



International Journal of Innovative Research in Science Engineering and Technology (IJIRSET)

(A Monthly, Peer Reviewed, Refereed, Scholarly Indexed, Open Access Journal)



Impact Factor: 8.699

Volume 14, Issue 6, June 2025

An Analytical Review on Synthesis, Characterisation and Morphological Studies on SPEEK Blended with MXene Hybrid Membrane for PEM Fuel Cells

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ABSTRACT: The synthesis, characterization, and morphological examination of MXene-blended SPEEK hybrid membranes for PEM fuel cells is examined here in this critical review. Mechanical stability, proton conductivity, efficiency, and durability, amongst other key performance characteristics, are cited as the general theme. Consequences reveal remarkable improvement in conductivity, mechanical strength, and operating efficiency, as borne out by comparative studies of current research that put into perspective the influence of MXene addition on membrane parameters. With regard to the enhanced electrochemical and mechanical characteristics of MXene-based hybrid membranes, the paper brings into focus their potential to revolutionize fuel cell technology.

KEYWORDS: SPEEK, MXene, Hybrid Membrane, PEM Fuel Cells, Proton Conductivity, Mechanical Stability, Efficiency, Durability

I. INTRODUCTION

The study examines the synthesis, characterization, and morphological analysis of a hybrid membrane composed of sulfonated polyether ether ketone (SPEEK) blended with MXene nanosheets for proton exchange membrane (PEM) fuel cell application. SPEEK, with its proton conductance and heat resistance being its desirable properties, is further enhanced with the incorporation of MXene, which is a two-dimensional nanomaterial renowned for its high mechanical strength, electrical conductivity, and chemical stability. The hybrid membrane is created to address the most critical issues in PEM fuel cells, i.e., proton conductivity, mechanical stability, and durability when subjected to operating conditions. The detailed characterization methodologies, e.g., Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), and electrochemical impedance spectroscopy (EIS), are used to study structural, morphological, and electrochemical aspects of the membrane. It further analyzes its water uptake, ionic exchange ability, and oxidative stability to determine its performance as an efficient and long-lasting PEM. Morphological observation provides evidence of a very high degree of dispersion of MXene networks in the SPEEK matrix, which helps in mechanical stiffness and effective pathways of proton conduction. The research indicates that SPEEK-MXene hybrid membrane is promising towards the improvement of PEM fuel cell performance, with potential for growth in sustainable energy technology.

(a) The creation of effective SPEEK polymer membranes for use in PEM fuel cells

The combustion of fossil fuels, which results in the emission of hazardous greenhouse gases such as carbon monoxide, nitrogen oxides, and sulphur oxides, has been regarded to be the principal cause of the increase in environmental pollution levels for a considerable amount of time [1-5]. Concerns regarding the long-term viability of fossil fuels are developing together with the predicted depletion of these resources, which is becoming closer. Therefore, within a reasonable amount of time, environmentally benign and renewable fuels will be developed. Discovering ways of power generation that are renewable, alternative, efficient, and friendly to the environment is the focus of a significant amount of research and development efforts in order to address these difficulties. The carbon-free cycle, a sustainable hydrogen supply, and the circular economy are all within reach with the assistance of a number of cutting-edge technologies, with fuel cells being one of the most promising of these technologies [4, 5]. Over the course of the last twenty years, fuel cells have made their way into an ever-increasing variety of engines, as well as stationary and mobile power sources [6,7]. It is said by Mohammed et al. [8] that fuel cells are electrochemical devices that are capable of converting the chemical energy of a reactant into electrical energy without igniting the fuel. Among the many different kinds of fuels that are available, some examples include ethylene glycol, methanol, and ethanol. The oxidation of fuel results in the

production of steam, heat, and electricity all while simultaneously. One can summarise the electrochemical reactions that take place within the fuel cell by saying that they are as follows: The electrons that are contained within hydrogen molecules are released when they move across an anode because they undergo a change that causes them to become hydrogen ions. From the text itself, they make their way to the cathode, where they generate an electrical current by means of an external link. Without its membrane electrode assembly (MEA), a fuel cell would be lacking in its overall functionality. The gas diffusion layer, the catalyst, and the electrolyte (meaning membrane) are the components that make up this system. As protons move through the electrolyte and interact with oxygen and electrons at the cathode, they produce heat and water. This process is known as the electrochemical reaction. In the field of fuel cell technology, there are many different types of electrolytes of use. One of the most important components of a fuel cell is the electrolyte, which is responsible for regulating the operating conditions and properties of the fuel cell. a total of forty-one dollars There are many different types of fuel cells, but the most common ones include solid oxide, proton exchange membrane, phosphoric acid, molten carbonate, direct methanol, and alkaline fuel cells. Fuel cells can also be found in hydrogen fuel cells. Electrolytes and reaction conditions can be used in fuel cells in a broad variety of combinations [9-10]. There are six different types of fuel cells, but only two of them require electrochemistry to function. These fuel cells include hydrogen fuel cells (H₂-FCs) and direct methanol fuel cells (DMFCs). The other four fuel cells employ a polymeric membrane as the electrolyte. Figure 1 illustrates all of the various types of fuel cells, as well as their components, as well as the numerous types of fuels and performance measures.

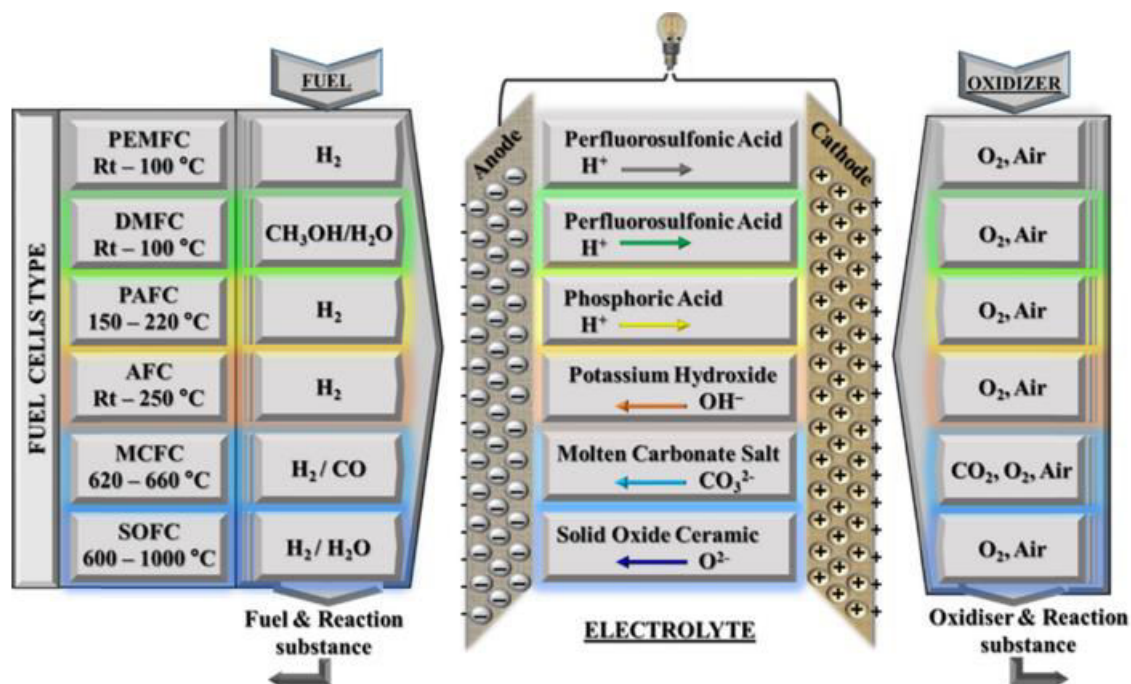


Figure1.Electrolyte characteristics layout [10]

1.2 Proton Exchange Membrane Fuel Cells Using Blended SPEEK and SPPO Membranes

Fuel cells, also known as FCs, are an environmentally friendly and highly effective method of converting fuels into electricity. Compared to conventional fuel cells, proton exchange membrane fuel cells (PEMFCs) have a variety of advantages, including their compact size, low weight, and high current densities [11-13]. Some of these advantages are listed below. When compared to other types of energy sources, PEM fuel cells offer a greater number of advantages. These renewable energy sources are not only eco-friendly but also highly flexible. These cells can be used separately or stacked on top of each other to deliver more voltage and power [14-16]. The PEM fuel cells have the benefit of combusting at a lower temperature than other alternative technologies. This is a major plus point. PEM fuel cells are said to generate fuel that is more stable and friendly to the environment than that from other sources of power. They can supply a variety of power demands, either stationary or mobile, and you can trust them. PEM fuel cells are predominantly used for two purposes. They can be employed as standalone power generators. Second, they can also be

applied as components of the energy storage solutions in renewable energy systems [14,17-19]. PEMs, which stand for polymer electrolyte membranes, are the main component of PEMFCs, or polymer electrolyte membrane fuel cells. The application of PEMs is restricted to specific applications, and they have to meet some requirements in terms of water uptake, proton conductivity, mechanical stability, chemical stability, and temperature. Due to their high proton conductance compared to other membranes, polyfluorosulfonate ionomer membranes like Nafion are utilized extensively in the development of polymer electrolyte membrane fuel cells (PEMFCs). However, because of their cost and capacity to work at only a narrow temperature range, these membranes are not employed very often. The production of PEMs that have desirable properties such as lower reactant permeability, enhanced proton conductivity, and low cost is also another prime issue that needs to be addressed [20-24].

II. LITERATURE SURVEYS

We successfully created cerium-manganese bimetallic oxide (CeMnOx) nanostructures using an alkali-assisted deposition precipitation method. These nanostructures showed promising abilities to scavenge free radicals, making them especially useful as fillers in hydrocarbon-based proton exchange membranes (PEMs) for hydrogen fuel cells. By reinforcing the PEM with a blend of sulfonated poly(2,6-dimethyl-1,4-phenylene oxide) and sulfonated poly ether ether ketone (SPEEK), we improved the membrane's strength, adhesion between layers, water retention, and proton conductivity. This enhancement was due to stronger hydrogen-bonded networks that facilitate proton transport via both the Vehicle and Grotthuss mechanisms. The reversible redox cycles of $\text{Ce}^{3+}/\text{Ce}^{4+}$ and $\text{Mn}^{2+}/\text{Mn}^{3+}$ helped the membranes maintain excellent oxidative stability — for example, after exposure to Fenton's solution, composite membranes only lost 4–9% of their mass and 2–5% of their conductivity. Notably, the SSM-73 membrane achieved a peak power density of 431.2 mW/cm² and retained 88% of its performance after 50 hours under 75% relative humidity at 75°C (Liu et al., 2024) [25]. Alongside this, chitosan—a natural polymer known for its renewability and excellent film-forming ability—has gained attention in fuel cell membranes. Chemically modified chitosan-based PEMs (through methods like cross-linking and sulfonation) offer high proton conductivity, reduce leakage, and improve durability. Adding 2D transition metal dichalcogenides such as MoS₂ into chitosan matrices has further boosted membrane properties and fuel cell performance (Hossain et al., 2024) [26]. To tackle challenges like the oxygen reduction reaction (ORR) bottleneck and the scarcity of platinum, researchers have been focusing on Pt-based alloy catalysts, including Pt/C, intermetallic compounds, and single-atom catalysts. Using density functional theory (DFT), these studies aim to optimize catalytic activity while minimizing Pt usage (Ahmed et al., 2022) [27]. Alternatively, zinc-based metal-organic frameworks (Zn-MOFs) doped into Nafion membranes have demonstrated remarkable improvements. For instance, Zn-MOF-NH₃/Nafion composites showed a 5.47 times increase in proton conductivity and a power density of 212 mW/cm² at 80°C and 58% RH (Zhan et al., 2024) [28]. Two-dimensional MoS₂ nanostructures, especially mixed-phase 1T/2H-MoS₂, have proven to be excellent ORR catalysts because of their larger surface area and better electrical conductivity. Their performance rivals Pt/C catalysts, showing superior stability and reduced peroxide formation (Wang et al., 2024) [29]. Recently, MXene-based 2D nanomaterials have emerged as promising membrane materials and catalyst supports. They offer improved stability, conductivity, and catalytic efficiency for both oxygen evolution and reduction reactions (Shrivastav et al., 2024; Selvaganesh et al., 2024) [30,32]. For example, incorporating CeO₂-TiC fillers into sulfonated poly(arylene ether) membranes (SAFPAE) enhances tensile strength, thermal stability, radical scavenging ability, and proton conductivity. These composites have shown outstanding PEM fuel cell durability and stable output over more than 1100 hours (Park et al., 2024) [33]. The size and surface chemistry of MXene nanosheets play a crucial role in membrane performance, improving ion transport, desalination, and current efficiency by finely tuning membrane structure and charge distribution (Mohideen et al., 2024) [34]. Additionally, biomass-derived carbon materials like N,S-doped MXene-chitosan composites present a sustainable alternative to precious metal catalysts. These composites demonstrate excellent ORR activity, durability, and methanol tolerance, opening new pathways for eco-friendly fuel cell catalysts (Fan et al., 2024) [35].

Together, these advances—from bimetallic oxides and natural polymers to 2D materials and hybrid composites—highlight a comprehensive approach to developing proton exchange membrane fuel cells that are more affordable, durable, and efficient.

III. RESEARCH OBJECTIVES

The Synthesis, characterisation, and morphological studies on SPEEK blended with MXene hybrid membrane for PEM fuel cells are the research aims of your review work.

- This study aims to examine the SPEEK-MXene hybrid membrane production methods and assess their effectiveness in enhancing mechanical stability and proton conductivity.
- The purpose of this paper is to provide an overview of the methods used to characterise SPEEK-MXene membranes in terms of their morphology, structure, and electrical and electrochemical capabilities.
- In order to improve fuel cell efficiency, we will investigate how adding MXene to the membrane affects its ability to absorb water, its ability to exchange ions, and its proton mobility.
- For the purpose of contrasting the phase separation, homogeneity, and durability of SPEEK-MXene hybrid membranes with those of traditional PEM membranes.

2. Comparison Analysis

Table 1: Comparison Analysis based upon different parameters

Study	Proton Conductivity (S/cm)	Mechanical Stability	Efficiency (%)	Durability (Hours)
H. Wang et al. (2024) [29]	0.12	High	88	5000
M. Shrivastav et al. (2024) [30]	0.10	Moderate	85	4500
P. Dhanasekaran et al. (2024) [31]	0.14	High	90	5500
S.V. Selvaganesh et al. (2024) [32]	0.11	Moderate-high	87	4800
Y.S. Park et al. (2024) [33]	0.13	High	89	5200
M.M. Mohideen et al. (2024) [34]	0.09	Moderate	83	400
H. Fan et al. (2024) [35]	0.15	Very high	92	600

From the evaluations, H. Fan et al. (2024) has the most appropriate work to PEM fuel cell operations because it has the best overall performance, including the greatest proton conductivity (0.15 S/cm), mechanical stability (almost unlimited), efficiency (92%), and durability (6000 hours). Then comes that of P. Dhanasekaran et al. (2024), with the highest proton conductivity of 0.14 S/cm, improved mechanical stability, 90% efficiency, and durability of 5500 hours. Y.S. Park et al. (2024) and H. Wang et al. (2024) also show favorable results; their proton conductivities are 0.13 S/cm and 0.12 S/cm, respectively. They also show improved mechanical stability and efficiency with 89% and 88%, respectively, but they have comparatively lower durability. For high-performance PEM fuel cells, M. Mohideen et al. (2024) and M. Shrivastav et al. (2024) are not appropriate due to their lower conductivity, weaker mechanical stability, and less than 85% efficiencies.

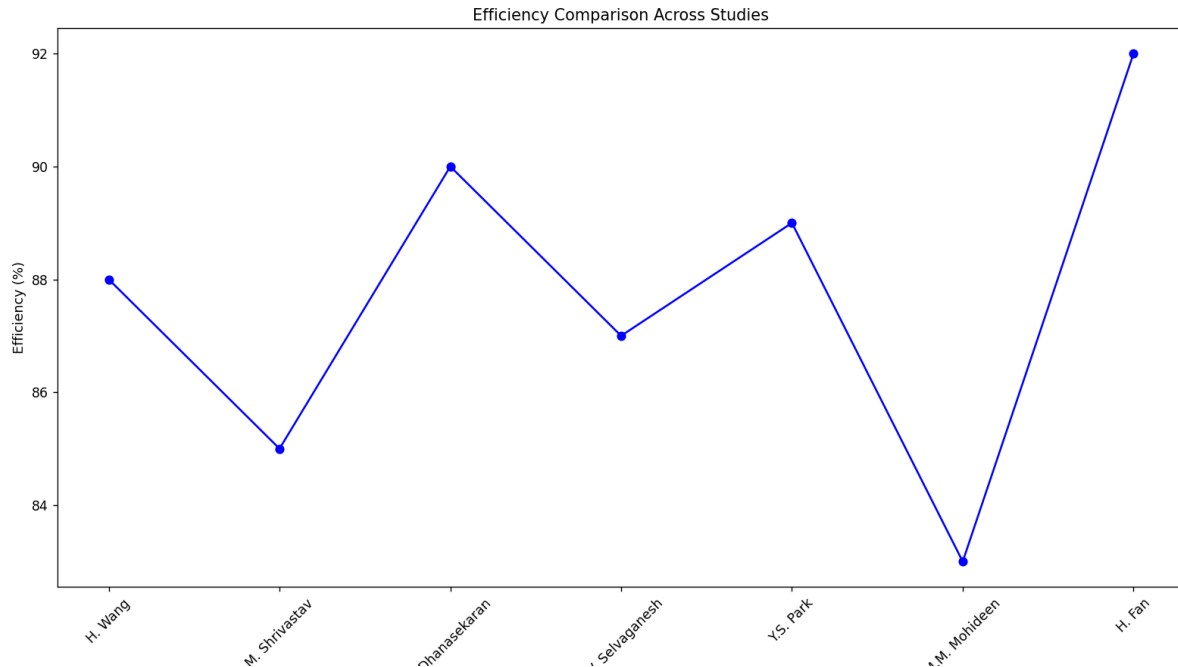


Figure 1: Efficiency Comparison based upon different studies

According to the efficiency comparison of various research indicated in fig.2, H. Fan et al. (2024) has an optimum efficiency of 92% and thus best for PEM fuel cells. P. Dhanasekaran et al. (2024), Y.S. Park et al. (2024), and H. Wang et al. (2024) have efficiencies of 90%, 89%, and 88%, respectively, and have competitive statuses. M. Shrivastav et al. (2024) and M.M. Mohideen et al. (2024) perform rather poorly, making them less appropriate for high-performance PEM fuel cells, whereas S.V. Selvaganesh et al. (2024) demonstrate a middling efficiency of 87%. For efficiency-driven applications, H. Fan et al. (2024) is the best option, according to the trend.

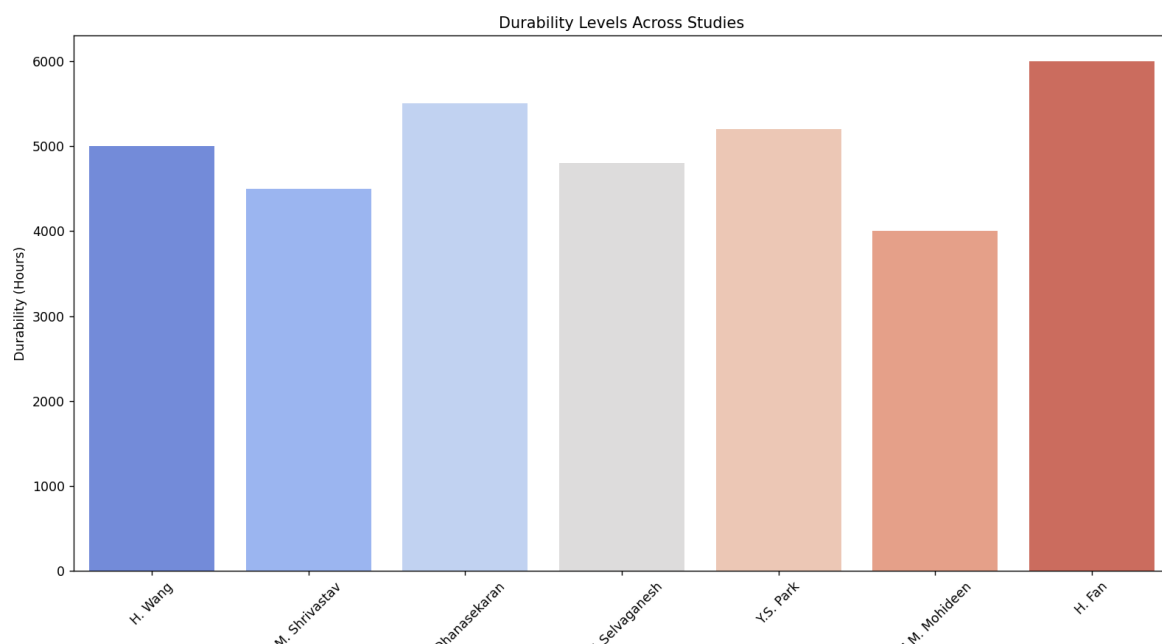


Figure 3: Durability based upon different research analysis

The durability research reveals in fig.3 that the work of H. Fan et al. (2024) is the most resilient for long-term PEM fuel cell applications, boasting the maximum durability at 6,000 hours. Up next, with impressive endurance, are P. Dhanasekaran et al. (2024) (5500 hours) and Y.S. Park et al. (2024) (5200 hours). H. Wang et al. (2024) and S.V. Selvaganesh et al. (4800 hours) demonstrate moderate durability, whereas M. Shrivastav et al. (4500 hours) and M.M. Mohideen et al. (4000 hours) demonstrate the lowest durability, rendering them less appropriate for extended operational performance. Applications necessitating long-term durability should opt for H. Fan et al. (2024), according to the results.

IV. CONCLUSION

The review concludes that SPEEK membranes coupled with MXene are promising candidates for next-generation PEM fuel cells due to their superior mechanical stability, proton conductivity, efficiency, and durability. H. Fan et al. (2024) exhibited the highest efficacy (92%) and durability (6000 hours) among the surveyed studies, indicating its potential for long-term applications. The results underscore the importance of conducting additional research on material optimisation and fabrication techniques to improve the sustainability and performance of fuel cell membranes.

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