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Performance And Durability Enhanced Composite Nanomaterial Membrane For Fuel Cell Applications

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ABSTRACT

The proton exchange membrane (PEM) based on polybenzimidazole (PBI) is developing into a promising alternative to Nafion for high-temperature proton exchange membrane fuel cells (HT-PEMFC). While Nafion membranes are effective at atmospheric pressure and low temperatures, their performance deteriorates significantly at temperatures above 80 °C, making them unsuitable for the operation of HT-PEMFCs. PBI membranes, on the other hand, have excellent thermal stability and durability, making them well-suited for high-temperature conditions. However, their relatively low proton conductivity (between 10-15 mS/cm) poses a challenge for efficient HT-PEMFC performance. This study aims to synthesise and investigate the effects of incorporating the ionic liquid 1-butyl-3-methylimidazolium chloride ([BMIM][Cl]) on the physicochemical properties, ionic characteristics, and overall performance of polybenzimidazole/graphene oxide (PBI-GO) composite membranes in HT PEMFCs. The PBI composite membranes were prepared with a fixed weight percentage of 2 wt% graphene oxide (GO) and different concentrations of [BMIM][Cl] (from 1 to 3 wt%) by the solution casting method. The results showed that the composite membrane with 2 wt% [BMIM][Cl] (PBI-GO-[BMIM][Cl] (2 wt%)) exhibited optimal ion morphology distribution and lower acid leaching (about 54% loss after 5 hours). In addition, the PBI-GO-[BMIM][Cl] (2 wt%) membrane showed a significantly improved maximum power density of 128.45 mW cm^{-2} at 160 °C compared to the PBI-GO-[BMIM][Cl] (2 wt%) composite membrane, which showed a maximum power density of only 106.70 mW cm^{-2} at 25 °C. The improved performance of the PBI-GO-[BMIM][Cl] (2 wt%) membrane indicates its potential as a cost-effective and highly efficient material for HT-PEMFC applications. The use of this membrane in fuel cell technology could lead to significant cost savings in maintenance and energy consumption, while contributing to a reduction in carbon monoxide and carbon dioxide emissions, in line with industry targets for sustainable energy solutions.

1.0 Introduction

The global increase in energy demand, driven by rapid population growth, industrialisation, and dwindling petroleum-based resources, has intensified the search for alternative energy solutions. Over-reliance on fossil fuels not only threatens the sustainability of resources but also contributes to environmental degradation. Burning fossil fuels releases harmful gases such as carbon monoxide (CO), nitrogen oxides (NO_x), and sulphur oxides (SOx), which have been linked to environmental problems such as acid rain, ozone layer depletion, and global climate change (Masron et al., 2023). Therefore, there is an increasing focus on developing renewable energy systems that are both environmentally friendly and efficient. Electricity, the most widely used form of energy, is predominantly generated from fossil fuels. Recent data shows that 86.4% of global electricity generation is based on fossil fuels such as oil, natural gas, and coal, while only 14.6% comes from renewable energy sources. This over-reliance on non-renewable resources has led researchers to explore cleaner, more sustainable alternatives such as fuel cells. Among the most promising technologies for energy conversion are proton exchange membrane fuel cells (PEMFCs). PEMFCs are highly efficient, produce no emissions, operate silently, and require minimal maintenance. In contrast to conventional methods of energy generation, fuel cells convert chemical energy directly into electrical energy through electrochemical reactions. They only require hydrogen (H_2) and oxygen (O_2) to generate direct current.

PEMFCs are particularly advantageous because they can operate at lower temperatures compared to other types of fuel cells. They are also quieter and use a solid proton exchange membrane for efficient proton conduction. In recent years, extensive research has been conducted to improve the durability, cost efficiency, and overall performance of PEMFCs. These efforts focus on optimizing the configuration, materials, and structure of the catalyst layer to improve fuel cell efficiency while reducing operating costs by increasing the conductivity of the proton exchange membrane (PEM). The core component of a PEMFC is the membrane electrode assembly (MEA), which consists of the PEM, a catalyst layer, and a gas diffusion layer. The MEA is crucial for driving the electrochemical reactions and water management within the fuel cell system. The PEM plays a significant role in influencing performance, durability, and transport phenomena. It acts as an electrolyte that facilitates proton conduction and, at the same time, prevents the flow of electrons. This constant proton conductivity is essential for the stable operation of the PEMFC. In addition to energy applications, proton exchange membranes are also used in water treatment, the food industry, and the pharmaceutical industry. Advances in PEM materials and operating methods are critical to ensure the commercial viability of PEMFCs. Overcoming both technical and economic challenges is key to realizing the full potential of fuel cells as a renewable energy solution, particularly in the development of high-performance, long-life composite nanomaterial membranes tailored to fuel cell applications.

2.0 Literature review

Fuel cells, in particular proton exchange membrane fuel cells (PEMFCs), have proven to be a promising technology for sustainable energy generation thanks to their high efficiency, zero emissions, and versatility in various applications. At the heart of PEMFC performance is the proton exchange membrane (PEM), a critical component responsible for proton conduction and the separation of fuel and oxidizing gases. The properties of the PEM are proton conductivity, thermal stability, and mechanical strength, which have a direct influence on the efficiency and durability of fuel cells. Over the years, various materials have been investigated to improve the overall performance of PEMs (Abidin et al., 2023). This review focuses on the progress that has been made in improving composite nanomaterial membranes, with an emphasis on Nafion membranes and polybenzimidazole (PBI) based alternatives for high-temperature PEMFC (HT-PEMFC) applications. Since the 1970s, Nafion membranes have been widely recognized as the standard for PEMFC applications due to their high proton conductivity and chemical stability. Nafion is a solid polymer electrolyte with a unique structure comprising a hydrophobic polytetrafluoroethylene (PTFE) backbone and hydrophilic sulfonic acid groups (SO_3H) (Yoo et al., 2023). This configuration enables excellent proton conduction, with values of around 100 mS/cm under fully hydrated conditions. Proton conduction in Nafion membranes depends on the presence of water molecules that facilitate the transfer of protons generated at the electrodes during fuel cell operation.

However, despite their excellent proton conductivity, Nafion membranes have some limitations, particularly at high temperatures and in low-humidity conditions. Since Nafion relies on water for proton conduction, maintaining high humidity is critical for consistent performance. At higher temperatures (above 80°C), the proton conductivity of Nafion decreases significantly, which affects the overall performance of the PEMFC (Xu et al., 2024). In addition, the high cost of Nafion membranes (approx. 0.25 €cm^{-2}) further limits their scalability for large-scale fuel cell applications. For fuel cells operating at temperatures above 100°C, maintaining proton conductivity and mechanical strength without relying on proton transport by water is a major challenge. Nafion membranes are less effective at these higher temperatures due to dehydration, resulting in a drastic drop in performance. Research efforts have therefore shifted to the development of alternative PEMs that can also function at high temperatures (Cai et al., 2024)

One promising alternative is polybenzimidazole (PBI), a heterocyclic polymer with a glass transition temperature between 425°C and 435°C, which makes it thermally and mechanically very stable. In contrast to Nafion, PBI does not rely on water for proton transport. Instead, it uses phosphoric acid (PA) as a proton conductor. PA-doped PBI membranes have proven proton conductivity values between 100 and 200 mS/cm at temperatures of up to 200°C. In addition, PBI membranes are less expensive than Nafion membranes, making them a practical possibility for high-temperature applications. Despite these advantages, PBI membranes face challenges in terms of proton conductivity (Xiao et al., 2023). Pure PBI has extremely low conductivity (10^{-9} mS/cm), so a secondary ion-conducting phase must be incorporated to improve performance. The use of PA as a proton conductor has been shown to be effective. However, it introduces new problems, including the need for high water content to maintain conductivity and the risk of phosphoric acid leaching during operation. Excessive PA loading can affect the mechanical properties of the PBI membrane by disrupting the interactions of the polymer chains. To overcome the limitations of Nafion and PBI membranes, researchers have explored the use of composite nanomaterials. These materials aim to improve the thermal and mechanical stability of the membranes while maintaining or increasing proton conductivity. One approach is to incorporate ionic liquids into PBI membranes. Ionic liquids are salts that remain in the liquid phase at low temperatures and serve as proton conductors without requiring water. For example, 1-butyl-3-methylimidazolium chloride ([BMIM][Cl]) has shown a proton conductivity of about 3 mS/cm at room temperature. It has been shown that the addition of [BMIM][Cl] to PBI membranes improves the proton conductivity in HT-PEMFCs and at the same time increases the thermal stability of the membrane.

However, there are still some problems with the use of ionic liquids. They tend to weaken the intermolecular forces between the polymer chains, resulting in lower mechanical strength of the composite membrane. In addition, ionic liquids are physically absorbed into the membrane, which can lead to problems with solubility and lower long-term stability. To address these challenges, researchers are investigating different strategies to stabilize composite materials with ionic liquids, including the development of new polymer matrices that better retain ionic liquids during fuel cell operation. Another promising way to improve PEM performance is to incorporate graphene oxide (GO) as a filler (Barnoon, 2023). GO is a two-dimensional carbon material with a large surface area and numerous functional groups, such as hydroxyl, carboxyl, and epoxy groups. These groups can be easily modified to improve proton conductivity and mechanical strength. The large surface area of GO improves the physical properties of the membrane, while its functional groups enable interaction with other membrane components. However, GO-based composite membranes face challenges related to the homogeneity of the material. At high concentrations, GO tends to agglomerate, resulting in uneven surfaces and reduced performance. In addition, the GO structure lacks functional groups that can serve as effective proton carriers, limiting its contribution to proton conduction (Zhang et al., 2024). Ongoing research aims to mitigate these issues by developing more homogeneous GO composites and exploring methods to improve the proton transport capabilities of GO. The development of high-performance, durable composite nanomaterial membranes for PEMFC applications remains an important area of research. While Nafion has long been the reference material for membranes, its limitations at high temperatures and high cost have driven the search for alternatives. PBI-based membranes, especially those doped with phosphoric acid, offer promising solutions for HT-PEMFCs, although challenges related to proton conductivity and mechanical stability remain. The incorporation of ionic liquids and graphene oxide into PEMs represents a significant advance in overcoming these challenges, offering improved conductivity and stability for high-temperature fuel cell applications. Further research is needed to optimise the composition and performance of composite membranes, particularly in terms of balancing proton conductivity, mechanical strength, and long-term durability. By overcoming these challenges, composite membranes made of nanomaterials can play a crucial role in the further development of fuel cell technology into a sustainable and efficient energy solution for the future.

3.0 Methodology

The first step in the production of a pure PBI composite membrane is to synthesize the PBI polymer by polycondensation processes, which are known to give the polymer excellent thermal and chemical stability. To produce the polymer solution, the PBI is dissolved in a suitable solvent. In this study, dimethylacetamide (DMAc) was selected as the solvent due to its high boiling point and ability to effectively dissolve PBI. In a typical preparation, 30 millilitres of DMAc was measured and added to a beaker, followed by 0.6 grammes of PBI mesh polymer. The mixture was then heated on a hot plate and stirred continuously for one hour to ensure complete dissolution of the PBI and to obtain a homogeneous polymer solution. The temperature was carefully controlled throughout the process to prevent degradation of the polymer. After one hour, the beaker was removed from the hotplate, and the homogeneous PBI solution was poured into a glass petri dish with a diameter of 100 mm. In the next step, the PBI solution was evenly distributed in the petri dish to form a thin membrane. The petri dish with the polymer solution was then placed in a convection oven set to 80°C for 12 hours to allow initial drying. The oven temperature was then increased to 150°C for a further 12 hours to ensure complete evaporation of the solvent and correct membrane formation. After the drying process, the PBI composite membrane was carefully removed from the petri dish by soaking it in distilled water at 60°C. This soaking step helps to release the membrane from the dish and ensures that it retains its integrity and uniform thickness. To improve the properties of the PBI membrane, a composite membrane of PBI and graphene oxide (PBI-GO) was produced using a similar but modified process. First, the PBI polymer was dissolved in dimethylacetamide (DMAc) to obtain a homogeneous PBI solution, as previously described. Then, 0.03 grams of graphene oxide (GO) were added to the solution. Graphene oxide is known for its exceptional mechanical and thermal properties, making it a suitable additive for reinforcing the PBI matrix.

The mixture was stirred vigorously to ensure an even distribution of the graphene oxide in the PBI solution. This step is crucial as agglomeration of the GO particles could affect the mechanical properties and uniformity of the resulting membrane. Once a homogeneous mixture was achieved, the PBI-GO composite membrane was produced using the solution casting method. The PBI-GO solution was poured into a glass petri dish with a diameter of 100 mm and dried in a convection oven. Initially, the oven was set to 80°C for 12 hours, then the temperature was increased to 150°C for a further 12 hours. This controlled drying process is important to obtain a composite membrane with the desired mechanical strength and thermal stability. Once the drying process was complete, the PBI-GO membrane was removed from the petri dish by immersing it in distilled water heated to 60°C. This final step ensured that the membrane could be easily detached from the petri dish without damaging its structure (Li et al., 2023). The production of the PBI-GO-[BMIM][Cl] (1–3 wt%) composite membrane involves a series of precisely defined steps to ensure optimal properties of the final product. First, the PBI polymer is dissolved in dimethylacetamide (DMAc) to obtain a uniform solution. This solution is stirred thoroughly to ensure complete dissolution of the polymer. Next, the ionic liquid 1-butyl-3-methylimidazolium chloride

([BMIM][Cl]) is added along with a solid portion of 2 wt% graphene oxide (GO). The choice of [BMIM][Cl] is based on its conductive properties and its compatibility with the PBI and GO matrix to improve the overall performance of the composite membrane. The resulting mixture is heated and stirred at 50°C for three hours to obtain a homogeneous mixture of PBI, GO, and [BMIM][Cl]. The weight percentage of the ionic liquid (1–3 wt%) is carefully adjusted to achieve the desired conductivity and mechanical properties of the final membrane. After obtaining a uniform mixture, 30 millilitres of the solution is poured into a glass Petri dish with a diameter of 100 mm. To produce the composite membrane, the solution is subjected to a controlled drying process in a convection oven. Initially, the oven is set to 80°C for 12 hours to partially vaporise the solvent. The temperature is then increased to 150°C for a further 12 hours to ensure complete removal of the solvent and correct formation of the membrane. Finally, the dried PBI-GO-[BMIM][Cl] (1–3 wt%) composite membrane is carefully removed from the Petri dish by soaking it in distilled water at 60°C, which facilitates its release without compromising its mechanical integrity. This methodical process for preparing pure PBI, PBI-GO, and PBI-GO-[BMIM][Cl] (1–3 wt%) composite membranes emphasise the critical importance of precise temperature control, solvent selection, and drying conditions. These factors are crucial to obtain materials with improved thermal, chemical, and mechanical properties suitable for a variety of advanced applications (Huang et al., 2014).

4.0 Discussion of analysis and findings

Figure 1 shows the physical appearance of the PBI, PBI-GO, and PBI-GO-[BMIM][Cl] (1–3 wt%) composite membranes. The images show that the PBI and PBI-GO, and PBI-GO-[BMIM][Cl] (1–3 wt%) membrane is characterised by a dark brown colour. This membrane also has a smooth, flat, and homogeneous surface morphology. It is noteworthy that the PBI-GO-[BMIM][Cl] (1–3 wt%) membrane exhibits higher flexibility compared to the PBI and PBI-GO membranes, indicating that the incorporation of [BMIM][Cl] contributes positively to the mechanical properties of the composite.

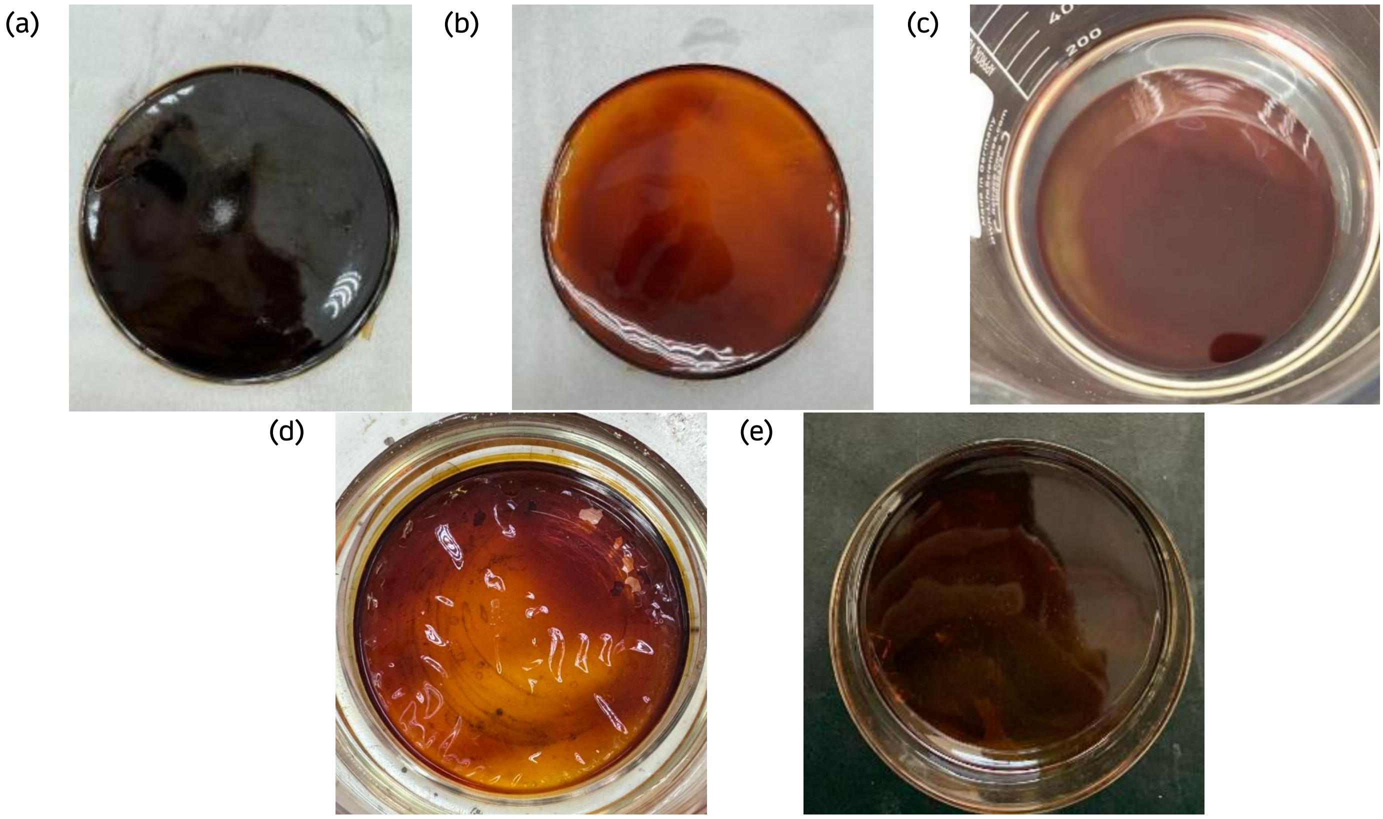
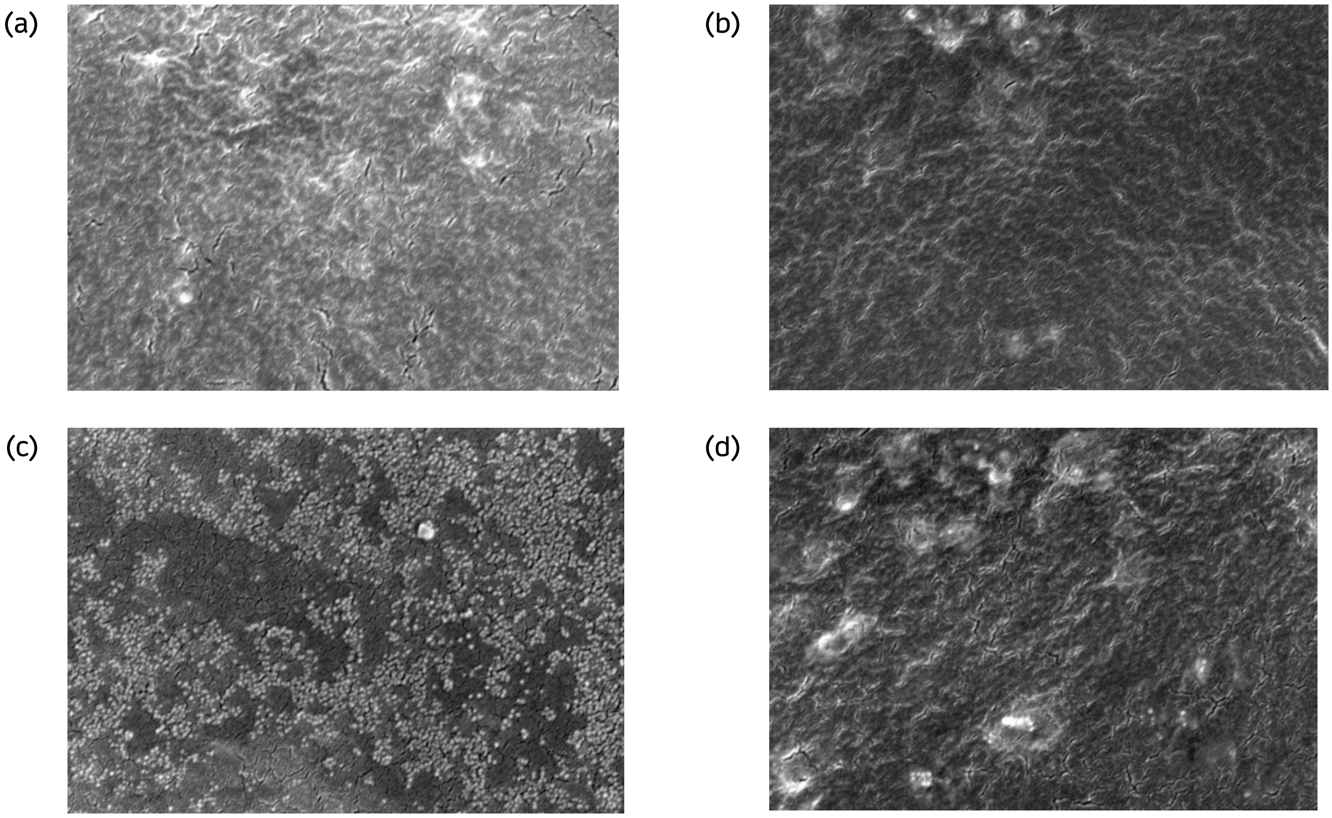


Figure 1.: Composite membrane (a) PBI; (b) PBI-GO; (c) PBI-GO-[BMIM][Cl] (1 wt.%); (d) PBI-GO-[BMIM][Cl] (2 wt.%); (e) PBI-GO-[BMIM][Cl] (3 wt.%)

The morphological properties of PBI, PBI-GO and PBI-GO-[BMIM][Cl] (1–3 wt %) composite membranes were analysed by field emission scanning electron microscopy (FESEM). The FESEM cross-sectional images shown in Figure 2 provide a detailed insight into the structural differences between these membranes and their effects on the performance and longevity of the fuel cells. A major challenge with high-temperature polymer electrolyte membrane fuel cells (HT-PEMFCs) is the degradation of the membrane, which has a direct impact on the efficiency and lifetime of the cell (Van et al., 2023). Figure 2 illustrates how this degradation manifests itself in the form of delamination on the catalyst layer on the membrane surface. This delamination can severely affect the performance of the HT-PEMFC single cell, demonstrating that membrane integrity is critical to maintaining efficient fuel cell operation (Kahraman et al., 2024). At higher operating temperatures, membrane degradation becomes more pronounced, mainly due to oxidative processes. Peroxide radicals, such as OH and OOH, attack the membrane surface and facilitate oxidative degradation. This degradation is further enhanced when oxygen interacts with the insufficient reduction of anodics on the membrane surface, leading to the formation of peroxides. These reactive peroxides then interact with transition metal ions originating from bipolar or metallic components within the fuel cell. The result is the formation of holes on thin, uneven membrane surfaces, which can lead to fuel leaks and contribute to the overall degradation of fuel cell performance (Shahbudin et al., 2008). In the case of the PBI-GO-[BMIM][Cl] (1–3 wt %) composite membranes, its performance at high temperatures is significantly impaired by the loss of phosphoric acid (PA) content. This loss leads to detachment of the membrane electrode assembly (MEA), an increase in cell resistance, and a decrease in proton conductivity (Cheng et al., 2023). As a result, the efficiency of the HT-PEMFC single cell deteriorates over time. The interaction between water and the ionic liquid group in the PBI-GO-[BMIM][Cl] (1–3 wt%) composite membranes reduce the ability of the membrane to retain PA. This emphasises the importance of the cross-linked networks in the membrane, which play a crucial role in limiting the contact between the PA molecules and maintaining the structural integrity of the membrane.



(e)

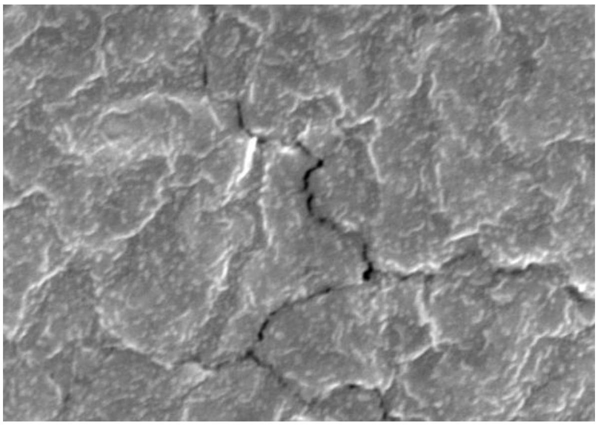


Figure 2.: FESEM images of composite membrane at 5000x magnification (a) PBI; (b) PBI-GO; (c) PBI-GO-[BMIM][Cl] (1 wt.%); (d) PBI-GO-[BMIM][Cl] (2 wt.%); (e) PBI-GO-[BMIM][Cl] (3 wt.%)

The FESEM images (Figure 2) also show important morphological differences between the different composite membranes. The PBI membrane exhibited a homogeneous surface, which is characteristic of its distinct polymer properties (Moorthy et al., 2023). In contrast, the surface morphology of the PBI-GO composite membrane showed remarkable changes due to the incorporation of 1-butyl-3-methylimidazolium chloride [BMIM][Cl] (Wilberforce et al., 2024). The presence of [BMIM][Cl] dispersed in the polymer matrix indicates that GO was uniformly integrated into the PBI matrix. This uniform dispersion likely improves the mechanical, thermal, and electrical properties of the membrane, contributing to its improved performance in fuel cell applications. Overall, the structural analysis suggests that the incorporation of materials such as graphene oxide and ionic liquids into PBI membranes significantly alters their morphology and performance. The homogeneous distribution of [BMIM][Cl] in the PBI-GO composite membrane indicates potential improvements in material properties, including increased mechanical strength and thermal stability. PBI-GO-[BMIM][Cl] (2 wt%) composite membrane shows the most homogenous surface with a good flow of ions or molecules, as shown in Figure 2. The issues observed in the PBI-GO-[BMIM][Cl] (3 wt%) composite membrane, such as PA loss and increased susceptibility to oxidative degradation, indicate areas where further optimization is required to improve the longevity and efficiency of HT-PEMFCs (Sun et al., 2023). This discussion highlights the importance of optimizing the composition and structure of the membrane to mitigate degradation processes, improve performance, and extend fuel cell lifetime. Further research focusing on improving the interconnected networks within these composite membranes could prove beneficial in reducing oxidative degradation and improving PA retention, ultimately leading to longer lasting and more efficient fuel cells (Bodkhe et al., 2023).

The acid leaching tests for fuel cell membranes, especially for proton exchange membranes (PEMs) used in polymer electrolyte membrane fuel cells (PEMFCs), are performed to evaluate the longevity and performance of the membranes under realistic conditions. PEMs, such as PBI-GO-[BMIM][Cl] composite membranes, play a crucial role in the conduction of protons and the separation of fuel and oxidant streams (Gao et al., 2023). In this study, five composite membrane samples were used to investigate their performance. The results can be summarised as follows in Table 1. A higher percentage of acid leaching correlates with loss of free ions attached to the composite membranes, which could decrease the performance of the composite membrane in a fuel cell. Initially, the PBI-GO membrane showed a higher peak acid leaching percentage than the PBI-GO-[BMIM][Cl] within the first five hours. In contrast, the PBI-GO-[BMIM][Cl] composite membrane showed a higher acid content of about 60% in the five hours before stabilizing. The acid solubility test was crucial to determine the acid retention capacity of the composite membranes, which significantly affects the degradation of high-temperature PEMFCs. PBI-GO-[BMIM][Cl] showed superior acid retention compared to PBI-GO due to the ionic liquid particles that capture and hold the acid molecules via covalent bonds, minimizing the loss of soluble acid. The hydrophilic nature of the filler in PBI-GO-[BMIM][Cl], together with hydrogen bonding, contributes to the reduction in acid solubility. However, an increase in the acid solubility rate was observed as the ionic liquid content decreased towards the end of the test. This increase can be attributed to the increased ionic liquid content in the composite membrane, which leads to a decrease in the surface area of PBI and its ability to trap acid molecules.

Table 1: Acid leaching test composite membrane

Composite membrane	Acid leaching after 5 hours (%)	Temperature (⁰C)
PBI	68	60
PBI-GO	64	60
PBI-GO-[BMIM][Cl] (1 wt.%)	57	60
PBI-GO-[BMIM][Cl] (2 wt.%)	54	60
PBI-GO-[BMIM][Cl] (3 wt.%)	58	60

As shown in Figure 3, the remarkable improvement in the maximum power density of the PBI-GO-[BMIM][Cl] (2 wt.%) composite membrane, which achieved 128.45 mW cm^{-2} at 160 °C compared to 106.70 mW cm^{-2} for the PBI-GO-[BMIM][Cl] (2 wt.%) at 25 °C, is attributed to the synergistic effects of incorporating [BMIM][Cl] (1-butyl-3-methylimidazolium chloride) into the membrane matrix. The addition of [BMIM][Cl] significantly enhances proton conductivity, as its mobile ions facilitate proton transport within the polybenzimidazole (PBI) and graphene oxide (GO) matrix. At 2 wt.%, [BMIM][Cl] forms an optimized, interconnected ionic network that accelerates proton movement, directly increasing ionic conductivity and resulting in the observed higher power density. Furthermore, the presence of [BMIM][Cl] increases the membrane's hydrophilicity, enabling it to retain water molecules that are essential for effective proton conduction, especially at elevated temperatures like 160 °C. This hydration support creates a continuous pathway for proton transport, thereby improving the membrane's overall electrochemical performance (Seng et al., 2021).

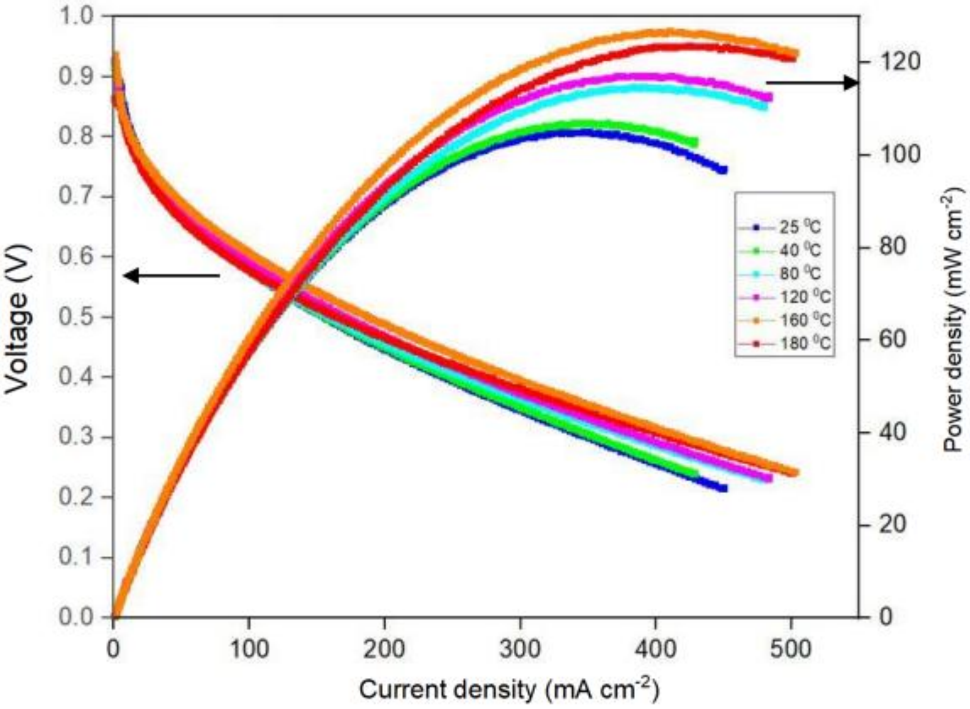


Figure 3.: Polarization curve PBI-GO-[BMIM][Cl] (2 wt.%)

5.0 Conclusion and Future Research

PBI-based composite membranes have gained significant attention among researchers in the pursuit of developing advanced materials for high-temperature proton exchange membrane fuel cells (HT-PEMFC). This study aimed to explore alternative proton exchange membranes (PEMs) for HT-PEMFC applications by focusing on the development and evaluation of PBI-GO-[BMIM][Cl] composite membranes. Further examination using FESEM confirmed the presence of ions within the PBI-GO-[BMIM][Cl] composite membrane. By employing a magnification of 5000, the ionic components could be visualized, highlighting the ion-rich structure of PBI-GO-[BMIM][Cl] composite membrane. The acid leaching test results further supported the superior performance of PBI-GO-[BMIM][Cl] composite membrane compared to PBI-GO composite membrane, reinforcing the potential of ionic fluid incorporation in enhancing membrane stability and durability. The findings of this study underscore the effectiveness of the ionic liquid [BMIM][Cl] in imparting the desired characteristics to the PBI-GO-[BMIM][Cl] composite membrane. Notably, the PBI-GO-[BMIM][Cl] (2 wt.%) demonstrated high potential for application in HT-PEMFCs, offering a promising alternative to conventional Nafion membranes. Unlike Nafion, which exhibits suboptimal performance at elevated temperatures due to its relatively low proton conductivity, the PBI-GO-[BMIM][Cl] (2 wt.%) composite membrane presents an improved solution that can withstand the demanding conditions of high-temperature fuel cell operations. In conclusion, the study has successfully identified PBI-GO-[BMIM][Cl] (2 wt.%) as a potential replacement for Nafion in PEMFC applications, especially under high-temperature conditions. The enhanced proton conductivity, ion-rich structure, and stable performance of this composite membrane make it a strong candidate for further development in HT-PEMFC technology. With its demonstrated efficiency, PBI-GO-[BMIM][Cl] (2 wt.%) could pave the way for more durable, high-performance fuel cells, thereby contributing to the advancement of clean energy technologies. Future research could focus on optimizing the membrane synthesis process, further improving its conductivity, and exploring its long-term operational stability to fully realize its potential in practical fuel cell applications.

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Author Contributions

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K.S. Leong: Conceptualization, Methodology, Writing- Original Draft Preparation; **K.S. Leong, K.S Andarany**: Data Curation, Validation, Supervision; **A. Sunatrah**: Validation, Writing-Reviewing and Editing.

Conflicts of Interest

The manuscript has not been published previously and is not under consideration by any other journals. All authors have approved the content for review, consent to its submission, and declare no conflicts of interest related to this manuscript.

6.0 References

Abidin, A. S. Z., Kurnin, N. A. A., & Samat, S. (2023). Morphological Analysis of Bottle Cap and Face Mask as Composite Materials. *International Journal Of Technical Vocational And Engineering Technology*, *4*(1), 18-23.

Barnoon, P. (2023). Thermal performance assessment of a low power proton exchange membrane fuel cell with various air-cooled channels. *International Journal of Thermofluids*, *20*, 100422.

Bodkhe, R. G., Shrivastava, R. L., Soni, V. K., & Chadge, R. B. (2023). A review of renewable hydrogen generation and proton exchange membrane fuel cell technology for sustainable energy development. *International Journal of Electrochemical Science*, *18*(5), 100108.

Cai, F., Cai, S., & Tu, Z. (2024). Proton exchange membrane fuel cell (PEMFC) operation in high current density (HCD): Problem, progress and perspective. Energy Conversion and Management, 307, 118348.

Cheng, H., Liu, Z., Luo, H., Pan, Z., Wang, X., Zhao, Q., ... & Li, X. (2023). Tuning the microstructure to improve corrosion resistance of additive manufacturing high-entropy alloy in proton exchange membrane fuel cells environment. *Corrosion Science*, *213*, 110969.

Gao, X., Chen, J., Xu, R., Zhen, Z., Zeng, X., Chen, X., & Cui, L. (2023). Research progress and prospect of the materials of bipolar plates for proton exchange membrane fuel cells (PEMFCs). *International Journal of Hydrogen Energy*.

Huang, C., Wu, Z., & Zheng, J. (2024). Effects of concentrated CO_2 on the performance of a PBI/H_3PO_4 high temperature proton exchange membrane fuel cell. Journal of Power Sources, 614, 235053.

Kahraman, H., & Akın, Y. (2024). Recent studies on proton exchange membrane fuel cell components, review of the literature. *Energy Conversion and Management*, *304*, 118244.

Li, Z., Wang, Y., Mu, Y., Wu, B., Jiang, Y., Zeng, L., & Zhao, T. (2023). Recent advances in the anode catalyst layer for proton exchange membrane fuel cells. *Renewable and Sustainable Energy Reviews*, *176*, 113182.

Masron, Z. (2023). Palm Oil Mill Effluent (POME) Pretreatment Using Tapioca Starch as A Coagulant. *International Journal Of Technical Vocational And Engineering Technology*, *4*(1), 32-40.

Moorthy, S., Sivasubramanian, G., Kannaiyan, D., & Deivanayagam, P. (2023). Neoteric advancements in polybenzimidazole based polymer electrolytes for high-temperature proton exchange membrane fuel cells-A versatile review. *International Journal of Hydrogen Energy*, *48*(72), 28103-28118.

Seng, L. K., Masdar, M. S., & Shyuan, L. K. (2021). Ionic liquid in phosphoric acid-doped polybenzimidazole (PA-PBI) as electrolyte membranes for PEM fuel cells: A review. Membranes, 11(10), 728.

Shahbudin, S., Hussain, A., Samad, S. A., & Tahir, N. M. (2008, October). Training and analysis of support vector machine using sequential minimal optimization. In *2008 IEEE International Conference on Systems, Man and Cybernetics* (pp. 373-378). IEEE.

Sun, X., Guan, J., Wang, X., Li, X., Zheng, J., Li, S., & Zhang, S. (2023). Phosphonated ionomers of intrinsic microporosity with partially ordered structure for high-temperature proton exchange membrane fuel cells. *ACS Central Science*, *9*(4), 733-741.

Van Der Linden, F., Pahon, E., Morando, S., & Bouquain, D. (2023). A review on the Proton-Exchange Membrane Fuel Cell break-in physical principles, activation procedures, and characterization methods. *Journal of Power Sources*, *575*, 233168.

Wilberforce, T., Olabi, A. G., Muhammad, I., Alaswad, A., Sayed, E. T., Abo-Khalil, A. G., ... & Abdelkareem, M. A. (2024). Recovery of waste heat from proton exchange membrane fuel cells–A review. International Journal of Hydrogen Energy, 52, 933-972.

Xiao, F., Chen, T., Zhang, J., & Zhang, S. (2023). Water management fault diagnosis for proton-exchange membrane fuel cells based on deep learning methods. *International Journal of Hydrogen Energy*, *48*(72), 28163-28173.

Xu, K., Fan, L., Sun, J., Chen, A., & Xu, C. (2024). Comprehensive performance assessment and multi-objective optimization of high-power proton exchange membrane fuel cell system under variable load. *Fuel*, *363*, 130942.

Yoo, T. Y., Lee, J., Kim, S., Her, M., Kim, S. Y., Lee, Y. H., ... & Hyeon, T. (2023). Scalable production of an intermetallic Pt–Co electrocatalyst for high-power proton-exchange-membrane fuel cells. *Energy & Environmental Science*, *16*(3), 1146-1154.

Zhang, G., Qu, Z., Tao, W. Q., Mu, Y., Jiao, K., Xu, H., & Wang, Y. (2024). Advancing next-generation proton-exchange membrane fuel cell development in multi-physics transfer. Joule, 8(1), 45-63.