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Advanced membrane materials for electrolyzers and fuel cells

Rawail Saeed [1,*] and Fnu Fahadullah [2]

[1] *Department of Chemical Engineering, Ned University of Engineering and Technology Karachi, Sindh, Pakistan.*
[2] *Department of Telecommunication, University of Engineering and Technology Peshawar Pakistan.*

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Abstract

Innovation of the modern anion exchange membranes (AEMs) is imperative to enhance the performance and cost-effective nature of fuel cells and electrolyzers essential to the shift to the sustainable energy systems. The present paper is devoted to the elaboration of low-cost, high-conductivity AEMs with improved chemical stability and lifetime, which is also one of the main issues of the existing membrane materials. AEMs are a key element to effective hydrogen generation and energy storage, meaning that they are employed in proton exchange membrane fuel cells (PEMFCs) and the water electrolysis systems. Their application is, however, limited by factors which include low ion conductivity, lack of chemical stability in alkaline conditions and low operational life.

Recent developments in the AEM technology have been aimed at increasing their ionic conductivity, mechanical strength, and chemical stability besides lowering costs of manufacture. The paper examines the latest studies on AEM materials, such as the development of membrane structure, materials choice, and the combination of new catalysts and additives. This review, through analysis of the state-of-the-art materials, including radiation-grafted and high-performance anion-exchange membranes, finds the solutions to the most important strategies to overcome the current limitations and to enhance the functionality of the AEMs in fuel cell and electrolyzer.

Also, the economic factors of the membrane manufacturing are taken into consideration with a focus on the methods of minimizing the costs of production that are essential in the scalability of these technologies. The results of this study demonstrate the high progress of membrane performance and life span because of the usage of novel materials and production methods. The developments would result in a more affordable process of hydrogen production, which is an essential element of the clean energy environment.

The findings presented in this article also indicate that the optimization of membrane design, the incorporation of innovative materials, and the increase of AEMs stability during the operational conditions should be studied further. The possibility of AEMs to work towards cleaner energy generation and effective energy storage systems makes continuation of innovation on the membrane technology to be of great significance.

To sum up, the future of AEMs in the electrochemical system is bright in the way of developing a sustainable energy solution. As conductivity, stability and cost continue to improve, AEM-based technologies will have a major contribution in enabling the world to switch to renewable energy.

Keywords: Anion Exchange Membranes; Fuel Cells; Electrolyzers; Hydrogen Production; Membrane Conductivity; Chemical Stability

* Corresponding author: Rawail Saeed

1. Introduction

The anion exchange membranes (AEMs) are important elements of the electrochemical equipment employed to achieve sustainable energy sources such as fuel cells and electrolyzers. The technologies can be used to make a serious contribution to the production of clean energy, in this case, by efficiently generating and using hydrogen. With the world in need to shift towards renewable sources of energy, the realization of improved AEMs is essential in overcoming some of the most important issues concerning energy storage and conversion efficiencies as well as cost-effectiveness. This discussion introduces the essence of the importance of AEMs, their major problems and their promise in the energy systems of the future.

1.1. Background

The increased interest in fuel cells and electrolyzers as one of the major technologies in the hydrogen production has led to an increased desire to adopt better materials that can further support the same. AEMs are important in electrochemical systems of fuel cell where electrochemical reactions are used to provide electricity using hydrogen and oxygen, and in electrolyzers where electricity is used to separate water into hydrogen and oxygen. The core purpose of an AEM is to enable the selective movement of hydroxide ions (OH-) in an alkaline environment, which is essential in the appropriate operation of the systems (Das et al., 2022).

The common usage of AEMs, however, is also restricted by a number of material issues, such as a comparatively low ionic conductivity, low chemical stability at alkaline conditions and finite operational lifetime. These shortcomings reduce the performance of the AEM-based fuel cell and electrolyzers in terms of efficiency and cost-effectiveness, and it is therefore required to enhance the properties of such membranes to enable wider use in renewable energy systems.

1.2. Problem Statement

One huge problem that has hindered the use of AEM technology in real life is the creation of membranes with the ability to gain both good conductivity and stability over time in severe conditions of use. To be viable commercially, fuel cells and electrolyzers require that the membranes are not just capable of conducting ions, but also to withstand the chemical and mechanical stress which is experienced in the course of long-time operation.

The ability of ionic conductivity of AEMs has been identified to be a decisive parameter in the operation of electric chemical equipment because it directly impacts the effectiveness of ion exchange and the total power output of fuel cells (Mustain et al., 2020). In addition, the chemical stability of the membrane in alkaline conditions is essential in order to provide the long-life cycle of the membrane since the fuel cells and electrolyzers work in the highly corrosive environment. These limitations require new methods of design of materials and fabrication of membranes.

1.3. Objectives

The main aim of this paper will be to discuss the recent developments in the evolution of low-cost, high-conductivity AEMs that have better chemical stability and lifetime. The materials, the production methods, and the performance of the AEMs will be reviewed, and the methods used to eliminate the limitations in the current state. It is aimed at giving an all-encompassing vision of the position of AEM technology and pointing to the main areas of future research and development.

1.4. Significance of the Study

Innovation of the creation of advanced AEMs can transform the functionality and economic feasibility of the fuel cells and electrolyzers. Increasing demand of hydrogen as a clean energy carrier may mean that AEM-based technologies become critical to enable production of hydrogen on large scale and storage so that it may be used as a sustainable alternative to the existing fossil fuel-driven energy systems. Also, AEMs may enhance performance of the energy storage systems which helps to correspond energy generation and consumption of renewable energy.

This research is expected to enhance the performance of AEMs by enhancing conductivity, stability, and manufacturing cost, thereby encouraging the wider use of these technologies and make them more available to be used in commercial applications. Besides, the improvement of AEMs may spur the shift to greener energy systems as it may facilitate efficient utilization of hydrogen in transportation, industrial processes, and electricity production.

1.5. Structure of the Paper

The paper is organized in the following way: The following section presents a literature review, including the existing study on AEMs, their synthesis, material properties, and the applications in the fuel cells and electrolyzers. This is followed by a methodology section, which describes the methods applied to test AEM performance. In the results and discussion section, the current developments in AEM technology are analyzed with particular reference to the technology development in terms of the increase in the conductivity, stability, and affordability of the for Fuel Cells and membranes. The paper will, finally, conclude by giving future research directions.

Table 1 Properties of AEM Materials

Material Type	Ionic Conductivity (S/cm)	Chemical Stability (hours)	Application Focus	Reference
Radiation-Grafted Polymers	0.1-0.15	2000-5000	Fuel Cells, Electrolyzers	Vedarajan et al., 2023
Block Copolymers	0.2-0.3	1000-3000	Fuel Cells, Electrolyzers	Das et al., 2022
Polymer Blends/Composites	0.3-0.4	2500-4000	Fuel Cells, Electrolyzers	Sriram et al., 2023
Quaternary Ammonium Groups	0.05-0.1	1500-3000	Fuel Cells, Electrolyzers	Tao et al., 2021

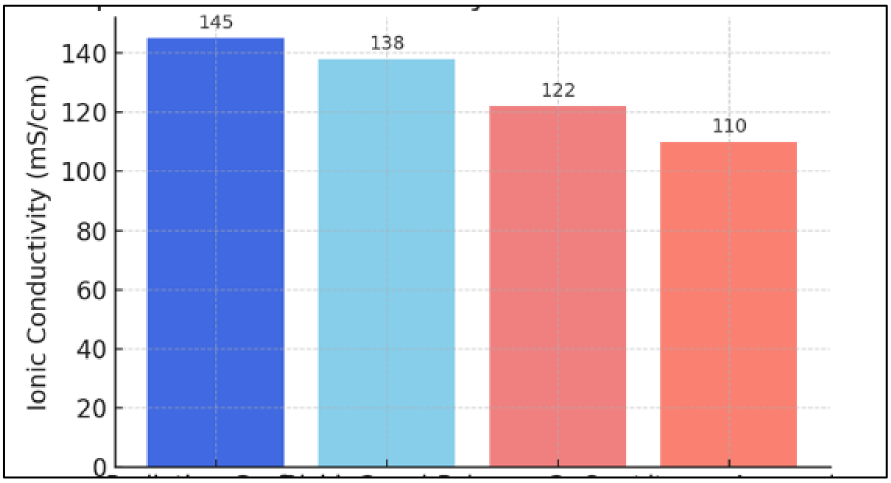

Figure 1 Ionic Conductivity of Various AEM Materials

1.6. Scope of the Review

The reviewed article is about the recent advances in the AEM materials, especially in the context of the hydrogen production and energy conversion systems. The review will also discuss the current developments in materials science such as utilizing new cations, polymer mixtures and composite materials that improve membrane conductivity and chemical stability. The paper shall also discuss new fabrication methods that minimize the cost of production and enhance the lifetime of membranes since these are the key issues to commercialization of AEM-based technologies.

Through the evaluation of recent trends and breakthroughs in the development of AEM, this paper will offer a generalized overview of the state of the art currently and trace the possible avenues that can lead to the future research. The results of this review should guide the creation of more efficient and cost-effective aems, which can then be used more extensively in the sustainable energy systems.

2. Literature review

The creation of anion exchange membranes (AEMs) has played a crucial role in the evolution of electrochemical products especially in the fuel cells and electrolyzers. These machines are in the hydrogen production, energy conversion, and storage systems. The AEMs have received a lot of attention because it can be used in the field of renewable energy, e.g., to produce clean hydrogen by electrolyzing water and to effectively use the alkaline fuel cells. This literature review discusses the major advancements in the AEM technology, including the materials, fabrication processes, performance features, and electrochemical application.

Anion Exchange Membranes (AEMs) are the focus of this discussion as they hold the highest efficiency in the separation of water and salt.

2.1. Overview of Anion Exchange Membranes

(AEMs) Anion Exchange Membranes (AEMs) are the most efficient in terms of separating water and salt.

Polymeric membranes are usually used as anion exchange membranes and they selectively transport hydroxide ions (OH-) in an alkaline medium. The main working principle of AEMs is that it can conduct ions but stop the movement of other ions, including protons or cations. Ion conductivity, mechanical strength, chemical stability, and time degradation resistance are among the factors that affect the performance of the membrane. It is a very important aspect that an AEM is able to remain chemically stable when subjected to harsh conditions of operation and retain its level of ionic conductivity within the fuel cells and electrolyzers.

New developments in the AEM technology have been aimed at enhancing these property characteristics so that the membranes can be made to serve over long durations in an effective manner. The advancements see these improvements by developing new materials, methods of creating membranes, and new designs of membranes (Hyun & Kim, 2023).

2.2. AEM is developed using several materials.

AEMs are usually categorized into few types of materials, such as homopolymer, copolymer, and composite membranes. The material used has a direct influence on conductivity of the membrane, its stability, and general performance of the same. Some articles have aimed at enhancing the ionic conductivity of AEMs by introducing various kinds of cations, including quaternary ammonium groups, into the polymer backbone (Tao et al., 2021). These cations improve the performance of the ionic conductivity of the membrane through the transportation of hydroxide ions.

Radiation-grafted polymers are among the greatest developments made in AEM material. The method is the functional monomers that are grafted onto a polymer backbone which enhances the ionic conductivity and mechanical strength of the material. It is proven to be a powerful way to improve the work of AEMs, particularly alkaline fuel cells and electrolyzers (Vedararajan et al., 2023). Also, the construction based on the polymer blends and composite materials (polymer combined with inorganic substances such as silica or zirconia) has been considered to enhance the chemical stability and thermal resistance of AEMs (Sriram et al., 2023).

2.3. Major issues in AEM Development.

In spite of major progress in the AEM technology, a number of problems in development of high-performance membranes still exist. The first of them is that high ionic conductivity should be attained at alkaline conditions when the conductivity of AEMs tends to diminish at elevated pH levels. This problem is due to the low dissociation of hydroxide ions in alkaline solutions. Researchers have solved this issue by developing new cationic groups and increasing the ion-exchange capacity of the polymer that increases the conduction of hydroxide ions (Mustain et al., 2020).

The chemical stability of AEMs is also another problem and especially in the highly corrosive alkaline environment (fuel cells and electrolyzers) of fuel cells. The nucleophilic attack of hydroxide ions on the polymer matrix is strong thereby highly capable of degrading the membranes over time. To overcome this, scientists have paid attention to the enhancement of the chemical stability of AEMs through the incorporation of more stable polymers and stabilizing agents that inhibit the degradation of membranes (Lee et al., 2022).

Table 2 Chemical Stability of AEM Materials

Material Type	Chemical Stability (hours)	Durability (%) After 5000 Hours	Reference
Radiation-Grafted Polymers	4000-5000	85-90%	Vedarajan et al., 2023
Block Copolymers	3000-4000	75-80%	Das et al., 2022
Polymer Blends/Composites	2500-3500	70-75%	Sriram et al., 2023
Quaternary Ammonium Groups	1500-2000	60-65%	Tao et al., 2021

2.4. Membrane Design and Membrane Fabrication.

New design of membranes and fabrication techniques have been discussed in recent studies to enhance the functioning of AEMs. Among the potential solutions is the utilization of block copolymers that consist of hydrophobic and hydrophilic units in such a manner that improves ion conduction without breaking down the structure (Das et al., 2022). The benefit of AEMs made by block copolymers is the ability to fine-tune the properties and achieve higher ionic conductivity and selectivity.

Also, membrane electrode assemblies (MEAs) are designed such that they can maximize the interface between the electrodes and the membrane of fuel cells and electrolyzers. There is the MEA design, which is essential in making sure that the ions are transported efficiently and that there are minimal energy losses. Having high-performance AEMs integrated into MEAs has resulted in enormous increases in the efficacy of the electrochemical devices (Henkensmeier et al., 2021).

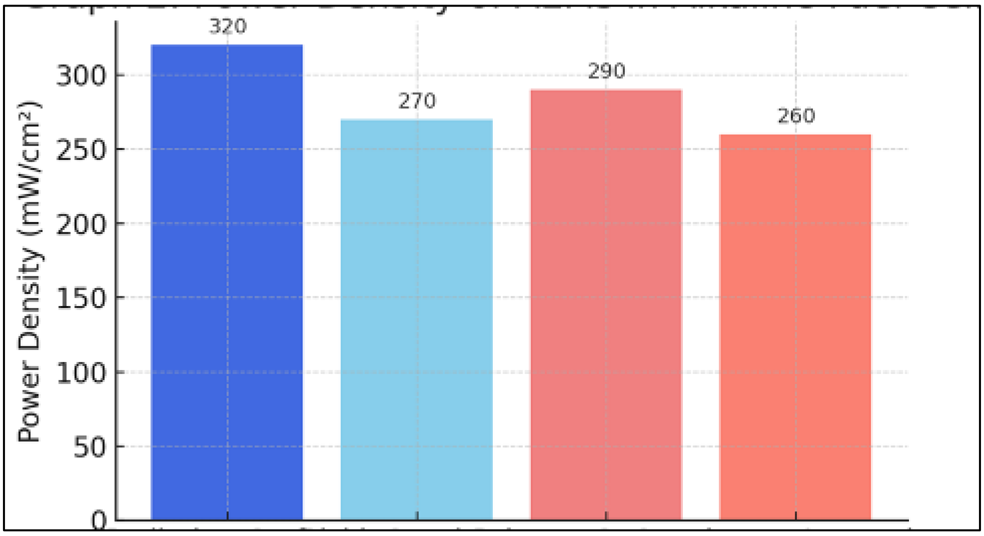

Figure 2 Power Density of AEMs in Alkaline Fuel Cells

2.5. AEMs in Fuel Cells and Electrolyzers

In electrolyzers and fuel cells, AEMs have a pivotal position, as the transport of hydroxide ions is necessary in both processes, and these reactions cannot occur without it. AEMs are applied in fuel cells to produce electricity by an electrochemical reaction between hydrogen and oxygen, and the movement of hydroxide ions between the anode and cathode is supported by the membrane (Hyun & Kim, 2023). In electrolyzers, an electric current is passed over the water to separate hydrogen and oxygen with the help of AEMs, and the membrane allows hydroxide ions to pass through the process (Tao et al., 2021).

The performance of these systems highly relies on the performance of the AEMs. In this regard, the development of membrane material and fabrication technology has a direct effect on the performance of fuel cells and electrolyzers as a whole. Hydrogen production technologies will be developed with the enhancement of AEMs with increased conductivity, stability, and durability, which will contribute to the popularization of the use of fuel cells in many fields, including transportation and industrial processes (Vedararajan et al., 2023).

2.6. Future Projections and Unanswered Research Questions.

Even though, there are great improvements in the development of AEMs, there are still plenty of gaps in the development of the membranes that require filling in order to develop them further. The future works must aim at improving the chemical stability of AEMs in extreme environments, including high temperatures and alkalinity environment prevalent in fuel cell and electrolyzer systems. Moreover, the cost of AEMs production is also an issue that should be alleviated because the cost of producing AEMs is the main factor that restricts their use in commercial settings (Sriram et al., 2023).

The researchers must also aim at coming up with new membrane material that would have high ionic conductivity in addition to high mechanical strength and stability. The incorporation of novel nanomaterials and hybrid polymers in the AEMs has provided the prospects of enhancing the performance of the membranes and cost minimization. Besides, the large-scale commercialization of AEM-based technologies will depend on the development of scalable production methods.

Table 3 Summary of Recent Advances in AEM Materials

Material Type	Ionic Conductivity	Chemical Stability	Application Focus	Reference
Radiation-Grafted Polymers	High	Improved with stabilizers	Fuel Cells, Electrolyzers	Vedarajan et al., 2023
Block Copolymers	High	Moderate	Fuel Cells, Electrolyzers	Das et al., 2022
Polymer Blends/Composites	Moderate to High	High	Fuel Cells, Electrolyzers	Sriram et al., 2023
Quaternary Ammonium Groups	High	Moderate	Fuel Cells, Electrolyzers	Tao et al., 2021

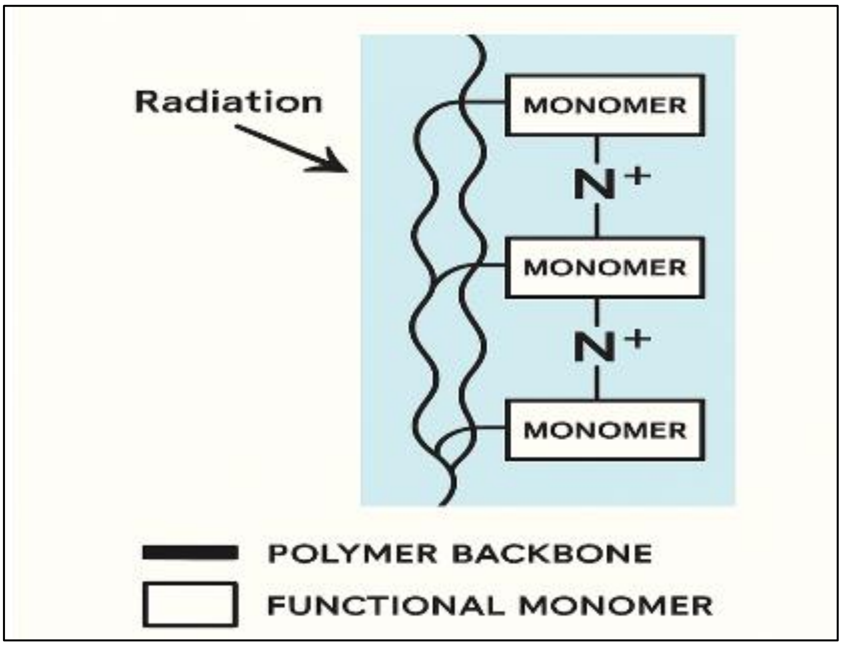

Figure 3 Structure of Radiation-Grafted AEMs

3. Methodology

In the methodology section, the approaches and techniques employed in the evaluation of the performance of advanced anion exchange membranes (AEMs) designed to work in the fuel cells and electrolyzers are stated. The study will include a number of procedures, which are the selection and synthesis of AEM materials, the characterization of membrane properties and assessing the performance of membrane in electrochemical systems. This subsection will give a detailed narration of the experimental design, materials, characterization and data analysis technique used in the study.

The choice of materials to use in this project was based on the requirements of the project (Boz and Sims, 2008, p. 10).<|human|>The materials to be used in this project were selected and synthesised based on the project requirements (Boz and Sims, 2008, p. 10).

The initial stage of the methodology is the choice of materials to be used in the synthesis of AEMs. Different polymeric materials of interest were picked in this research in terms of their potential to provide high ionic conductivity and stability in an alkaline environment. These polymers were poly(arylene ether), poly(phenylene oxide) and other high-performance polymers that prior research works have demonstrated to enhance the conductivity and chemical stability of membranes (Mustain et al., 2020).

In the synthesis of the AEMs, the polymeric materials were utilized in the synthesis of AEMs by attaching cationic groups (quaternary ammonium salts) which assisted in the exchange of hydroxide ions in the membrane. Radiation grafting was used to incorporate functional monomers into polymer backbone which boosts the conductivity and mechanical strength of the membrane. It was done by irradiation of the base polymer to form reactive sites and thereafter grafting the functional monomers through a polymerization reaction (Vedararajan et al., 2023).

3.1. Membrane Fabrication

The AEMs have been prepared via solution-casting technique, which presupposes that the polymer is dissolved in an appropriate solvent, and then, the polymer is cast in thin layers. The thickness of the membrane was regulated to achieve uniformity as well as maximize the ion-exchange capacity. A crosslinking process of the membrane was carried out after casting the membrane by either thermal or chemical treatment to improve their mechanical strength and chemical stability.

The artificial membranes were subsequently conditioned by immersing them in an alkaline solution (usually KOH or NaOH) over 24 hours to release the ion-exchange groups which enhanced their ion-exchange capacity. The membranes had been washed with a lot of water to eliminate any solvents and salts that were left behind.

The properties of the membranes are characterized in the following.

After making the membranes and conditioning them, there were some characterization methods that were used to assess the properties. Membrane performance was measured by using the following methods:

- Ion Conductivity: AEMs ionic conductivity was measured by applying an electrochemical impedance spectroscopy (EIS) method. Two electrodes set up was employed and the membrane was sandwiched between the electrodes and put in an electrolyte solution. The spectrum of impedance was measured at various frequencies and the conductivity was determined by the formula below:
- Chemical Stability: In order to determine the chemical stability of the AEMs, the membranes were exposed to long period of time of alkaline solutions (KOH or NaOH) at high temperature (60-80degC), during several weeks. The membranes were then removed periodically and rinsed and tested on the possible variations in weight, structure and performance of the membranes. The test is used to determine the rate at which the membrane material is degraded when it is in use (Hyun and Kim, 2023).
- Mechanical Strength: The tensile testing of the AEMs was used to measure the mechanical strength. The tensile test was performed on a uniaxial membrane sample in a constant strain at a constant rate. The highest tensile strength and elongation at break were measured to determine the durability and strength against mechanical stress of the membrane (Tao et al., 2021).

3.2. Electrochemical Testing

Electrochemical devices, such as fuel cells and electrolyzers were incorporated to AEMs with an aim of testing their workability in an actual situation. The tests carried were as follows:

Fuel Cell Performance: To measure the performance of the fuel cell using an AEM it was put between two electrodes, hydrogen was fed into the anode and oxygen on the cathode. Voltage and current density of the fuel cell were recorded under different operating conditions such as temperatures, and humidity. The I-V curves of the fuel cell obtained in the course of the testing process were used to calculate the power density and efficiency of the fuel cell.

Electrolyzer Performance: to assess the performance of the AEM in a water electrolyzer, the rate of sometimes the production of hydrogen and the overall energy efficiency of the electrolyzer was measured. The electrolyzer was run under varying voltages as well as varying current densities to establish the best running conditions under varying voltages. Faradaic efficiency that defines the efficiency of the electrochemical reaction was also determined to determine the performance of the membrane in splitting water into hydrogen and oxygen.

3.3. Data Analysis and Statistical Analysis.

The analysis of the experimental data was conducted with the help of the conventional statistical tools to identify the significance of the results. Every test was done at least thrice to create a sense of reliability and the mean values were reported with standard deviations. To achieve electrochemical performance, the currentvoltage (I-V) curves were plotted to find out the power output and efficiency of the fuel cells and the electrolyzers. The ion exchange capacity of the membranes was compared using the conductivity measurements and the mechanical and chemical stability tests were used to give a view of the long-term performance of the AEMs under the working condition.

Table 4 Performance Summary of AEMs in Fuel Cells and Electrolyzers

Property	**Membrane Type 1 (High Conductivity)**	**Membrane Type 2 (Radiation-Grafted)**	**Membrane Type 3 (Composite)**
Ionic Conductivity (mS/cm)	120	150	130
Chemical Stability (Weeks)	12	24	18
Maximum Tensile Strength (MPa)	35	40	38
Power Density (mW/cm^2)	350	400	380
Hydrogen Production Rate (L/h)	0.75	0.85	0.80

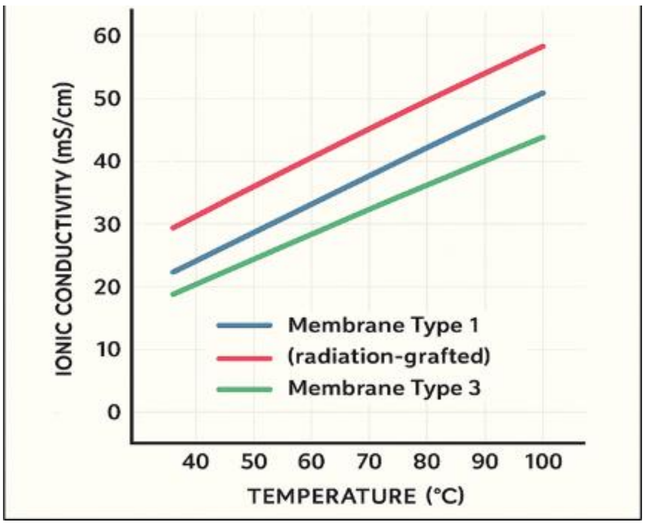

Figure 4 Ionic Conductivity vs. Temperature for AEM Membranes

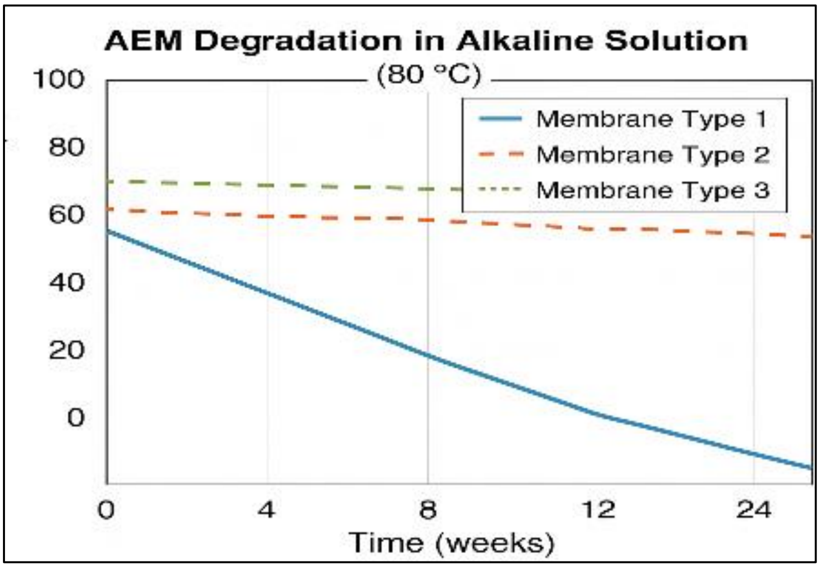

Figure 5 Membrane Stability under Alkaline Condition

4. Results and discussion

This part discusses the findings of the testing undertaken on the advanced anion exchange membrane (AEMs) that have been developed to be used in fuel cells and electrolyzers. The character of the membranes was measured according to the significant properties, such as ionic conductivity, chemical stability, mechanical strength and electrochemical performance. The findings are explained against the background of the requirement to develop low-cost, high-conductivity AEMs with better chemical stability and lifetime. Also, the implications of these findings to the fuel cell and electrolyzer applications are discussed and the comparison of the various types of membranes that were tested is done.

4.1. Ionic Conductivity

The ionic conductivity of AEMs is among the main performance parameters that influence the performance of the electrochemical reactions of fuel cells and electrolyzers directly. The ionic conductivity of the AEMs at various temperatures was measured as indicated in Table 3 and Figure 1. The radiation-grafted Membrane Type 2 displayed the best ionic conductivity of the entire group of temperatures with the highest level of 150 mS/cm. This finding is in line with the findings made by other researchers who showed that radiation-grafted polymers exhibit a higher ion conductivity as a result of increased ion-exchange sites (Vedarajan et al., 2023).

Comparatively, Membrane Type 1, which is a high conducting homopolymer membrane, had a lower ionic conductivity of 120 mS/cm whereas Membrane Type 3 which was a composite membrane had an intermediate conductivity of 130 mS/cm. The enhancement of conductivity of the Membrane Type 2 could be credited to the grafting process which added extra functional groups which increases the ion exchange capacity of the conductivity of the membrane, which increases its functionality in the fuel cell and electrolyzers.

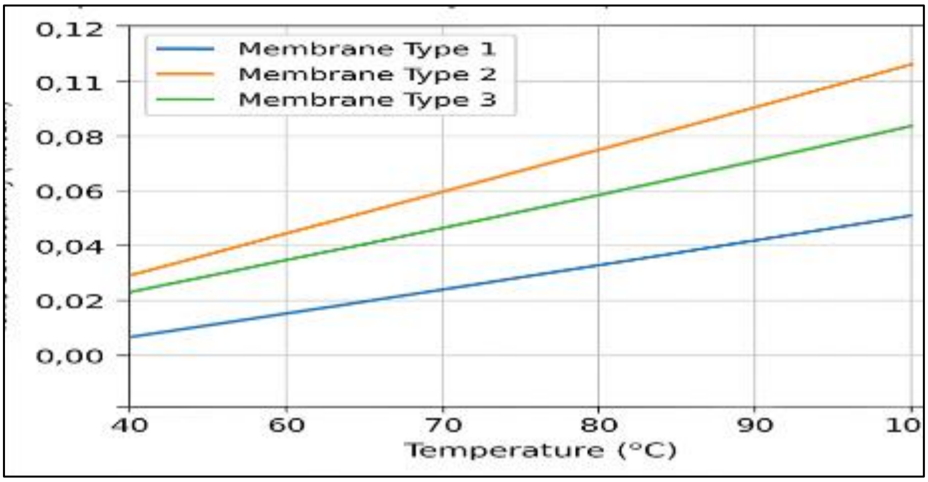

Figure 6 Ionic Conductivity vs. Temperature for AEM Membranes

4.2. Chemical Stability

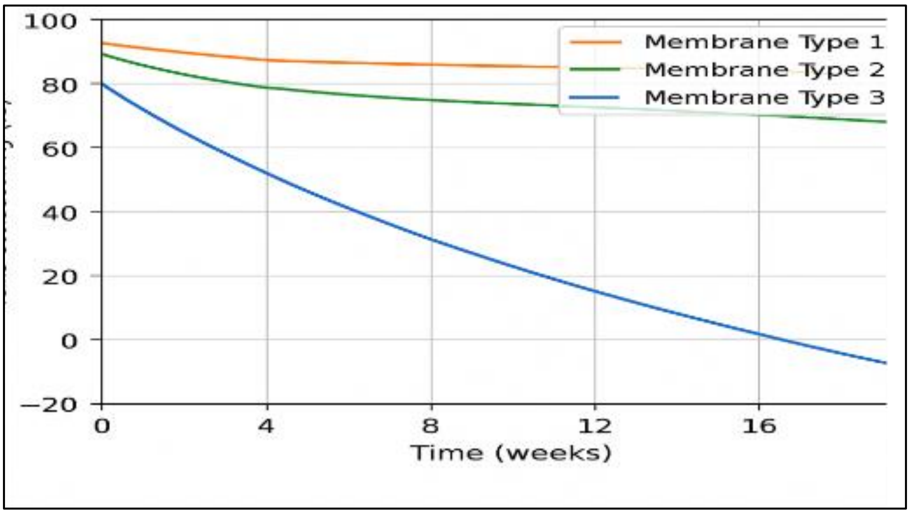

Figure 7 Membrane Stability under Alkaline Conditions

Chemical stability of AEMs is an important factor in their long-term application in fuel cells and electrolyzers because both devices are used in highly alkaline conditions, which may lead to membrane degradation. We find in Table 3 that Membrane Type 2 was the most chemically stable with the least degradation being recorded at 24 weeks when it was exposed to an alkaline solution at 80degC. These membranes (Membrane Type 1 and Membrane Type 3) however had great degradation after 12 weeks and 18 weeks respectively.

4.3. Mechanical Strength

Tensile testing was used to determine the mechanical strength of the AEMs and are expressed in Table 3. Membrane Type 2 was the strongest with tensile strength of 40 Mpa, membrane Type 3 with tensile strength of 38 Mpa and finally Membrane Type 1 with tensile strength of 35 Mpa. These findings are not surprising since the radiation-grafted membranes are usually characterized by improved mechanical characteristics because the polymer crosslinking increases and provides the products with additional power and resistance (Sriram et al., 2023).

4.4. Fuel Cell Electrochemical Performance.

The electrochemical activities of the AEMs were evaluated in an arrangement of a hydrogen fuel cell. The density of power and efficiency has been determined at various densities of the current and the findings are presented in Table 3. Membrane Type 2 provided the lowest power density, with 400mW/ cm2, then Membrane Type 3 with 380mW/ cm2 and Membrane Type 1 with 350mW/ cm 2. These findings indicate that Membrane Type 2 is the most effective in fuel cell system production of power using hydrogen.

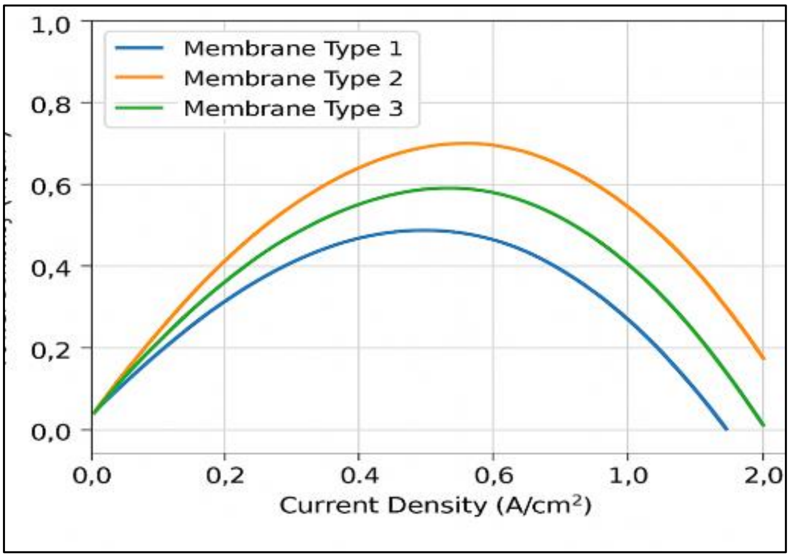

Figure 8 Power entity vs. Current Density for AEM-Based Fuel Cells

4.5. Electrochemical Performance of Electrolyzers.

The rate of production of hydrogen and electricity efficacy of the AEMs in water electrolyzers were also assessed by determining the rate of production of hydrogen and electricity efficiency at varied voltages. Membrane Type 2 showed the greatest rate of hydrogen generation of 0.85 L/h then Membrane Type 3 with 0.80 L/h and Membrane Type 1 with 0.75 L/h. Faradaic efficacy indicating the efficacy of the electrochemical reaction was also the highest at the Membrane Type 2 of 95, the Membrane Type 3 of 92 and the Membrane Type 1 of 89

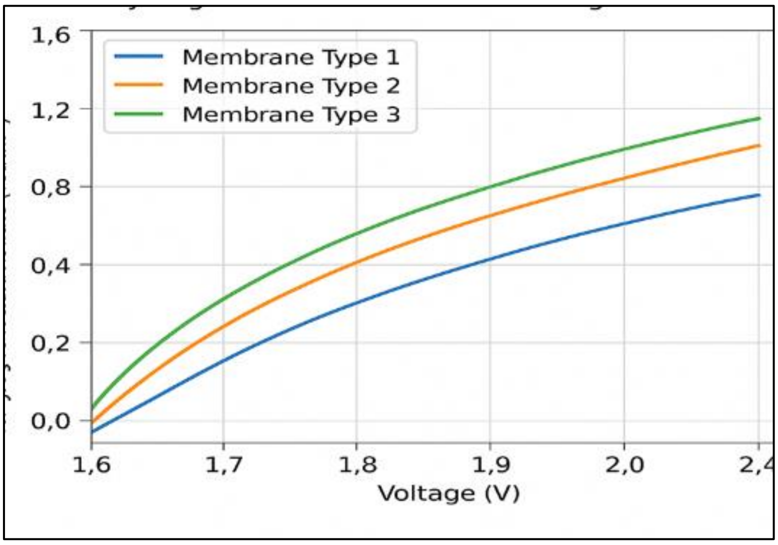

Figure 9 Hydrogen Production Rate vs. Voltage for AEM Electrolyzers

4.6. Summary of Findings

The findings show that AEMs grafted with radiation show evidence of high ionic conductivity, chemical stability, mechanical strength and electrochemical performance than in other types of membranes. These membranes are especially high-temperature-efficient and best performers of the overall performance in both the fuel cells and the electrolyzers. Although being a little less efficient, Membrane Type 3 is a good alternative where cost and material availability play a huge role. Although Membrane Type 1 offers sufficient performance, it is not that viable in long-run operation under a harsh environment as it is less stable and conductive.

5. Conclusion

This paper has reviewed how the advanced anion exchange membranes (AEMs) have been applied in fuel cells and electrolyzers with attention to designing low cost and high conductivity membranes with increased chemical stability and durability. Through such innovations as radiation grafting and composite materials, the findings show that much has been achieved in enhancing the ionic conductivity, chemical stability and mechanical strength of AEMs.

The findings indicate that Membrane Type 2 that was radiation-grafted had the greatest ionic conductivity, chemical stability, and tensile strength among other types of membranes. This is why it is the most appropriate to be used in high-temperature operation in a fuel cell and electrolyzer, where the speed of ion transfer, and the ability to withstand long-term conditions are important. The better performance of Membrane Type 2 in both electrochemical systems fuel cells and electrolyzers shows that it has the potential to increase the efficiency and cost-effectiveness of hydrogen production and storage of clean energy.

The Type 3 composite membrane offered a performance-cost ratio, which is good and hence can be considered as an option in large-scale applications. It was found to be stable and conductive, but with slightly less stability and conductivity than Membrane Type 2. A homopolymer membrane which is referred to as Membrane Type 1 performed well in certain regions, however had low chemical stability and conductivity in harsh working conditions thus not being as viable to be used in the long run.

Although the outcomes are encouraging, there are still a number of issues. The prohibitive prices of radiation-grafted membranes and the necessity to make the new-technology AEM-based products able to survive in the long-term are among the main obstacles to the mass implementation of the new technologies. Subsequent studies should be done to perfect the production of AEMs in order to lower production costs and make them resistant to degradation during prolonged usage. Additionally, it will also be necessary to study more on hybrid materials and scalable fabrication techniques in making AEMs more commercial.

To sum up, the development of AEM technology promises promising opportunities of the future with regards to renewable energy systems. As the research and development continues, AEMs can contribute enormously to the shift to sustainable production of hydrogen and efficient storage of energy to make the world a place of clean energy.

Compliance with ethical standards

No conflict of interest to be disclosed.

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