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Polymer Electrolytes for Fuel Cell Applications: A Comprehensive Review

Abstract

Fuel cells are a clean and effective energy conversion technology that has a low environmental impact and a high power density. Ionic conductivity, thermal stability, as well as overall system performance are all significantly influenced by the electrolyte, one of the fuel cell's essential parts. The flexibility, processability, and capacity to overcome the drawbacks of traditional liquid electrolytes have made polymer electrolytes—which include solid, gel, as well as composite systems—the subject of much investigation. With an emphasis on their classification, ionic transport mechanisms, and production techniques, this paper offers a thorough examination of polymer electrolytes for fuel cell applications. Recent developments in ionic liquid-based systems, sustainable biopolymer-derived electrolytes, and nanocomposite membranes are given particular attention. Important issues including cost, durability, as well as water management are covered, along with solutions. In order to direct the creation of subsequent-generation polymer electrolytes that will allow for the widespread commercialization of fuel cells, future perspectives are finally described.

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Introduction

The search for clean and sustainable energy technology has been fueled by the growing demand for energy worldwide and the pressing need to cut greenhouse gas emissions. Because of its great efficiency, scalability, as well as environmentally friendly operation, fuel cells have garnered a lot of attention among them (Aricò et al., 2005, and O'Hayre et al., 2016). In contrast to traditional combustion-based sources of power, fuel cells use electrochemical reactions to directly transform the chemical energy in fuels, like methanol or hydrogen, into electrical energy; when hydrogen is used, the only byproducts are heat and water (Kordesch and Simader, 1996). Because of these special qualities, fuel cells are ideal for a wide range of uses, from stationary power systems and portable electronics to transportation as well as aerospace.

The electrolyte is also one of the most significant components of a fuel cell that is charged with the responsibility

of transporting ions across the electrodes and excludes fuel crossover and conductive electronics. Conventional liquid electrolytes, such as the phosphoric acid and the alkaline solution, can undergo ionic conduction, however, they are often accompanied by adverse properties, such as corrosion, volatility, and leakage that present the fuel cells with difficulties during the long-term provides the opportunity of being both stable and actualized (Li et al., 2019). Electroselectrolyte polymers have been far more actively explored as alternative substances to circumvent these issues because they offer beneficial properties of adjustable ionic conductivity, productability and mechanical plasticity (Bose et al., 2020).

Polymer electrolytes can broadly be classified as solid polymer electrolytes (SPEs), gel polymer electrolytes (GPEs) and composite polymer electrolyte (CPEs). Despite their great mechanical stability, matrix-based SPEs like polyethylene oxide (PEO), and polybenzimidazole (PBI) are often low ionic conductors at room temperature (Li et al., 2003). Since they prevent the escape of liquid electrolytes into a polymer host, i.eid-, PVDF-HFP, PMMA, or PAN, GPEs combine the characteristics of a liquid-state or solid-state electrolyte as they display a superior conductivity and flexibility besides lower leakage rate (Ahmad et al., -2021). They also incorporate inorganic fillers (SiO 2, TiO 2, and graphene oxide) to fill them in order to enhance conductivity, thermal stability, and fuel crossover resistance (Sehgal et al., 2018).

The Grotthuss methods where the protons are interchanged between the hydrogen-bonds are the most important systems of ionic transportation in the polymer electrolytes and the vehicle mechanism where the ion exchange occurs on the solvent molecules (Kreuer, 2001). Another characteristic related to the ion movement that is determined by the segmental movement of the polymer chains is on the polymer hosts like PEO. The impact of these conduction processes superficially depends on the temperature, polymer structure, the extent to which it is humid and the incorporation of additives that help in other ways.

The development of polymer electrolytes that possess high performance has made enormous advancements in recent years by using bio-based, ionic liquid, and nanomaterials (Bose et al., 2020.;). Li et al., 2019). The strategies are targeting the resolution of long term issues such as high cost, water control, high temperature dehydration and limited longevity.

In this review, all the classification, ion conduction mechanisms, preparation methods, structural alterations and most recent developments of polymer electrolyte with fuel cell applications have been detailed. The challenges and opportunities to future research in the scope of the fuel cell technologies commercialization are also analysed in order to guide the rational design of the next-generation polymer electrolytes.

Classification of Polymer Electrolytes

SPEs, GPEs as well as CPEs are the three main categories into which polymer electrolytes are often divided. The composition, ionic transport processes, mechanical characteristics, and compatibility for various fuel cell systems vary between the classes.

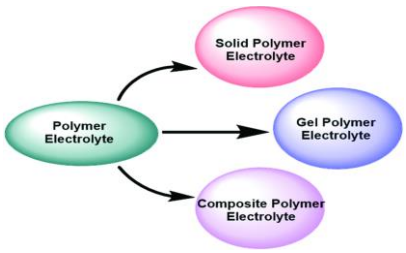

Figure 1: Shows how polymer electrolytes are categorized as solid, gel, and composite (see Figure 1(Vineeth et

al. 2022)

2.1 Solid Polymer Electrolytes (SPEs)

A dry polymer matrix with ion-conducting functional groups and doped with appropriate salts makes up solid polymer electrolytes. Poly(ethylene oxide) (PEO), polybenzimidazole (PBI), as well as sulfonated fluoropolymers like Nafion are examples of common matrices. SPEs solve the leakage problems with liquid electrolytes and are mechanically strong (Li et al., 2003). However, temperature and hydration have a significant impact on their proton conductivity. For instance, while being the industry norm for proton exchange membrane fuel cells (PEMFCs), dehydration causes Nafion membranes to lose conductivity at temperatures higher than 80 °C (Zhang et al., 2008). Phosphoric acid-doped PBI-based membranes have been created to allow for high-temperature fuel cell functioning without the need for external humidification (Li et al., 2019).

2.2 Gel Polymer Electrolytes (GPEs)

GPEs are formed with a liquid electrolyte trapped in a polymer host which may be PVDF-HFP, PAN and PMMA. This hybrid construction includes mechanical resilience of polymers and high ionic conductivity of liquid electrolytes (Ahmad et al., 2021,). GPEs can be of great use in direct methanol fuel cells (DMFCs) since they can prevent methanol crossover, but retain a high proton conductivity (Sehgal et al., 2018). They are demand lightweight flexible energy devices due to their processability and flexibility.

2.3 Composite Polymer Electrolytes (CPEs)

Inorganic fillers, such as SiO 2, TiO 2, ZrO 2, graphene oxide, and montmorillonite are added to create CPEs either with SPEs or GPEs. These fillers improve the mechanical, thermal stability, and ionic conductivity as well as diminish the cross-over of fuels (Bose et al., 2020). Sehgal et al. (2018) have discovered that nanofillers induce the polymer and electrolyte interaction and pave additional conduction channels, which increase the proton transportation. The recent finds have showed that there has been tremendous enhancement of conductivity and durability with the ionic liquids, hybrid organic inorganic and the nanostructured fillers (Kreuer, 2001).

Table 1: Solid, Gel, and Composite Polymer Electrolytes for Fuel Cell Applications

Type of Polymer Electrolyte	Examples	Key Properties	Advantages	Limitations	Fuel Cell Applications	References
Solid Polymer Electrolytes (SPEs)	Nafion, SPEEK, PBI, Poly(ethylene oxide) (PEO)	Solid-state, high proton conductivity, good mechanical strength	No leakage, good thermal & mechanical stability, simple cell design	Low ionic conductivity at room temperature, high cost, humidity dependent	PEMFCs, DMFCs, HT-PEMFCs	Kreuer (2001); Zarrin et al. (2017)
Gel Polymer Electrolytes (GPEs)	PVA–H_3PO_4, PAN–H_2SO_4, PVDF–based gels	Semi-solid, high ionic mobility, flexible & soft structure	Easy fabrication, excellent electrode–electrolyte interface, higher conductivity than SPEs	Limited mechanical strength, solvent evaporation/drying issues	DMFCs, PEMFCs, HT-PEMFCs	Kim et al. (2016); Kumar et al. (2020)
Composite Polymer Electrolytes (CPEs)	Nafion–SiO_2, SPEEK–TiO_2, PVA–ZrO_2 hybrids	Combination of polymer + inorganic fillers, improved barrier & stability	Reduced methanol crossover, enhanced thermal & mechanical properties, tunable conductivity	Complex synthesis, cost of nanofillers, reproducibility issues	PEMFCs, DMFCs	Jiang et al. (2009); Bose et al. (2019)

1. Ionic Transport Mechanism

A high ionic conductivity of the electrolyte in which ionic conductivity of the electrolyte plays a major role in the effectiveness of the fuel cell that allows the passage of charges between electrodes. The translocation of protons or ions across polymer electrolyte can occur in different ways based on polymer structure and Degree of hydration and addition of other substances like acids, ionic liquids and nanofillers. The most common conduction trajectories include the Grotthuss mechanism, the vehicle mechanism and conduction with the aid of segmental motion of the polymer.

3.1 Vehicle Mechanism

The protons are transported in the vehicle process through solvation and transportation by the carrier molecules, commonly, water (H 2 O) or other solvents. As an illustration, protons are conducted by the hydrated Nafion membranes where hydrogen ions (H 3 O+) form the major route of conduction (Zhang et al., 2008). Here, conductivity is very dependent on water uptake and when the high temperatures are experienced, dehydration leads to significant deterioration in performance (Li et al., 2003).

3.2 Grotthuss Mechanism (Proton Hopping)

Protons move quickly over a hydrogen-bonded network via the Grotthuss mechanism, negating the need for carrier molecules to physically diffuse. Rather, in functionalized polymer backbones, protons "hop" between nitrogen and oxygen atoms or between water molecules (Kreuer, 2001). Since phosphoric acid-doped polybenzimidazole (PBI) membranes retain conductivity even in anhydrous or low-humidity environments, this process is very crucial (Li et al., 2019).

3.3 Segmental Motion of Polymer Chains

Some polymer hosts, including PEO are bridged between ionic conduction and movement in polymer chains. Hopping and migrating to the ionttres move along the backbone of the polymer promoting the development of conduction channels of temporary conduction (Armand et al., 1979). In process, SPEs prevail when mobility is limited by the absence of a significant liquid content.

3.4 Influence of Nanofillers and Ionic Liquids

Such recent improvements demonstrated that ionic liquids and nanofillers additions (SiO2, TiO2 and graphene oxide) increase ionic transport due to the formation of constant conduction networks, the increment of conduction sights, and a higher acid retention (Sehgal et al., 2018, and Bose et al., 2020). The strategies contend with a compromise between mechanical/thermal stability and conductivity essential to long-term duty of fuel cells.

4. Methods of Preparation of Polymer Electrolytes

Several fabrication techniques have been developed to tailor structural and electrochemical characteristics of polymer membranes; the most common are solution casting, in-situ polymerization, electrospinning, sol gel and chemical linking. Polymer electrolyte preparation is a paramount factor determining electrolyte morphology, ionic conductivity, thermal stability and overall performance with fuel cell.

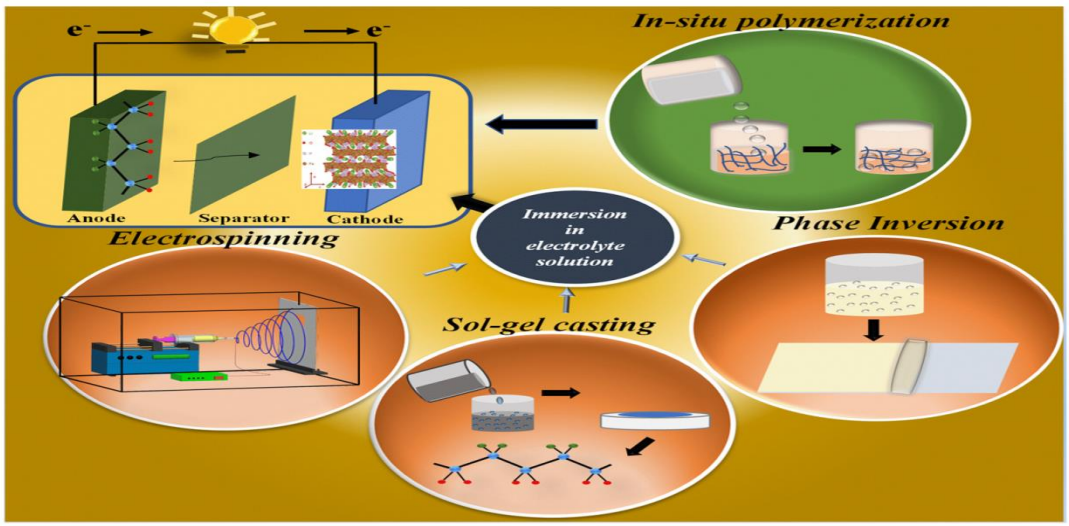

Figure 2: Diagrammatic representation of various methods of the preparation of polymer electrolytes (Aruchamy et al. 2023).

4.1 Solution Casting Method

Because it is inexpensive and simple, a technique known as the solution casting technique is among the most widely applied techniques. This method implies the use of a thin film formed by the dissolution of a polymer in an appropriate solvent and the inclusion of dopants, acids, and even ionic liquids into it after which the solution is deposited onto the substrate and allowed to dry (Bose et al., 2020). The approach has widely been used to synthesize sulfonated poly(arylene ether ketone) and nafion membranes. Limits to reproducibility may be due to remnants of residual solvent and lack of control of thickness, but can be overcome.

4.2 In-Situ Polymerization

In-situ polymerization is required to produce a directly assembled polymer electrolyte membrane by combining monomers polymerization in the presence of an electrolyte solution and additions. It is expected that this approach will guarantee high-interfacial binding, property spread occurring, and decrease phase separate (Ahmad et al., 2021). The protons exchange fuels membranes that in situ polymerize are better than the conventional casting on the basis of mechanical strength and protons conductivity.

4.3 Electrospinning

High intervened nanofibrous membranes can be used to obtain high porosity branched nanofibrous membranes taking into account the flexible electrospinning technology. Ultrafine fibers are generated through the process and deposited onto a substrate by subjecting a polymer melt or solution to high voltage electric field (Sehgal et al., 2018). Electrolytes polymerizing by electrospinning have good surface to volume ratios, as well as, facilitate ionic transportation routes and increase water uptake. The recent research has demonstrated that Nafion/PVDF-HFP blends electrospun demonstrates a high propensity towards direct methanol fuel cell (DMFCs) due to a high proton conductivity and low methanol crossover.

4.4 Sol–Gel Process

Sol-gel is used in order to cast hybrid organic-inorganic polymer electrolytes. The method suggests the dissolution of the metal alkoxides and inorganic precursors in polymer solution and later hydrolysis/condensation of resulting compounds to form a in-situ inorganic gel inside the polymer matrix per se (Li et al., 2019). Outcomes of this method include superior thermal conductivity, increased proton conductivity and low mechanical stability.

Combinationally, it can be said that due to their greater capacity of keeping water, silica-Nafion hybrid membranes prepared by the sol-gel-based procedure can be applied in a high-temperature operation.

4.5 Cross-Linking and Blending

The concept of cross-linking is frequently applied with the intention to increase the chemical, thermal and mechanical stability of polymer electrolyte. Cross-linking UV light or cross-linking chemical reagents may be used to create networks of three dimensional polymers, which are more stable to the working conditions (Kreuer, 2001). Polymer blending as a counterexample is the incorporation of more than one polymers as a way of balancing their properties. Examples are PVDF-HFP and PEO, which are compounded together to form more conductive and flexible.

5. Applications of Polymer Electrolytes in Fuel Cells

Fuel cell performance, stability, as well as effectiveness are all significantly influenced by polymer electrolytes. Their main job is to serve as proton-conducting membranes, which allow ionic conductivity between electrodes while blocking electronic short circuiting and fuel crossover. Polymer electrolytes have been used in a variety of fuel cell designs, such as HT-PEMFCs, DMFCs, as well as PEMFCs, depending on their structural as well as electrochemical properties.

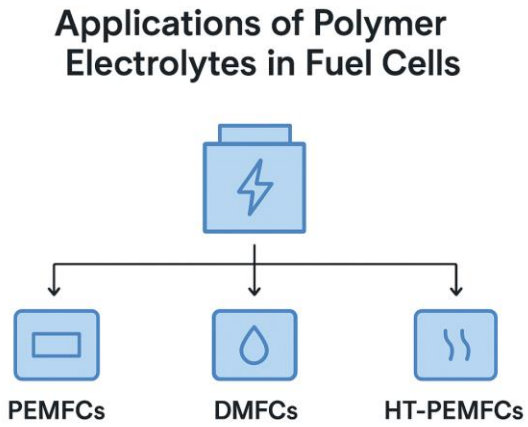

Figure 3. Applications of Polymer Electrolytes in Fuel Cells.

5.1 Proton Exchange Membrane Fuel Cells (PEMFCs)

PEMFCs are the fuel cells that have been researched and commercialized the most, especially for portable and transportation applications. They need polymer electrolytes with strong proton conductivity, effective water management, as well as mechanical durability because they work at very low temperature (60–80 °C) (Zhang et al., 2008). This category is dominated by nafion-based membranes because of their superior conductivity and endurance; nonetheless, they still have difficulties with fuel crossover, high cost, and restricted conductivity under low humidity (Bose et al., 2020). Alternative polymer electrolytes, like polybenzimidazole (PBI)-based membranes and sulfonated poly(ether ketone) (SPEEK), have been studied for improved performance in order to overcome this.

5.2 Direct Methanol Fuel Cells (DMFCs)

Methanol as a direct-to-liquid fuel Direct liquid fuel is currently being developed as direct methanol (direct to

liquid fuel) and is a viable choice in DMFCs, unsuitable devices with low-power requirements and a portable format. However, the efficiency becomes extremely reduced as a result of methanol driving through electrolyte membrane. Polymers require the use of methanol, thus Fuel does not use it efficiently because it is highly permeable to methanol like Nafion (Sehgal et al., 2018). Nafion-silica hybrids, Nafion/PVDF, and PEO in the configuration of gel polymer electrolytes have been modified as membranes to reduce crossover and retain proton conductivity (Li et al., 2019).

5.3 High-Temperature PEMFCs (HT-PEMFCs)

PEMFCs have other merits in working at temperatures of 120-200 C such as an enhanced reaction rate, minimized catalyst CO poisoning, and less complex water treatment. Phosphoric acid doped polymen based on polybenzimidazole (PBI) have been used to conduct protons in an anhydrous environment and have gained interest in this respect (Li et al., 2003; Ahmad et al., 2021). These membranes are conductivity homogeneous-durable and exhibit high impurity toleration, as compared to the conventional hydrated membranes.

6. Recent Advances in Polymer Electrolytes for Fuel Cells

Over the past ten years, research in polymer electrolytes in fuel cells has achieved considerable progress on the area of increasing the durability, mechanical stability, heat resistance and proton conductivity of such electrolytes in the diverse working conditions. Contrary to their performance, conventional membranes, including those of perfluorosulfonic acid (PFSA) like Nafion, are both expensive, low-humidity, and dramatic in performances with high temperatures. Many ways of evading these restrictions are invented.

6.1 Nanocomposite Polymer Electrolytes

The use of nanofillers such as graphene oxide (GO), zirconia (ZrO_2), titania (TiO_2) and silica (SiO_2) into polymer matrices is one of these tactics. Sehgal et al. (2018) conclude that these fillers raise water retention, prevent fuel crossover, and open novel proton-conduction channels. As an illustration, the Nafion/GO nanocomposites exhibit reduced permeability to methanol and higher proton conductivity as compared to pristine Nafion.

6.2 Ionic Liquid–Based Polymer Electrolytes

Due to their inherent ionic conductivity, large electrochemical window and low vapour pressure, ionic liquids (ILs) have been immobilized or incorporated into polymer matrices. This approach enhances high temperature performance, and protons transfer under anhydrous conditions. Ahmad et al. (2021) reported that polymer/IL hybrid electrolytes are promising in the next-generation high-temperature PEMFCs.

6.3 Bio-Based and Sustainable Polymer Electrolytes

Chitosan, cellulose and lignin-based membranes are bio-derived polymer electrolytes, which are low-cost, biodegradable, and environmentally friendly materials due to the need to achieve sustainability. Sulfonic and phosphoric acid functionalization has shown chitosan to be highly ionically conductive and a strong film forming polymer, suggesting its application as a sustainable alternative to petroleum-based polymers (Bose et al., 2020).

6.4 Cross-Linked and Block Copolymer Membranes

Phase-separated domains have been used to optimize proton transport and chemical cross-linking and block copolymer design have been used to enhance membrane stability. Li et al. (2019) state that cross-linked sulfonated poly(arylene ether sulfone) membranes are more mechanically durable and chemically resistant than non-cross-linked. Hydrophobic and hydrophilic block copolymers also make it possible to regulate the distribution of water, which increase conductivity and dimensional stability.

6.5 High-Temperature and Anhydrous Proton Conductors

Phosphoric acid-doped polybenzimidazole (PBI)-based membranes remain a major part of high-temperature PEMFCs (HT-PEMFCs). To further improve conductivity in the anhydrous state, the current studies have focused on the stabilization of acid retention, optimizing acid doping and incorporation of inorganic nanoparticles (Li et al., 2003). These advances reduce the CO poisoning risk and improve water management by increasing the operating temperature range of the PEMFCs to 200 °C.

7. Challenges and Limitations of Polymer Electrolytes in Fuel Cells

Although much has been achieved, several challenges related to the cost of materials, durability and capacity requirements make it hard to commercialize polymer electrolyte membranes (PEMs) into the fuel cell. All these limitations need to be surpassed in order to develop long-term, workable, and economical systems.

7.1 High Cost of Materials

Due to their high proton conductivity and stability, perfluorosulfonic acid (PFSA)-based, such as Nafion, membranes remain the standard electrolyte. Their high cost of production, however, makes them not highly commercially viable, especially in the transport sector, where cost-compete with the conventional fuels is an important factor (Zhang et al., 2008). Another high priority is research on producing low-cost substitutes, such as hydrocarbon or bioderived membranes.

7.2 Proton Conductivity and Water Management

The performance of polymer electrolytes is seriously influenced by hydration. Since standard membranes are not high in water, conductivity decreases quickly in high temperatures or in low levels of humidity (Li et al., 2003). Water management is further complicated by the possibility of dehydration at the anode or flooding at the cathode that would reduce fuel cell efficiency. The maximization of conductivity under dry environments is still a considerable challenge, even though high-temperature polymer electrolytes, including phosphoric acid-doped PBI, reduce some of these issues (Li et al., 2019).

7.3 Fuel Crossover and Selectivity

Polymer membrane crossover in direct methanol fuel cell (DMFC) reduces fuel consumption and cell efficiency. Although nafion is highly conductive, its conductivity is reduced by high methanol permeability (Sehgal et al., 2018). Despite the development of hybrid and composite membranes using nanofillers in a bid to minimize crossover, there is still a challenge of striking a balance between high conductivity and low permeability.

7.4 Mechanical and Thermal Stability

High heat loads, swelling/shrinkage cycles and mechanical stress require membranes capable of surviving long fuel cell operation. In high temperatures, many of the hydrocarbon-based polymers are dimensionally unstable and lack durability (Bose et al., 2020). The characteristics are improved with the help of cross-linking and nanofiller reinforcement, but ionic mobility and flexibility can be sacrificed.

sss7.5 Chemical Degradation and Durability

Polymer electrolytes can be eroded chemically by reactive oxygen species (ROS), e.g. hydroxyl radicals generated during fuel cell operation. These radicals attack the polymer backbone to cause thinning, pinhole formation, and finally collapse of the membrane (Ahmad et al., -2021). The critical material design challenge is to improve oxidative stability whilst maintaining a high proton conductivity.

8. Future Perspectives

Simultaneous advancements in materials chemistry, multi-scale design, manufacturing, as well as durability

engineering will be necessary to advance polymer electrolytes for fuel cells. A number of convergent paths seem particularly promising:

8.1 Water-independent proton conductors and high-temperature operation.

Kinetics and CO tolerance are enhanced by raising the working temperature (120–200 °C), but this necessitates membranes that maintain conductivity at low humidity levels. It is anticipated that stable anhydrous conductors will be produced by further improving acid-base polymer pairings (such as imidazole/phosphonate functions) and phosphoric-acid-doped PBI (acid retention, anti-leaching designs) (Li et al., 2003; Li et al., 2019). At high temperatures, molecular techniques including block-copolymer nanophase segregation, side-chain engineering, and controlled cross-linking can maintain proton routes while maintaining mechanical integrity (Bose et al., 2020).

8.2 Hybrid and nanostructured pathways for selective transport.

Future efforts will probably take advantage of 2D fillers as well as porous frameworks (e.g., silica networks formed via sol–gel within polymers) to engineer continuous, percolating protons highways that have low methanol permeability (Zhang et al., 2008). Nanocomposite and hybrid organic–inorganic designs—leveraging SiO_2, TiO_2, ZrO_2, graphene oxide, as well as heteroatom-doped carbon— generate tortuous paths that suppress fuel crossover while simultaneously providing acid sites and water-binding domains (Sehgal et al., 2018).

8.3 Ionic liquids, protic ionic liquids, and deep eutectic media.

Ionic liquids (ILs) or protic ILs embedded in polymer matrices provide nonvolatile, wide-window media that maintain conductivity at high temperatures and low humidity. Nanoconfinement and specifically designed polymer–IL interactions (H-bonding, acid–base pairing) can minimize IL leaching and maximize mechanical robustness (Ahmad et al., 2021, and Bose et al., 2020).

8.4 Sustainable and circular materials.

For low-cost, low-impact membranes, bio-derived backbones (such as chitosan, cellulose, and lignin) functionalized with sulfonic or phosphonic groups are appealing. Alongside electrochemical metrics, design constraints should include end-of-life strategies, recyclability, and green processes (aqueous casting, solvent recovery) (Bose et al., 2020 and Sehgal et al., 2018).

8.5 Durability by design: radical mitigation and chemical stability.

In conditions of practical stresses, future membranes have to resist hydrolysis and radical attack. The strategies also contain cross-link motifs that maintain ion channels without scission of chains, stable backbones (aromatic polysulfones, PBI), antioxidant additives, and radical-quenching nanofillers (Ahmad et al., 2021; Zhang et al., 2008).

8.6 Data-guided discovery and operando diagnosis.

High-throughput synthesis and testing in conjunction with machine learning can map composition, structure, and property spaces to target conductivity and selectivity windows at predetermined temperatures and humidity levels. Parallel to this, operando spectroscopy as well as imaging (mechanical strain, acid leaching, water distribution) will bridge the gap between design theories and actual degradation processes (Bose et al., 2020).

Conclusion

Fuel cell durability, overall efficiency, and commercial viability are all significantly influenced by polymer electrolytes. Significant advancements have been achieved in the last few decades in modifying their chemical structure, morphology, and composite design to solve the long-running trade-off between strong mechanical and thermal stability, low fuel crossover, and high ionic conductivity. Because they can combine the strong ionic

conductivity and liquid-based systems with the mechanical robustness of solids, GPEs in particular have become attractive options.

Notwithstanding notable advancements, issues like methanol crossover for DMFCs, membrane dehydration at high temperatures, radical-induced degradation, and the scalability of synthesis techniques continue to be significant obstacles to commercialization. Current studies on bio-derived polymers, ionic liquids, and nanostructured fillers provide practical methods to increase mechanical integrity, improve proton transport channels, and allow operation in high-temperature or low-humidity environments. Multifunctional as well as sustainable designs that satisfy financial and environmental requirements while simultaneously enhancing performance metrics are key to the future for polymer electrolytes. Accelerating advances will require the integration of scalable fabrication processes, in-situ diagnostics, and machine learning-assisted material discovery. Furthermore, the creation of recyclable, bio-inspired, and green membranes may open the door for the worldwide, ecologically conscious use of fuel cells.

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