STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 14, Special Issue 3, 2026
DOI (Journal): 10.37591/JoPC

https://journals.stmjournals.com/jopc

Research JoPC

# High-Performance Polymer Composite Membranes for Selective Ion Transport in Advanced Energy Conversion Systems

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***Abstract***

*The development of high-performance Polymer Composite Membranes (PCM) with enhanced ion transport is essential for Polymer Electrolyte Membrane Fuel Cells (PEMFC). However, low-humidity conditions and filter agglomeration still limit long-term membrane stability. This research designs a functionalized PCM integrating cross-linked Poly (Vinyl Alcohol)/Poly (Ethylene Glycol) (PVA/PEG) matrix with sulfonic acid functional groups and Titanium Dioxide ($TiO_2$) nanofillers to improve selective ion transport under low-humidity conditions. Two types of PCM were fabricated using controlled solution casting and chemical cross-linking to enhance mechanical stability and dimensional integrity. The resulting membranes were comprehensively characterized using X-ray diffraction (XRD) to evaluate crystallinity, Fourier transform infrared spectroscopy (FTIR) for functional group analysis, and scanning electron microscopy (SEM) to examine morphological features. Physicochemical properties, including water uptake, swelling ratio, and ion exchange capacity (IEC), were systematically analyzed. Electrochemical impedance spectroscopy (EIS) was employed to determine ionic conductivity and transport efficiency. The second type achieved reduced water uptake of 28.1%, controlled swelling ratio of 14.6%, and improved IEC of 1.48 meq/g. XRD analysis confirmed reduced crystallinity and increased amorphous regions for enhanced ion mobility. SEM analysis revealed a denser and more compact morphology with uniformly distributed $TiO_2$ nanoparticles. FTIR analysis confirmed improved hydrogen bonding interactions and continuous proton-conducting pathways. EIS analysis showed ionic conductivity improvement from $1.41\times10^{-3}$ S/cm to $2.00\times10^{-3}$ S/cm with bulk resistance reduction from 85Ω to 60Ω, confirming superior electrochemical performance for PEMFC applications. demonstrated superior conductivity, reduced crystallinity, enhanced proton transport, and balanced mechanical integrity for PEMFC applications.*

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Received Date: May 22, 2026
Accepted Date: June 02, 2026
Published Date: June 10, 2026

**Citation:** Shanthi Kumaraguru, Prashant V. Thokal, P. William, Ganesh P. Dawange, Dharmendra Kumar Roy, Pravin B. Khatkale. High-Performance Polymer Composite Membranes for Selective Ion Transport in Advanced Energy Conversion Systems. Journal of Polymer & Composites. 2026; 14(Special Issue 3): S724–S736p.

**Keywords:** Polymer composite membranes, selective Ion transport, proton conductivity, functional nanofillers, polymer electrolyte membrane fuel cells, energy conversion systems.

## INTRODUCTION

In advanced electrochemical energy conversion systems, the role of efficient ion transport in

 

composite polymer electrolytes is important since the inorganic fillers and functional polymer matrices enhance the ionic conduction and the mobility of ions at the interfaces. But keeping the membrane stable with selective transport for different working conditions has been a big challenge in membrane engineering [1]. Controlled surface interaction and regulated transport pathway have been achieved in hydrophobic-polymer modified ion-exchange membranes that have enhanced selectivity for like-charged ions, but membrane permeability and transport resistance still hinder large-scale electrochemical separation efficiency [2]. Although hydration channels between micropores in the polymer membrane are technically challenging to achieve a stable ionic conduction under practical operating conditions, these have generated immense interest due to the enhanced ionic diffusion and transport selectivity [3]. Low-humidity operation is usually a problem in PEMFC, due to a lack of water retention and loss of conductivity. Water management and proton transport efficiencies were enhanced by carbon nanotube sheet-sandwiched diffusion layers, but for longer-term membrane durability and interfacial compatibility, both need optimization [4]. The crosslinked nanocomposite proton exchange membrane made of sulfonated polysulfone showed better self-humidification, proton conductivity, and dimensional stability than other membranes, but significant swelling and conductivity degradation under high stress conditions still remained, compromising the reliability of the membrane [5]. The proton conductivity of PEMs was improved by surface modification of proton transfer species through the creation of better interfaces, but the pathways for proton hopping and the preservation of mechanical integrity of the membrane during long-term operation were not resolved [6]. The anti-swelling gel polymer electrolyte membranes successfully restrained dimensional instability and improved ionic transport performance, but the trade-off between ion conductivity and anti-swelling properties is still a key issue [7]. Proton channels were aligned in proton exchange membranes to further reduce the resistance and enhance the conductivity of proton conduction along the channels, but it is still difficult to ensure a pathway of proton conduction is structurally uniform and has long-term electrochemical stability [8].

To design high-performance PCM for future energy conversion systems with improved ion transport, dimensional stability, and electrochemical performance. The goal involves a physicochemical characterization, structural behaviour, and proton conductivity assessment of $TiO_2$ incorporated membranes in controlled conditions. The substantial contributions are as follows:

- Improving proton transport performance of $TiO_2$-based PVA/PEG/sulfonic acid PCM.
- Full evaluation based on water uptake, swelling ratio, IEC, and EIS analysis.
- Structural and morphological validation using XRD, FTIR, and SEM analyses to ensure reduction in crystallinity, increase in functional interactions, and increase in membrane densification.

The motivation, objective, and significance of developing advanced PCM are presented in this research. Section 2 discusses the related works on PCM and ion transport systems. Section 3 covers material selection, membrane preparation, optimization of composition, casting of solution, cross-linking, and physicochemical properties evaluation. The results of the structural and morphological analyses are discussed in Sections 4 & 5. Sections 6 and 7 end with a discussion of optimal membrane performance, limitations, and future scope.

## RELATED WORKS

The recent research efforts were directed towards advanced PCM with superior ion transport, conductivity, structural stability, and electrochemical performance for energy conversion applications. Electrolyte membranes of polyvinyl alcohol/polyethylene glycol/sulfosuccinic acid (PVA/PEG/SSA) with the addition of Aluminium Oxide ($Al_2O_3$) nanofillers enhanced ion transport and physicochemical stability [9]. For the conductivity analysis, the amount of water absorbed was 42%, and the conductivity obtained was $3.1\times10^{-3}$ S/cm for XRD. But too much filler loading resulted in agglomeration of nanoparticles and decreased membrane uniformity. A composite membrane of two-dimensional (2D) Transition Metal Carbide/Nitride (TMCN) materials was used to control selective ion transport via

 

designed nanochannel architectures [10]. Permeability analysis showed almost 85% ion selectivity, with improved ionic flux; there were oxidation problems and complex fabrication that reduced the scalability and stability.

For fuel cell applications, covalent organic framework (COF) composite membranes were created to enhance proton conduction and durability [11]. Proton conductivity was obtained up to 0.11 S/cm under humidified conditions for electrochemical characterization, which was expensive because of precursor synthesis and complicated because of complex fabrication. For PEMFC use, the proton exchange membranes with reinforcement showed good conductivity retention and mechanical strength [12]. Tensile and electrochemical analyses demonstrated high tensile strengths of 32 Megapascal and retained conductivity. However, lower humidity conditions caused a substantial drop in the efficiency of operation. Proton transport and dimensional stability of Sulfonated Poly Arylene Ether Sone (SPAES) membranes were improved by adding sulfonated titanium dioxide nanotubes and graphitic carbon nitride nanosheets [13–14]. The electrochemical impedance analysis reached a conductivity of 0.089 S/cm without a uniform membrane because of the filler dispersion problems.

Layered double hydroxide was also used to enhance the hydroxide conductivities and hydration properties of the electrolyte membranes of alkali fuel cells, with a conductivity of 41.6 mS/cm, but too much moisture absorption reduced the dimensional stability [15–18]. Filler-filled polymer electrolyte membranes had a conductivity of 0.076 S/cm with the same enhanced ion mobility, but with a loss of structural integrity due to swelling [19–20]. The non-equilibrium model of ion-transport across ion-selective membrane/electrolyte interfaces was reliable for predicting ionic flux behaviour [21–22]. The numerical simulations achieved a 18% greater accuracy of the transport prediction, and the experiments were not enough, so there is a lack of adaptability in complex electrochemical sensing environments. Sputtered gas diffusion layers of $TiO_2$ showed an improvement in PEMFC water retention and fuel cell efficiency of almost 14% under low humidity conditions [23], but the coating degradation compromised long-term reliability and scalability.

**Research Gap**

Despite significant progress in PCM for ion transport, there are still some drawbacks in the existing systems. PVA/PEG/SSA–$Al_2O_3$ membranes [9] have been found to have the drawback of nanoparticle agglomeration and poor uniformity at higher filler loading. MXene-based membranes [10] exhibit high selectivity, but are prone to oxidation instability and are difficult to fabricate. COF membranes [11] have a superior conductivity, but the precursors used are costly, and the synthesis is challenging. Reinforced PEMs [12] have poor performance at low humidity. Filler dispersion is a problem for SPAES systems [13]. To address these issues, the present research proposes a membrane of PVA/PEG/$TiO_2$ that was uniformly dispersed, compatible, and that maintained stable proton pathways. Optimized casting and cross-linking improve the homogeneity, and $TiO_2$ improves the amorphous structure and ion transport. The membrane exhibits balanced conductivity, low swelling, and good electrochemical stability as evidenced by XRD, FTIR, SEM, and EIS analysis.

The novelty of the proposed membrane resides in the combination of a cross-linked PVA/PEG matrix, sulfonic acid functionalization, and uniformly dispersed $TiO_2$ nanofillers through a controlled fabrication strategy. This design simultaneously improves proton conductivity, dimensional stability, and ion transport efficiency while minimizing nanoparticle agglomeration and swelling. Unlike previously reported polymer composite membranes, the proposed membrane provides a balanced enhancement of electrochemical, structural, and physicochemical properties under low-humidity operating conditions, making it highly promising for advanced PEMFC applications.

## MATERIALS AND METHODS

To evaluate ion transport behavior, structural stability, and electrochemical performance, two IDs of PCM were prepared using PVA, PEG, sulfonic acid functional groups, and $TiO_2$ nanofillers via controlled solution casting and chemical cross-linking. Physicochemical properties were analyzed.

 

Structural and morphological characteristics such as crystallinity, functional group interactions, and surface morphology were examined using XRD, FTIR, and SEM, respectively. EIS was performed to determine ionic conductivity and proton transport behavior, as illustrated in Figure 1, which shows the stepwise fabrication, characterization, and performance evaluation for selective ion transport applications.

**Materials Selection**

The choice of appropriate material is one of the most important aspects of manufacturing high-performance Polymer Composite Membranes (PCM) for selective ion transport. Poly Vinyl Alcohol (PVA) was chosen as the main polymer matrix because of its good film-forming property, hydrophilic property, and high mechanical strength. Poly Ethylene Glycol (PEG) was added to improve membrane flexibility, water retention, and ionic mobility. The sulfonic acid functional groups were added to increase proton conductivity and active ion-conducting sites. The nanofillers selected were Titanium Dioxide ($TiO_2$), which possesses high surface area, thermal stability, and the ability to enhance ion transport pathways under low humidity. A cross-linking agent was added to enhance the mechanical strength, dimensional stability, and swelling resistance. Homogeneous casting solutions were prepared in distilled water. The compositional design was to obtain high ionic conductivity, high ion selectivity, low degree of swelling, and excellent electrochemical performance for PEMFC application.

**Preparation of Polymer Matrix**

The PCM was fabricated by controlled solution casting followed by chemical cross-linking. Continuous magnetic stirring was used to dissolve PVA in distilled water at a high temperature. PEG was added in a slow manner to increase flexibility and water-keeping capacity. To enhance proton transport, sulfonating agents were added, and subsequently, to prevent agglomeration, $TiO_2$ nanoparticles were incorporated by stirring and ultrasonication. A cross-linking agent was added to increase mechanical stability and decrease solubility. The homogeneous mixture was poured onto glass plates and dried under controlled conditions to create stable composite membranes suitable for use in ion transport applications. Stepwise fabrication of PCM was illustrated in Figure 2, dissolution of PVA, addition of PEG, addition of sulfonic acid, dispersion of $TiO_2$, chemical cross-linking, solution casting, controlled drying, and formation of the final membrane for selective ion transport applications.

**Membrane Composition**

A series of PCM samples was fabricated by systematically varying the concentration of $TiO_2$ nanofiller with a fixed concentration of PEG and sulfonic acid functional groups in all formulations. This phase is to explain the impact that TiO2 loading on ion transport will have, while maintaining uniform polymer chemical properties. PVA's content is changed to provide a fair composition. To ensure a constant flexibility and water retention, PEG is kept at 10 wt%. To guarantee consistent proton-conducting sites, the sulfonic acid functional groups are set at 2 wt%. To find out how changing the $TiO_2$ content from 0 to 5 wt% affects crystallinity, morphology, and ionic conductivity. To enable trustworthy comparison, all membranes are manufactured under the same processing parameters. Membrane compositions are listed in Table 1.

The membrane samples were all prepared under the same process parameters so that the structural, physicochemical, and electrochemical properties are comparable. The polymer matrix was composed of PVA as the host polymer, PEG (10 wt%) as a plasticizing and water-retaining component, and sulfonic acid functional groups (2 wt%) as proton-conducting sites.

**Table 1.** Composition of polymer composite membranes.

| Membrane ID | PVA (wt%) | PEG (wt%) | Sulfonic acid (wt%) | $TiO_2$ (wt%) |
|---|---|---|---|---|
| PCM-1 | 88 | 10 | 2 | 0 |
| PCM-2 | 83 | 10 | 2 | 5 |

 

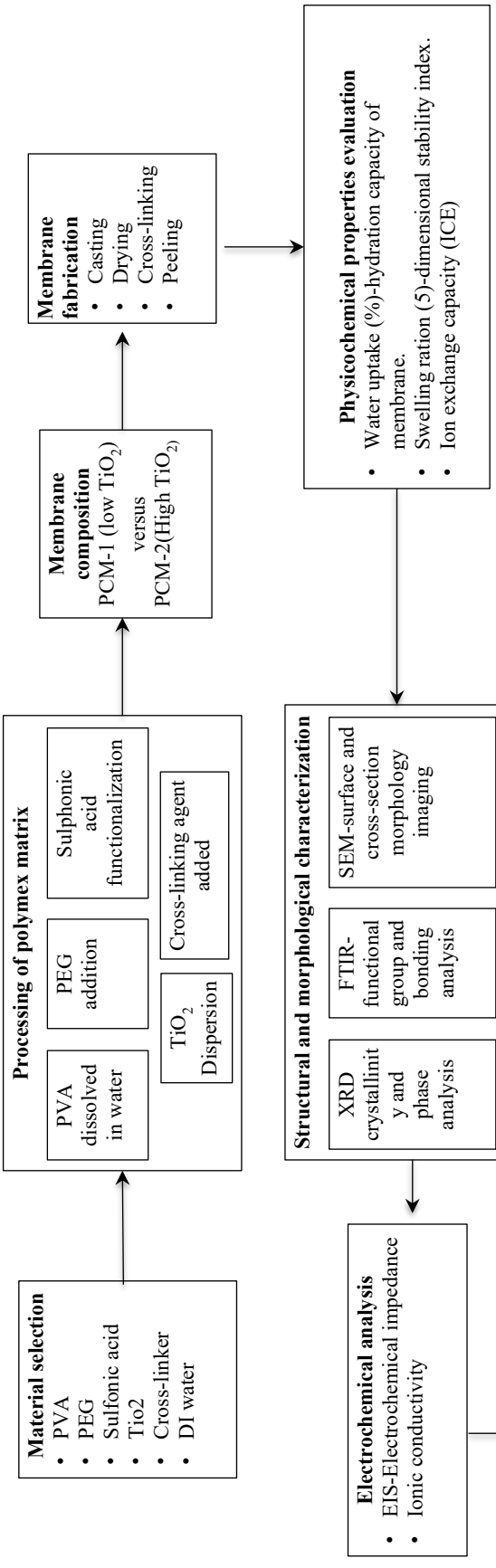


**Figure 1.** Fabrication and characterization methodology of polymer composite membranes.

 

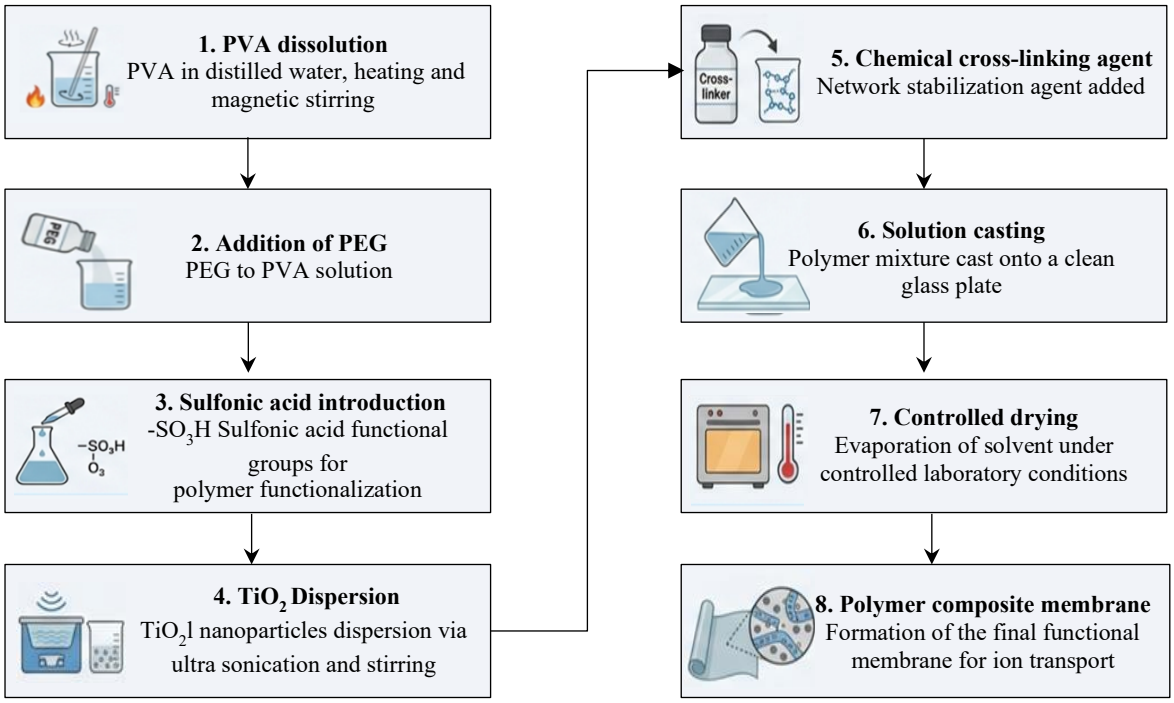


**Figure 2.** Fabrication process of polymer composite membrane for fuel cells.

$TiO_2$ nanoparticles were incorporated at 0 wt% and 5 wt% in PCM-1 and PCM-2, respectively, while maintaining identical concentrations of PEG and sulfonic acid to isolate the effect of $TiO_2$ on membrane performance.

**Membrane Fabrication (Casting, Cross-linking & Drying)**

The prepared PCM-1 and PCM-2 solutions were subsequently converted into solid membrane films by the controlled solution casting, cross linking and drying. Solutions were carefully poured onto clean and level glass plates at the controlled condition in order to have uniform thickness and no bubble in the solution. The cast films were allowed to stand for 12–24 hrs for solvent leveling. Membranes were allowed to dry in air for 24 hours and then were dried under mild heating at 50-60°C for 6–10 hours. Cross linking with chemicals was performed for 2–4 hours at 50–60°C to improve mechanical strength and dimensional stability.

The membranes were then peeled and left in a desiccator for 24 hours prior to characterization. The stepwise membrane fabrication process of PCM-1 and PCM-2 is shown in Figure 3, which involves homogeneous solution casting on the levelled glass plates, initial resting for 12 to 24 h, controlled drying at room temperature for 24 h, mild thermal drying at 50–60 °C for 2 to 4 h, peeling the membrane, and finally storing in desiccator for 12 to 24 h to stabilize before characterization and electrochemical analysis.

**Application of Fuel Cell Ion Transport Membranes**

The developed PCM has good transporting properties of ions, which is suitable for PEMFC as proton-conducting separator between anode and cathode. When hydrogen is released from the anode, it becomes a proton which can selectively move through ion-conducting channels, and an electron moves through an external circuit, yielding electrical energy. Oxygen combines with protons and electrons at the cathode to produce water as the only product. PEG helps to retain water, sulfonic acid helps to create proton conducting sites and the $TiO_2$ helps to establish ionic pathways, allowing for low humidity operation. The membranes also have excellent potential for use in direct Methanol Fuel Cells, in electrolyzers and as battery separator.

 

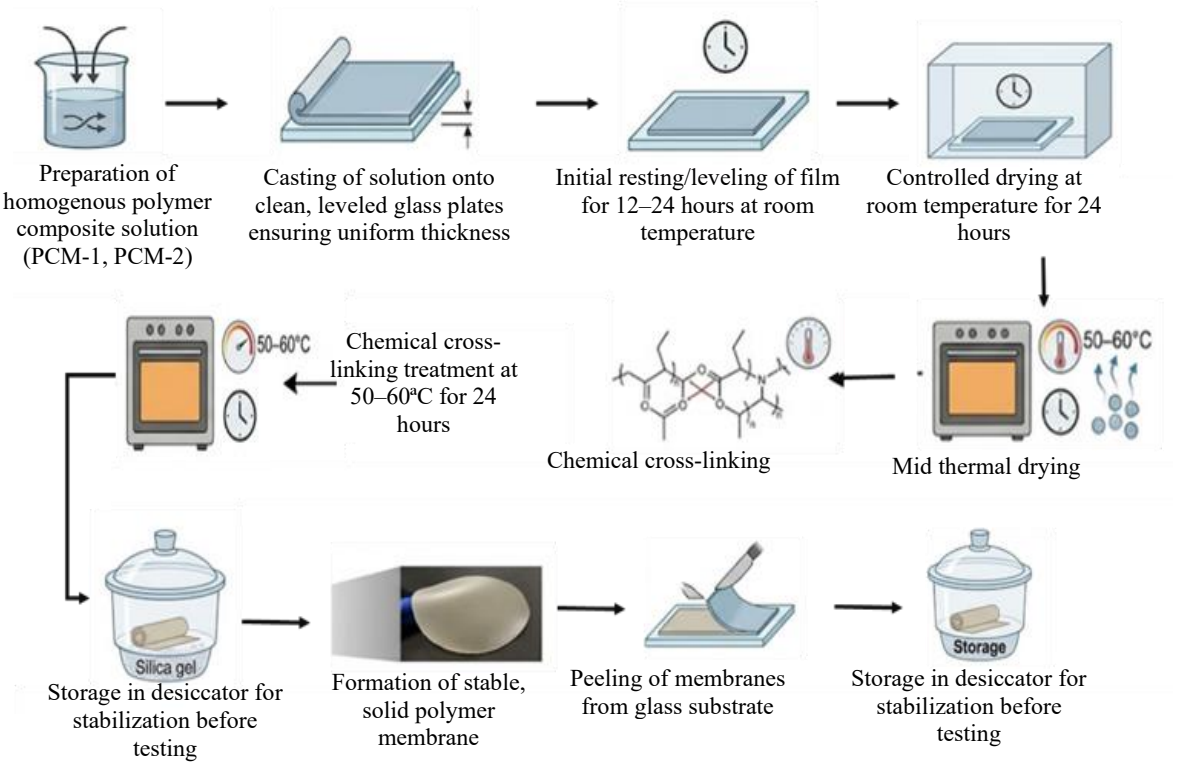


**Figure 3.** Membrane fabrication process: casting, cross-linking, and drying of PCM.

**Physicochemical Properties Evaluation**

The fabricated PCM-1 and PCM-2 were tested to understand their interaction with water, dimensional stability and ion-exchange property. These properties directly affect the efficiency of ion transport, membrane durability and performance in electrochemical applications. The tests performed are water uptake, swelling ratio, and ion exchange capacity (IEC).

Water Uptake Test is used to measure water absorption of PCM and is used as an indicator of porosity and hydrophilicity. Membrane samples were dried in a desiccator for obtaining Dry Weight ($V_d$) and then placed in distilled water for 24 hours. Excess surface water was removed after soaking, and the wet weight ($V_w$) was measured; the water uptake ($Wat\ Upt$) was calculated from Equation (1)

$$Wat\ Upt(\%) = \frac{V_w - V_d}{V_d} \times 100 \quad (1)$$

Where $V_w$ is the weight after immersion and, $V_d$is the dry membrane weight before immersion.

The Swelling Ratio Test is used to assess the dimensional stability of PCM materials in the presence of water, which is critical for the structure during fuel cell operation. The dimensions of dry membrane were measured and recorded as ($M_d$). The swollen dimension, $M_s$, was obtained after 24 hours of immersion in distilled water and calculated from Equation (2).

$$Swelling\ Ratio\ (\%) = \frac{M_s - M_d}{M_d} \times 100 \quad (2)$$

Where $M_s$ are length or area of swollen membrane, $M_d$ is length or area of dry membrane.

Ion Exchange Capacity (IEC) is the number of proton-conducting sites (–$SO_3H$ groups) that directly affect proton conductivity. The membranes were protonated by using an acidic solution, washed using distilled water, immersed in Sodium Chloride (NaCl) solution for exchanging the H+ ions with Na+ ions, and protonated H+ ions were titrated with standard NaOH solution and the results were obtained by using Equation (3).

 

$$IEC\left(\frac{meq}{g}\right) = \frac{D_{NaOH} \times W_{NaOH}}{V_d} \quad (3)$$

Where $D_{NaOH}$ is the concentration of NaOH solution, $W_{NaOH}$ is the volume of NaOH consumed in titration ($W$), $V_d$ is dry weight of membrane. The Water uptake, swelling ratio and IEC also reflect the membrane performance and reflect hydrophilicity, dimensional stability, proton sites, balanced transport, mechanical stability, and improved electrochemical energy conversion efficiency.

**Microstructural Analysis**

Experimental analysis was carried out by detailed microstructural analysis using X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), and scanning electron microscopy (SEM) to examine the internal structure, functional group interactions, and surface morphology of the fabricated PCM-1 and PCM-2. These characterizations were used to relate the structure to the ion transport and electrochemical performance.

**XRD Analysis**

Crystalline and amorphous nature of composite membranes was evaluated using X-ray Diffraction (XRD). The addition of $TiO_2$ affected the PVA crystalline peak intensity, which further indicated that $TiO_2$ incorporation decreased the crystallinity, increased amorphous regions, enhanced the polymer chain mobility, and improved the proton conduction pathway. The crystallite size of the polymer domains was estimated by the Scherrer in Equation (4)

$$E = \frac{S\lambda}{\beta \cos\theta} \quad (4)$$

where, $E$ is crystallite size, $S$ is shape factor, $\lambda$ is the X-ray wavelength, $\beta$ is full width at half maximum, and $\theta$ is Bragg diffraction angle. The XRD results showed that PCM-2 had the lowest crystallinity, which led to better ion transport and proton conductivity.

**FTIR Analysis**

Functional groups and chemical interactions were identified in PCM using Fourier Transform Infrared Spectroscopy (FTIR). Successful membrane functionalization was confirmed by characteristic peaks of PVA (–OH stretching), PEG (C–O–C stretching), and sulfonic acid groups ($–SO_3H$). The broadening and shift in hydroxyl and sulfonic acid peaks indicated strong hydrogen bonding interaction, which helps to improve proton conduction pathways. The changes of peak intensity due to the incorporation of $TiO_2$ nanoparticles showed interfacial polymer–filler interactions that supported the stability of membranes, water retention, and the efficiency of ion transport.

The observed shifts and broadening of the hydroxyl and sulfonic acid absorption bands indicate strong hydrogen-bonding interactions between $TiO_2$ nanoparticles and the PVA/PEG polymer matrix. These interactions confirm good filler–polymer compatibility and facilitate the formation of continuous proton-conducting pathways. The absence of significant phase separation in SEM images further supports effective interfacial adhesion and homogeneous filler dispersion.

**SEM Analysis**

Surface morphology and dispersion of the $TiO_2$ nanoparticles in the polymer matrix were studied by Scanning Electron Microscopy (SEM). PCM-1 exhibited a smooth and compact surface, and a lower ion transport pathway together with reduced porosity. The morphology of PCM-2 was found to be denser and more compact, with uniformly distributed $TiO_2$ nanoparticles and a reduced void volume, indicating that the incorporation of $TiO_2$ changes the morphology of the membrane, increases the free volume, and improves the ion conducting channels and electrochemical performance.

**RESULT**

The effect of $TiO_2$ addition on the ion transport behavior was determined by physicochemical analysis (water uptake, swelling behavior, and ion exchange capacity), structural characterization (XRD and FTIR), morphological investigation (SEM), and electrochemical impedance spectroscopy (EIS) of PCM-1 and PCM-2.

 

**Table 2.** Physicochemical properties of PCM membranes.

| Membranes | Water Uptake (%) | Swelling Ratio (%) | IEC (meq/g) |
|---|---|---|---|
| PCM-1 | 32.5 | 18.4 | 1.25 |
| PCM-2 | 28.1 | 14.6 | 1.48 |

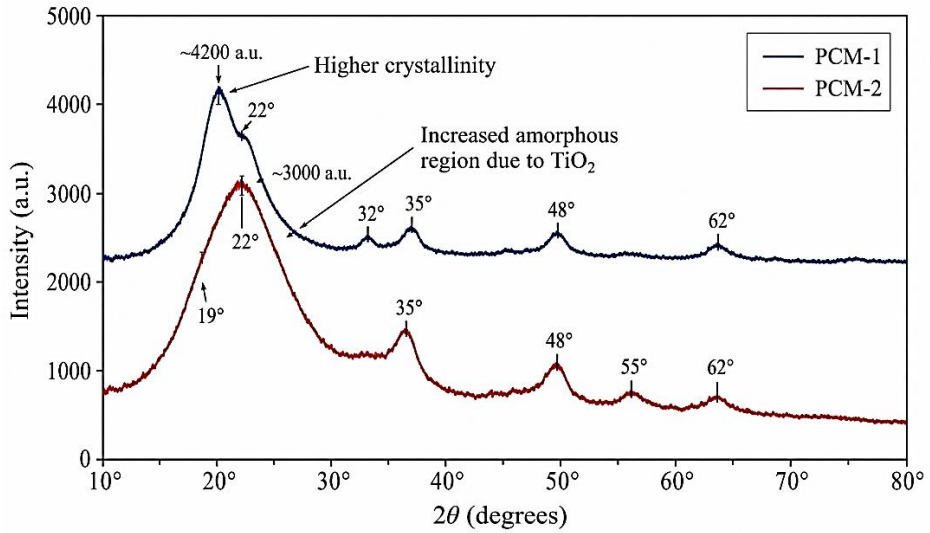


**Figure 4.** XRD pattern of PCM-1 and PCM-2 showing structural evolution and phase changes after $TiO_2$ incorporation.

**Physicochemical Properties of PCM Membranes**

To assess the effect of $TiO_2$ nanofiller on membrane performance, two compositions (PCM-1 and PCM-2) were analyzed. Table 2 presents the physicochemical properties of the prepared membranes. Improved performance is indicated by optimized water uptake, controlled swelling, and enhanced ion exchange capacity.

The results have revealed that the physicochemical properties of PCM-2 are better than PCM-1. The water uptake has been reduced from 32.5% to 28.1% and from 18.4% to 14.6% for swelling ratio, respectively, which shows better dimensional stability. Simultaneously, the IEC enhances from 1.25 to 1.48 meq/g, which further supports the improved proton-conducting sites. In general, PCM-2 shows a balanced hydration control with an excellent ion transport efficiency.

**XRD Analysis**

The diffractograms of PCM-1 and PCM-2, as shown in the figure, display a distinct structural evolution following the incorporation of $TiO_2$ (2θ (degrees) on the x-axis, intensity on the y-axis 10–80°). PCM-2 shows a semi-crystalline PVA peak at $2\theta \approx 19\text{-}22°$ that is of higher intensity (~4200 a.u.), which means that there is more ordered chain packing. In PCM-2, the same region demonstrates decreased peak intensity (~3000 a.u.) and peak broadening (Figure 4), which signifies a decrease in crystallinity and increase in amorphous content. Further reflections at ~32°, 35°, 48°, 55° and 62° indicate the presence of $TiO_2$, confirming the incorporation of the filler, and imply better proton-transport pathways. The XRD patterns of PCM-1 (pristine polymer membrane) and PCM-2 ($TiO_2$-incorporated membrane) are shown in Figure 4, revealing structural changes upon the addition of the filler.

**FTIR Analysis**

FTIR spectra of PCM-1 and PCM-2, plotted as transmittance (%) on the **y-axis** versus wavenumber ($cm^{-1}$) on the x-axis (500–4000 $cm^{-1}$), were used to identify functional groups and polymer–nanofiller interactions. Both membranes exhibit a broad O–H stretching band at 3200–3500 $cm^{-1}$, C–O–C

 

vibrations at 1000–1150 $cm^{-1}$, and S–O stretching in the ~600–1200 $cm^{-1}$ region, confirming functionalized PVA/PEG and proton-conducting groups. Compared to PCM-1, PCM-2 shows peak shifts and intensity variations, indicating stronger $TiO_2$-assisted hydrogen bonding, a more stable polymer network, and improved ionic transport pathways. Figure 5 FTIR spectra of PCM-1 and PCM-2 showing characteristic O–H, C–O–C, and S–O bands, with peak shifts/intensity changes in PCM-2 indicating $TiO_2$–polymer interactions and enhanced hydrogen bonding.

**SEM Analysis**

The SEM micrographs were used to analyze the cross-sectional morphology of PCM-1 and PCM-2. The scale bar represents 500 µm in both types. PCM-1 exhibits a rough, porous structure with visible voids, indicating a loosely packed polymer matrix that may lead to higher swelling and lower mechanical strength. In contrast, PCM-2 shows a denser and more compact morphology with reduced porosity and improved homogeneity. Bright, finely distributed spots confirm uniform dispersion of $TiO_2$ nanoparticles within the matrix. This densified structure enhances mechanical stability, reduces swelling, and provides continuous ion-transport pathways, thereby improving the overall electrochemical performance of the membrane. Figure 6 SEM cross-sectional images of (a) PCM-1 porous structure with voids and (b) PCM-2 dense morphology with uniformly distributed $TiO_2$, indicating improved densification and homogeneity.

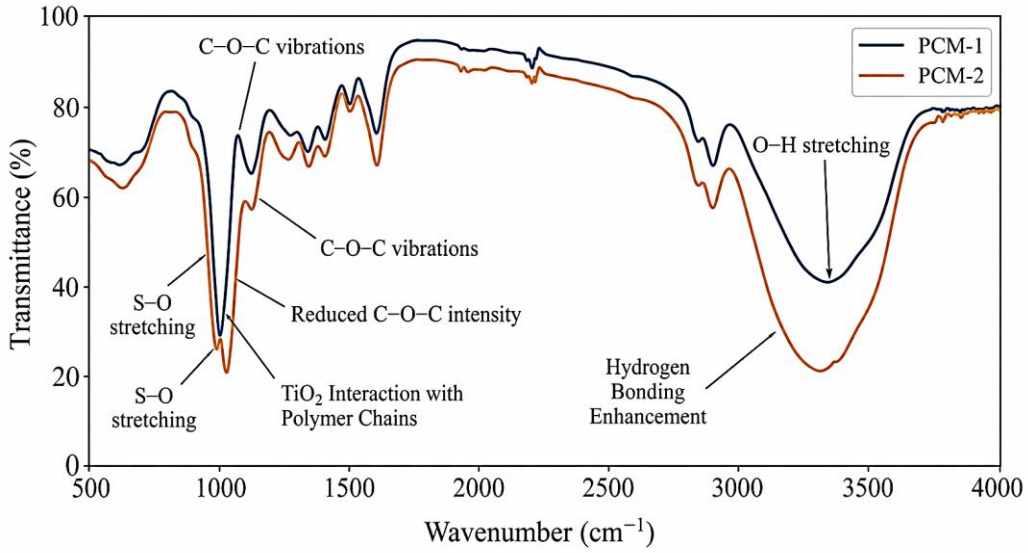


**Figure 5.** FTIR spectra of polymer composite membranes PCM-1 & PCM-2.

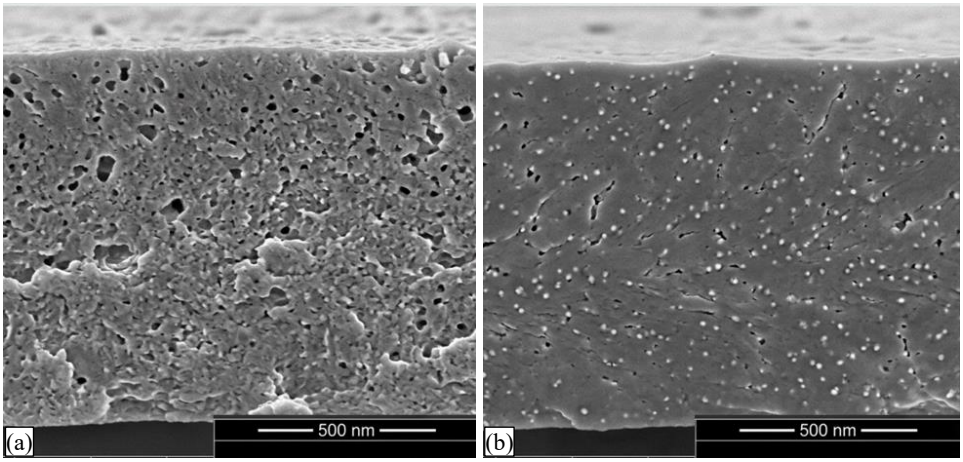


**Figure 6.** SEM cross-sectional morphology of PCM membranes: (a) PCM-1 and (b) PCM-2.

 

**Table 3.** EIS parameters and Ionic conductivity

| Membrane | Bulk resistance S (Ω) | Thickness M (cm) | AreaBA (cm²) | Ionic conductivity σ (S/cm) |
|---|---|---|---|---|
| PCM-1 | 85 | 0.012 | 1.0 | $1.41 \times 10^{-3}$ |
| PCM-2 | 60 | 0.012 | 1.0 | $2.00 \times 10^{-3}$ |

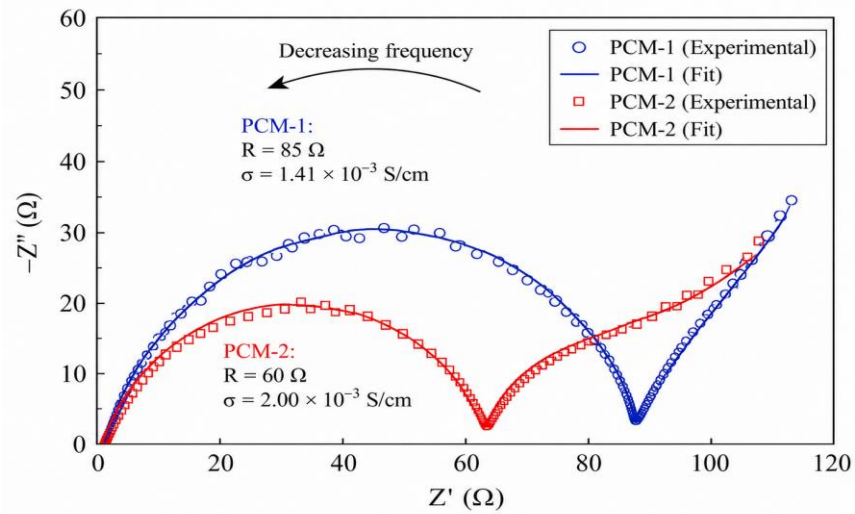


**Figure 7.** EIS impedance spectra of PCM-1 and PCM-2 membranes.

**Electrochemical Impedance Spectroscopy (EIS)**

EIS evaluated ionic transport properties of PCM-1 and PCM-2 using Nyquist plots of $-Z''$ (Ω) versus $Z'$ (Ω). PCM-1 exhibited a larger semicircle, indicating a higher bulk resistance of 85 Ω. PCM-2 showed reduced bulk resistance of 60 Ω, confirming enhanced proton transport and lower charge-transfer limitation. The synergistic effect of $TiO_2$ nanofillers and sulfonic acid groups increased amorphous regions, strengthened interfacial pathways, and facilitated proton hopping, improving overall ionic conductivity. The ionic conductivity was calculated using the following Equation (5)

$$\sigma = \frac{M}{S \times B} \tag{5}$$

Where: $\sigma$ is the ionic conductivity (S/cm), $M$ denotes the membrane thickness (cm), $S$ represent bulk resistance (Ω), obtained from Nyquist plot, $B$ refer the effective electrode area (cm²). PCM-2 shows higher conductivity than PCM-1, confirming enhanced ion transport pathways and reduced charge-transfer resistance. Table 3 and Figure 7 show EIS impedance spectra ($-Z''$ vs $Z'$) of PCM-1 and PCM-2, where PCM-2 exhibits reduced arc size and lower bulk resistance after $TiO_2$ incorporation.

**DISCUSSION**

Previous research indicates that inorganic fillers in polymer matrices have the ability to enhance proton transport and have critical limitations. The $Al_2O_3$-reinforced PVA/PEG/SSA membranes [9] exhibited a tendency of nanoparticle aggregation at higher concentrations that hindered the ion conducting pathways. Likewise, composite membranes of $TiO_2$ nanotube and graphitic carbon nitride using SPAES technology showed increased conductivity but with uneven dispersion of the filler, which would lower the uniformity and consistency of the membranes' performance [13]. The limitations are addressed by the development of a cross-linked PVA/PEG membrane with $TiO_2$ nanofillers and sulfonic acid groups through controlled solution casting.

Compared with the Existing methods, this research presents better structural stability, lower crystallinity, higher amorphous regions, and better ion transport. The proposed system is more electrochemically active and overall efficient than the current membrane-related systems. The particle deployment means that the $TiO_2$ nanoparticles are evenly dispersed in the polymer matrix, which promotes strong interface interaction, reduces agglomeration, and optimizes membrane morphology

 

and continuous ion conduction pathways for better electrochemical properties.

## CONCLUSION

To formulate a high-performance PCM that has excellent ion transport, structural stability, and electrochemical performance for advanced energy conversion applications, especially fuel cells. The research aims to enhance proton conductivity, dimensional stability, and interfacial compatibility by incorporating $TiO_2$ nanofiller into a PVA/PEG/sulfonic acid polymer medium. Two membranes were produced with different compositions of $TiO_2$ (PCM-1 and PCM-2) by controlled solution casting and chemical cross-linking. The physicochemical investigation validated PCM-2's increased proton-conducting capacity and enhanced hydration control. X-ray diffraction analysis showed lower crystallinity and more amorphous areas, therefore improving ion mobility. Strong contact between $TiO_2$ nanofillers and polymer functional groups was verified by FTIR, which favors stable proton-conducting routes. SEM analysis indicated a dense morphology, lower voids and even dispersion of $TiO_2$ within the membrane matrix. The electrochemical performance was confirmed by EIS analysis with better ionic conductivity and lower bulk resistance. In general, the effect of $TiO_2$ nanofillers and sulfonic acid groups were seen to reduce crystallinity, increase the number of ion conducting pathways at the interface, and increase electrochemical stability. The membrane is very promising for applications in electrochemical energy conversion systems and polymer electrolyte fuel cells. In addition, it is more energy efficient, has more stable operating conditions and reliable long term ion transport properties in low humidity environments.

### Limitation and Future Scope

In the present research, only two membrane compositions were considered, and the fabricated and tested membranes were not operated in fuel cell conditions for extended periods. Future studies will include scaling-up fabrication, durability characterization, optimization of $TiO_2$ dispersion, cost estimation, and advanced modelling and simulation methods such as machine learning prediction and multi-scale simulation for industrial applications.

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