
2% Cellulose	78.36
Pristine	54.68

Membrane Dye Rejection Analysis

In order to comprehensively evaluate the separation efficacy of the fabricated bamboo cellulose PVDF membranes, a series of methylene blue (MB) dye rejection tests was conducted with an initial concentration of 2 ppm. Each membrane with 0%, 2%, 3%, 4%, 5%, and 6% of cellulose was meticulously replicated five times to obtain the average values, and the results are presented in Table 4.

The pristine membrane had the lowest initial dye rejection of 35.2% and exhibited the fastest decline over time, stabilizing at 27.5% after 50 min. As 2% of bamboo cellulose was incorporated into the PVDF membrane, the initial dye rejection of the membrane was found to be 39% after 10-min runs. It showed a relatively steep decline in performance, reaching 32.5% at 50 min. The dye results revealed that membrane dye rejection performance was increased by adding 3%, 4%, 5%, and 6% of cellulose in the PVDF membrane.

Inclusion of 6% cellulose demonstrated a fair performance with a MB rejection percentage of 51% for the first 10-min run, significantly higher than that of 5% cellulose, 4% cellulose, and 3% cellulose, with rejection percentages of 49%, 47%, and 44%, respectively. All the bamboo cellulose PVDF membranes dropped after a 20-min run, demonstrating that the membrane performance decreases over time. The dye rejection rate for 6% bamboo cellulose PVDF membrane decreased to 41% after a 50-min run and remained constant after a 70-min investigation. The downtrend underlines the membrane's lesser effectiveness in removing dye pollutants, implying a lack of resilience in rejecting MB dye. The lack of resilience could be caused by improper membrane casting, or the membrane was left too long without preservation before the dye rejection test. Lack of preservation can cause the membrane to slowly foul, decrease the membrane’s quality, and affect the testing result.

The observed improvement in MB dye removal from 27.5% with the pristine membrane to 41% with the 6% bamboo cellulose PVDF membrane showed that cellulose significantly improved the PVDF membranes’ dye adsorption capabilities. This enhancement can be ascribed to cellulose’s hydrophilic nature, which boosts the membrane’s attraction for water and dye molecules, resulting in improved dye interaction and adsorption. The results demonstrated cellulose’s potential for improving membrane performance, especially in dye removal applications. The hydrophilic characteristic of cellulose improves the surface properties of PVDF membranes by enhancing their attraction for water and dye molecules, allowing for improved dye adsorption. Cellulose’s hydroxyl groups can establish hydrogen bonds with dye molecules, increasing removal efficiency. This discovery emphasizes the need to incorporate hydrophilic elements such as cellulose into hydrophobic PVDF membranes to maximize their efficacy for wastewater treatment.

Table 4. The Membrane Dye Rejection Results

Sample	Membrane Dye Rejection (%)						
	10 min	20 min	30 min	40 min	50 min	60 min	70 min
6% Cellulose	51	51	47	45	41	41	41
5% Cellulose	49	44	41	40	39	39	39
4% Cellulose	47	45	42	38	37	37	37
3% Cellulose	44	41	38	35	34.5	34.5	34.5
2% Cellulose	39	36	34	33	32.5	32.5	32.5
Pristine	35.2	33.5	30	29	27.5	27.5	27.5

CONCLUSION

1. This research showed that incorporating cellulose into poly(vinylidene fluoride) (PVDF) membranes significantly improved their hydrophilicity, mechanical strength, and methylene blue dye adsorption capabilities, overcoming the inherent limitations of traditional PVDF membranes, such as hydrophobicity and low dye removal efficiency.
2. Characterization of these composite membranes demonstrated that the membranes' structural and functional features might be tuned to improve performance. Fourier transform infrared spectroscopy verified the existence of functional groups that promote dye adsorption. In contrast, due to cellulose integration, Field emission scanning electron microscopy demonstrated morphological alterations and enhanced pore structure. Water permeation flux studies demonstrated the membranes' increased permeability, while dye rejection tests revealed their greater capacity to remove methyl blue dye from aqueous solutions.
3. The findings lay the groundwork for developing scalable and ecologically friendly cellulose-incorporated PVDF membrane-based water treatment technologies, which present a viable approach to reduce water pollution and improve environmental sustainability.
4. While this study provided evidence for the efficacy of bamboo cellulose in enhancing PVDF membrane hydrophilic and dye removal performance, several aspects warrant further investigation. Long-term stability and fouling resistance tests under continuous operation are necessary to assess the practical applicability of these membranes. Additionally, the mechanical properties including tensile strength, elongation-at-break, and compaction resistance should be systematically characterized to ensure membrane durability under operational pressures.

ACKNOWLEDGEMENTS

The authors extend their appreciation to Umm Al-Qura University, Saudi Arabia for funding this research work through grant number: 26UQU4290372GSSR08.

Funding

This research work was funded by Umm Al-Qura University, Saudi Arabia under grant number: 26UQU4290372GSSR08.

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Article submitted: January 9, 2026; Peer review completed: May 23, 2026; Revised version received: July 27, 2026; Accepted: July 31, 2026; Published: August 27, 2026.
DOI: 10.15376/biores.21.4.10149-10165