

Architecting Biomimetic Proton Channels in Membranes for Energy and Environment Applications

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Abstract: Biological proton channels enable rapid and perfectly selective proton transport through highly confined and functionalized structures. Inspired by these natural systems, this review first elucidates the fundamental transport mechanisms underlying biological proton channels (e.g., Hv1, M2), emphasizing the role of hydrogen bonding networks and the Grotthuss mechanism. We then focus on the architectural design of biomimetic proton channels within membrane environments, systematically summarizing the evolution of these channels from one dimensional to two dimensional and three dimensional building blocks. Particular attention is paid to how these nanostructures are integrated into membrane matrices to break the traditional trade-off between proton conductivity and selectivity. Furthermore, the review highlights the critical role of these biomimetic membranes in energy and environment applications, including energy conversion, osmotic energy harvesting, and waste acid recovery. Finally, we provide perspectives on the challenges of long term stability and large scale fabrication for the practical implementation of these bio-inspired membrane technologies.

Keywords: biomimetic proton channels; dimensionality control; membranes; proton selectivity; applications

1. Introduction

Over the past decade, the fields of biomimetic nanofluidic and ion channel materials have witnessed a remarkable paradigm shift [1–5]. Inspired by biological channels (e.g., K⁺ channel, Na⁺ channel), researchers have constructed a variety of biomimetic ion channel materials using one dimensional (1D), two dimensional (2D), and three dimensional (3D) building blocks, fully demonstrating the immense potential of biomimetic design in the precise regulation of ion transport. However, despite the remarkable achievements in ion channel research, industrial scale applications of these concepts in proton (H⁺)-conductive membranes still face challenges.

More importantly, commercial membranes, represented by Nafion, rely on broad and randomly distributed hydration channels. Water loss at elevated temperatures leads to a dramatic drop in proton conductivity, severely limiting fuel cell efficiency [6,7]. Furthermore, due to the lack of effective size sieving and charge exclusion mechanisms, such materials struggle to suppress severe fuel crossover or the cross contamination of active metal ions (e.g., vanadium crossover in redox flow batteries), the conventional random packing design has reached its performance bottleneck. In contrast, natural biological proton channels, relying on sub-nanometer confined pores and highly ordered hydrogen bonding networks, achieve extremely high transport rates while exhibiting near-perfect selective exclusion of other chemical components [8–12]. The unique Grotthuss mechanism [13] of protons distinguishes them fundamentally from conventional monoatomic cations (e.g., K⁺, Na⁺). Unlike the vehicular mechanism where ions migrate physically through the medium, the Grotthuss mechanism involves a structural



diffusion process. In this relay like model, protons hop along an ordered network of hydrogen bonds (often termed water wires) through the cooperative cleavage and formation of covalent bonds among adjacent water molecules. This allows the protonic charge to be rapidly transferred across the sub-nanometer channel without the long range migration of individual oxygen atoms, significantly lowering the activation energy for transport.

However, despite the exceptional efficiency and selectivity of natural proton channels, their direct integration into industrial applications is severely hindered by the intrinsic fragility of protein structures. Natural proteins are highly sensitive to non-physiological environments and are prone to denaturation or loss of functionality under the harsh conditions typical of industrial processes, such as extreme pH and elevated temperatures. Moreover, biological channels lack the mechanical robustness required for large scale, long term operation in macroscopic membrane platforms. This implies that developing architecting biomimetic proton channels within membrane environments is driven not merely by the pursuit of superior conductivity, but more importantly, by the need to achieve high stability and ultrahigh selectivity in extreme environments. Bridging the gap between molecular scale channel design and macroscopic membrane fabrication is essential for next generation proton-conducting materials.

Therefore, this review systematically summarizes the structure-function relationships of biological proton channels and outlines the latest advances in integrating 1D, 2D and 3D biomimetic building blocks into membrane architectures. We highlight the key role of these biomimetic materials in energy and environmental fields, including energy conversion, osmotic energy harvesting, and waste acid recovery, providing a comprehensive perspective on their journey from bio-inspired concepts to practical membrane technologies.

2. Biological Proton Channels

Biological proton channels play a pivotal role in essential life processes, including photosynthesis, cellular pH regulation, and signal transduction. Their core mechanism involves the mediation of proton binding and transport by specific amino acid residues, a process that strictly adheres to the Grotthuss mechanism.

Taking the voltage gated proton channel Hv1 as a representative example, the transport mechanism is synergistically driven by a voltage-sensing domain composed of four transmembrane segments (S1 to S4) [14–16]. Research indicates that the negatively charged aspartic acid residue (Asp112) on the S1 helix and the positively charged arginine (Arg) residue on the S4 helix form a salt bridge via electrostatic attraction (Figure 1a) [17–19]. This salt bridge is capable of capturing hydronium ions (H_3O^+) and undergoing protonation, followed by dehydration to yield neutral water molecules, thereby establishing a critical proton bridge between the Asp-Arg residue pair (Figure 1b) [11]. Proton translocation subsequently proceeds via site hopping through a hydrogen bonding networks, a process known as Grotthuss mechanism [13]. Unlike the diffusion mechanisms of conventional ions, Grotthuss transport does not require the cooperative migration of a hydration shell, which accounts for its exceptionally high transport rates.

Similarly, the M2 protein of the Influenza A virus represents another class of prototypical proton channels. This channel utilizes a functional ring composed of four histidine (His) residues [20–23] to capture protons in acidic environments (Figure 1c,d). The imidazole groups of these His residues undergo reversible protonation, where the covalent binding of protons to nitrogen atoms triggers a protein conformational change, thereby stabilizing the proton bound state (Figure 1e) [24–27]. Subsequent deprotonation releases the proton into the internal water chain of the channel, enabling rapid Grotthuss conduction via a continuous hydrogen bonding networks [28,29]. Notably, biological proton channels lack a physically open pore large enough to permit the passage of solvated ions; their functional pore size is effectively smaller than a single atom. This near limit physical confinement serves as the structural foundation for the perfect selectivity and exclusion of other chemical species.

In summary, although various biological proton channels differ in molecular structure, their high efficiency and specificity in conduction follow a unified physicochemical principle (Figure 1f): the construction of continuous hydrogen bonding networks through the directional alignment of water molecules within sub-nanometer confined spaces, complemented by active residues at specific spatial sites to facilitate cooperative proton hopping. This synergy of confined space, functional sites, and hydrogen bonding networks constitutes the core design paradigm for the subsequent development of artificial biomimetic proton channel materials.

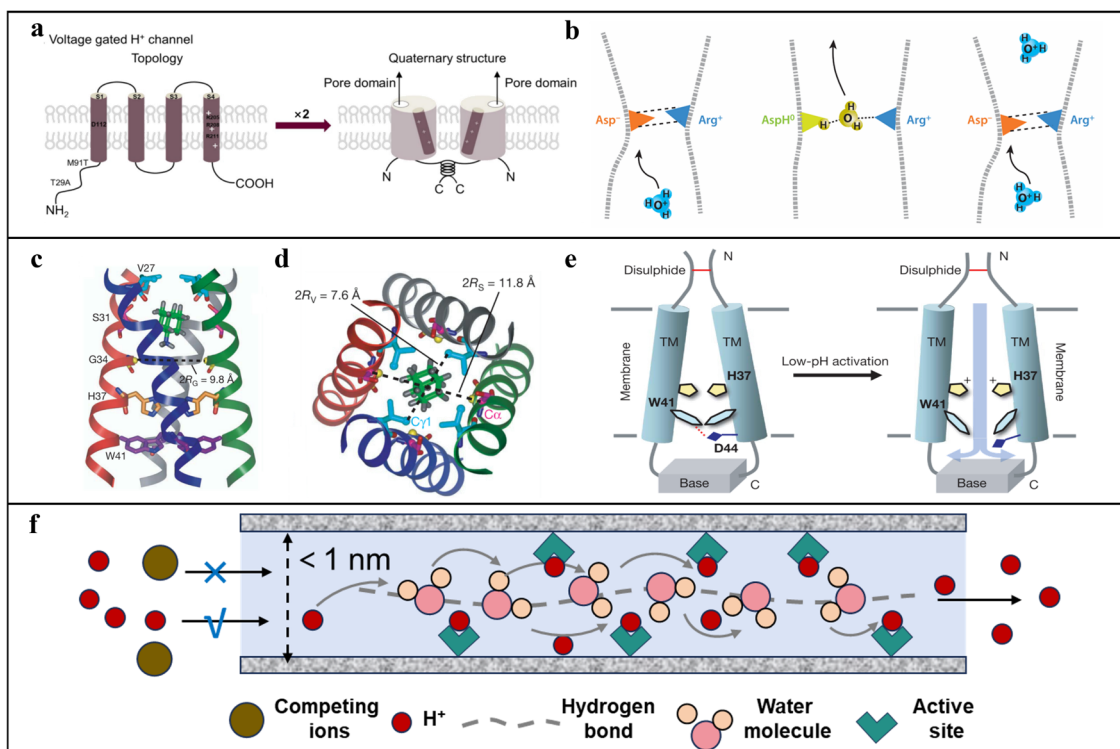


Figure 1. Biological proton channels and their transport processes. (a) Schematic illustration of the structure of the voltage-gated H⁺ channel (Hv1) [18]. Copyright 2023, Springer Nature. (b) Mechanism of selective proton conduction in Hv1 [11]. Copyright 2024, Annual Reviews. (c,d) Structure of the M2 protein within a lipid bilayer [23]. Copyright 2010, Nature Research. (e) Schematic representation of the M2 channel activation process [26]. Copyright 2008, Nature Research. (f) Universal pathway of proton transport in biological channels.

3. Multi-Dimensional Biomimetic Channels in Functional Membranes

In principle, any material platform capable of providing sub-nanometer spatial confinement and supporting ordered hydrogen bonding networks can be considered a candidate for biomimetic proton channels. While nanomaterials such as carbon nanotubes (CNTs), graphene oxide (GO), and synthetic polymers have demonstrated significant potential in meeting these basic criteria, Metal Organic Frameworks (MOFs), Covalent Organic Frameworks (COFs), and Hydrogen-bonded Organic Frameworks (HOFs) have emerged as the dominant platforms in recent years. This preference is driven by their exceptional designability. The periodic nature of these crystalline frameworks allows researchers to arrange the spatial distribution of functional groups in a deterministic manner and achieve precise pore size engineering. Compared with random material systems, this high degree of controllability makes it easier to replicate biological waterline environments.

To translate the atomic-scale precision of biological proton channels into macroscopic engineering platforms, researchers have explored diverse spatial dimensions as building blocks for membrane fabrication. This evolution in dimensionality spanning from 1D, 2D, to 3D, reflects a fundamental shift in design strategy: moving beyond simple molecular mimicry toward the rational construction of continuous proton-conducting networks within functional membranes. This section categorizes these advancements, highlighting how the orientation of 1D channels, the laminar stacking of 2D materials, and the interconnected pores of 3D frameworks dictate the final membrane performance, including flux, selectivity, and stability in practical electrochemical devices, although it is not intended to be an exhaustive enumeration.

3.1. 1D Materials

1D channels are regarded as the most direct and ideal platforms for mimicking biological proton channel structures due to their highly regular linear geometry and well-defined transport pathways (Figure 2a). The key of their design lies in utilizing sub-nanometer confined spaces and precisely regulating the physicochemical environment of the inner pore walls (e.g., hydrophobicity/hydrophilicity and the distribution of hydrogen-bond donors/acceptors) to replicate the Grotthuss proton hopping mechanism found in native channels.

The exploration of artificial proton channels began with the imitation of linear structures such as natural gramicidin A. Early studies utilized covalently synthesized rigid-rod molecules as transmembrane scaffolds [30,31].

By modifying poly-p-phenylene backbones with linearly arranged hydroxyl groups, researchers successfully constructed continuous hydrogen-bond chains within hydrophobic lipid bilayers. Although these channels lacked a distinct physical cavity, they demonstrated that ordered hydrogen bonding sites alone could achieve efficient selective proton transport (Figure 2b).

Subsequent research shifted toward supramolecular self-assembly systems with dynamic tunability. The Hou group utilized the self-assembly of pillar[5]arene macrocycles to construct a series of artificial nanotubes with precise pore sizes (Figure 2c) [32,33]. Within these sub-nanometer pores, confined water molecules align to form oriented 1D water wires, through which protons achieve ultrafast transport via the Grotthuss mechanism. Research at this stage achieved high efficiency proton conduction and expanded applications into biomedical fields, such as high efficiency water channels and damaged cell repair.

To further simulate the complex gating and high selectivity of the viral M2 proton channel, the Zeng group developed artificial channels based on helical amide foldamers [34,35]. These foldamers maintain a stable helical conformation through a covalent backbone. Their extremely narrow internal pores (~ 3 Å) not only exclude the vast majority of ions (H^+/Cl^- , H^+/K^+ , H^+/Na^+ selectivity of 279.6, 64.1, 254, respectively), but also achieve or even surpass the conduction rates of natural channels through the synergistic effect of basic sites on the inner pore walls (transport water at a rate of $1.6 \times 10^9 \text{ H}_2\text{O} \cdot \text{S}^{-1} \cdot \text{channel}^{-1}$) (Figure 2d). Recently, the design of 1D channels has moved beyond the limitation of single-molecule transmembrane structures toward long range hierarchical assembly [36]. By utilizing the hierarchical self-assembly of peptide molecules, researchers have realized proton nanochannels with micrometer scale lengths. This multiscale construction from point to line provides molecular level templates for developing proton exchange materials with macroscopic orientation characteristics (Figure 2e).

In addition to organic supramolecular systems, CNTs serve as ideal 1D physical models, demonstrating the massive enhancement effect of nanoconfinement on proton conduction (Figure 2f) [37]. Inside sub-1-nm CNTs, the formation of 1D water wires enables proton conductivity an order of magnitude higher than that of bulk water. This discovery defines the physical limits of proton transport within 1D confined spaces and provides a critical theoretical foundation for understanding interlayer confined transport in 2D materials. More importantly, the successful integration and vertical alignment of these 1D building blocks within polymer or lipid-like matrices represent a crucial step toward creating biomimetic membranes with highly oriented and discrete proton-conducting pathways.

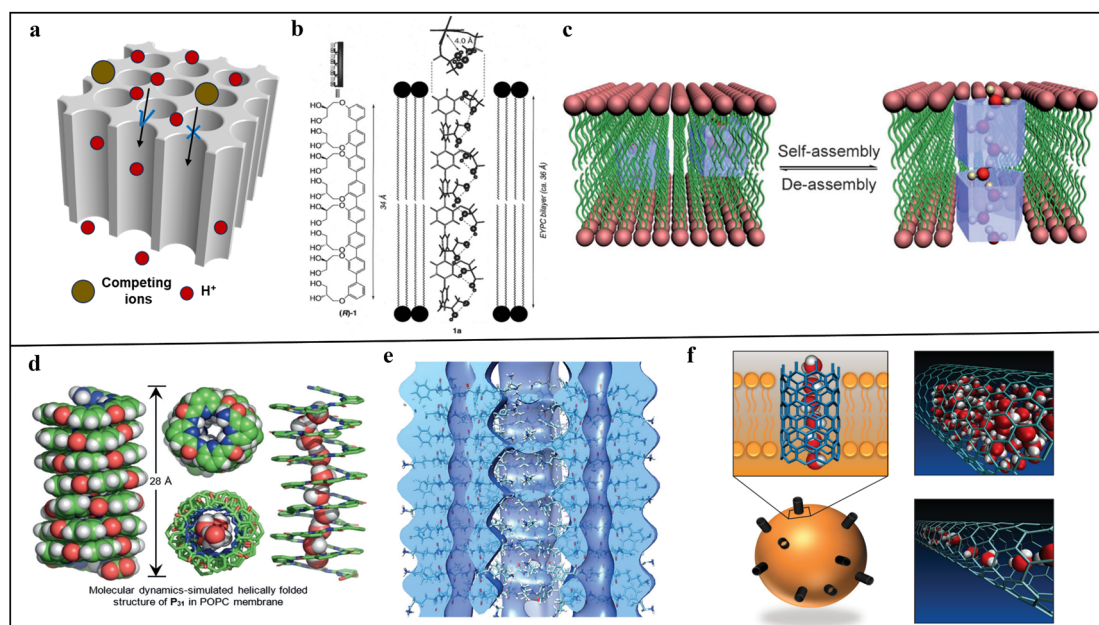


Figure 2. 1D biomimetic proton channel materials. (a) Schematic illustration of 1D biomimetic proton materials. (b) Molecular structure of rigid-rod polyols [30]. Copyright 1997, American Chemical Society. (c) Artificial nanochannels formed by the self-assembly of pillar[5]arenes [32]. Copyright 2011, Wiley-VCH. (d) Structure of helical folded organic nanotubes based on hydrogen-bonded aromatic amide foldamers [35]. Copyright 2020, Wiley-VCH. (e) Surface representation from 3D cryo-EM reconstruction of an artificial proton nanochannel with fourfold symmetry constructed via the hierarchical self-assembly of cyclic peptides [36]. Copyright 2024, Wiley-VCH. (f) Schematic representation of carbon nanotube porins (CNTPs) [37]. Copyright 2016, Nature Research.

3.2. 2D Biomimetic Proton Channels in Membranes

2D materials provide an ideal platform for mimicking the ultrafast proton transport of biological membranes, due to their highly tunable sub-nanometer confinement spaces. Unlike 1D channels that often require matrix support, 2D nanosheets can be assembled into cohesive laminar membranes (Figure 3a). This structural characteristic allows for the creation of continuous and stable hydrogen bonding networks across macroscopic areas. The advantage of these 2D biomimetic membranes lies in their ability to induce long range spatial arrangement of water molecules within the interlayer galleries, effectively bridging the gap between molecular sieving and practical membrane separation.

Mimicking biological proton channels (such as the M2 protein) centers on the integration of spatial confinement, functional active sites, and sophisticated hydrogen bonding networks to achieve high selectivity and rapid conduction. Gao' group [38] leveraged the regular interlayer galleries of COFs to simulate this characteristic (Figure 3b). Their research revealed that when the interlayer spacing is compressed to the sub-nanometer scale, physical confinement effects completely block the passage of large ions. Meanwhile, protons can undergo hopping conduction through hydrogen bonding networks assisted by hydrophilic groups on the COF surface, achieving a diffusion coefficient comparable to that of bulk water and realizing perfect selectivity in a physical sense. Furthermore, Shi et al. [39] proposed the concept of a confined short hydrogen bond network. By densely decorating ionic COF surfaces with hydrophilic ligands, they achieved local hydronium ion enrichment and created low-energy-barrier transport pathways, significantly enhancing conduction efficiency.

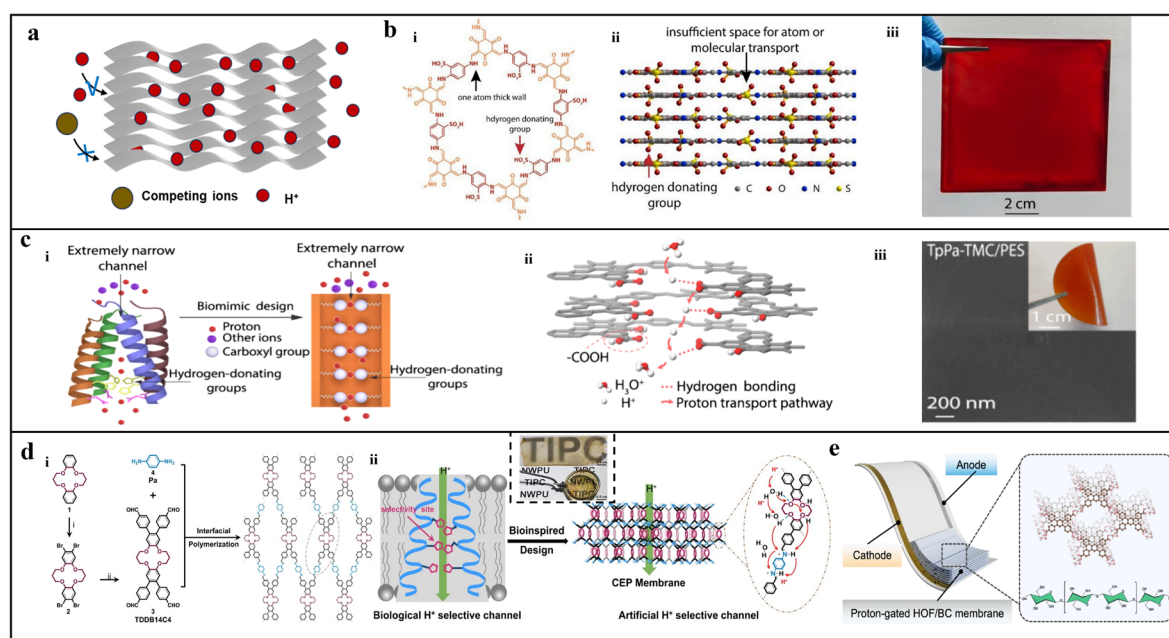


Figure 3. 2D biomimetic proton channels in membranes. (a) Schematic illustration of 2D biomimetic materials. (b) From left to right, (i): the molecular structure; (ii): a side view of the crystal structure, and (iii): an optical image of the biomimetic TpPa-SO₃H COF membrane [38]. Copyright 2024, Wiley-VCH. (c) (i): The design of the artificial proton channel membrane inspired by biological proton channel; (ii): the schematic of the proton transport mechanism, (iii): top-surface SEM image and optical image of TpPa-TMC/PES membrane [40]. Copyright 2025, American Chemical Society. (d) (i): Biomimetic 2D crown-ether-based polyimine membrane via interfacial polymerization; (ii): schematic representation of the fabricated artificial proton (H⁺) channel membrane inspired by M2 protein channel and the set is an optical photograph of the typical free-standing CEP membrane [41]. Copyright 2023, Wiley-VCH. (e) The structure of proton-gated HOF/BC membrane [42]. Copyright 2025, Springer Nature.

The selectivity of biological channels is determined by the interplay between pore size and the specific chemical environment of the inner walls. Building on this principle, Jian et al. [40] modified the inner walls of COF channels with carboxyl groups, which are highly efficient hydrogen-bond donors, as active sites for proton transport. Different from previous approaches that avoid amorphous structures, this work intentionally employed an amorphization strategy: by using a rapid interfacial polymerization method, the resulting COF layer became amorphous, causing most of the intrinsic nanopores to collapse or misalign. This dramatically reduced the effective pore size and porosity, creating an extremely narrow confinement (with effective pore dimensions smaller than the hydration diameters of common metal ions) that imposes strong steric hindrance on cation transport. Moreover,

the authors proposed for the first time a self-amplified selectivity mechanism. Specifically, the hydrated protons (which have a subnanometer size) occupy the narrow channels and physically block other cations. Because protons themselves are tiny (femtometer scale) but transport via the Grotthuss mechanism along hydrogen bonding networks, they are not subject to the same size exclusion. As the proton concentration increases, more hydrated protons occupy the channel, further enhancing the steric hindrance to competing cations. Consequently, the proton selectivity becomes higher at higher proton concentrations—a “self-amplifying” effect. This dynamic, concentration dependent selectivity mimics the gating behavior of biological channels, providing a new perspective for mimicking their dynamic response characteristics (Figure 3c).

Similarly, Wen and his colleagues [41] introduced crown ether units with molecular recognition capabilities into 2D polyimine frameworks (Figure 3d). This design mimics the gating or recognition units of biological channels. The crown ethers capture water molecules via hydrogen bonding to form hopping sites, and simultaneously anchor alkali metal ions through host-guest interactions, further enhancing proton selectivity through a chemical shielding effect. Consequently, the crown-ether-based polyimine membrane achieved a H^+/Li^+ selectivity of 215. The morphology of water molecules within 2D channels directly dictates the transport mechanism. In Lei’ work [42], he investigated the dynamic gating behavior within 2D HOFs channels, controlling the formation and rupture of water bridges by adjusting ambient humidity (Figure 3e). This design simulates the switching between open and closed states in biological channels, laying a theoretical foundation for the development of high performance solid state proton gating devices.

3.3. 3D Biomimetic Channels in Membranes

3D framework materials provide multi-dimensional transport pathways for protons by constructing interconnected pore networks (Figure 4a). Compared to 1D and 2D systems, the advantages of 3D biomimetic materials lie in their exceptionally high site density and customizable internal surface environments, which enable the simulation of complex, hierarchical hydrogen bonding relay systems found in biological system within a macroscopic membrane.

MOFs, characterized by their immense design flexibility [43,44], are frequently employed to mimic the intricate electrostatic fields and geometric confinement within biological proteins. Wang’ group [45] developed a series of sulfonated MOF channels (UiO-66-X, where X represents either $(NH_2)_2$ or $(NH-SAG)_2$, SAG referring to sulfonic acid groups) with sub-1-nm windows (Figure 4b). By densely populating the inner walls of the 3D pores with sulfonic acid groups, this design successfully replicates the chemical environment of natural proton channels, achieving superior proton conductivity as well as bio-level ultra-high proton selectivity. Consequently, the UiO-66- $(NH-SAG)_2$ channels exhibit a high H^+/Li^+ selectivity up to ~100, a H^+/Na^+ selectivity of ~80, and a H^+/K^+ selectivity of ~70. Furthermore, the team demonstrated [46] that sub-nanometer channels in MIL-53-COOH can facilitate ultrafast reverse-rectifying transport of protons against metal ions, effectively simulating the directional ion-pumping functions of biological membranes. Beyond molecular scale channel modification, mimicking the hierarchical drainage networks of complex natural tissues is key to enhancing 3D transport efficiency. Inspired by the vascular bundle structures of plants, Mao et al. [7] fabricated biomimetic membranes with superior water retention capabilities using the dynamic evolution of superstructure MOFs (Figure 4c). By mimicking the multilevel pore networks of biological tissues, this structure encapsulates and organizes extensive water molecule chains within the 3D framework to construct continuous superprotonic conduction pathways, demonstrating the significant enhancement of hierarchical topology on water management and proton transport.

To replicate the transport sites composed of acidic amino acid residues (e.g., Aspartic acid, Asp; Histidine, His) in biological proteins, researchers have utilized the chemical tunability of 3D scaffolds for precise site customization. Li et al. [47] introduced free carboxylic acid groups via post-synthetic modification into 3D HOFs to create biomimetic proton channels (Figure 4d). These inner-channel sites act as relay stations for proton translocation, capturing and stabilizing water to construct continuous transport chains, consequently enhancing conductivity by three orders of magnitude through the reinforced hydrogen-bonding networks.

Recent research has further shifted toward mimicking the dynamic response of biological systems to environmental changes. Inspired by the osmoregulation mechanisms of hyper thermophilic organisms, Wang and his group [48] constructed open-framework ionic polymers with breathing characteristics (Figure 4e). This structure utilizes cooperative hydrogen bonding to maintain water continuity at high temperatures, simulating the homeostatic maintenance features of organisms in extreme environments. This dynamic water retention mechanism effectively addresses the bottleneck of dehydration-induced failure in traditional materials at elevated temperatures ($>100\text{ }^\circ\text{C}$), providing a new physical model for understanding biological water management and proton transport.

The profound influence of these 3D confined environments on molecular transport is further elucidated in a recent comprehensive review. Chen et al. [49] systematically summarized the confinement effects within such nanocomposite architectures, emphasizing that the synergy between 3D filler pores and the polymer filler interface is key to manipulating transport thermodynamics. This theoretical framework, coupled with advanced membrane fabrication techniques, offers a clear roadmap for the development of biomimetic 3D membranes with superior flux and selectivity.

In summary, the dimensionality of biomimetic building blocks dictates the intrinsic performance and practical applicability of the resulting membranes. 1D channels (e.g., nanotubes, foldamers) offer the most direct pathways for ultrafast proton transport with high selectivity, but they face challenges in long range alignment, large scale processability, and long term structural stability. 2D lamellar channels provide a superior balance between molecular-level selectivity and macroscopic membrane fabrication, leveraging interlayer nanoconfinement to achieve long range ordered hydrogen-bonding networks with good operational stability. 3D framework architectures (e.g., MOFs, HOFs) excel in site density and structural robustness, enabling complex hierarchical water management that ensures high stability under extreme or non-humidified conditions. Consequently, a fundamental trade-off exists: 1D architectures prioritize the precision of single-channel mimicry, while 3D systems focus on macroscopic robustness and stability, with 2D systems bridging the gap for practical separation applications.

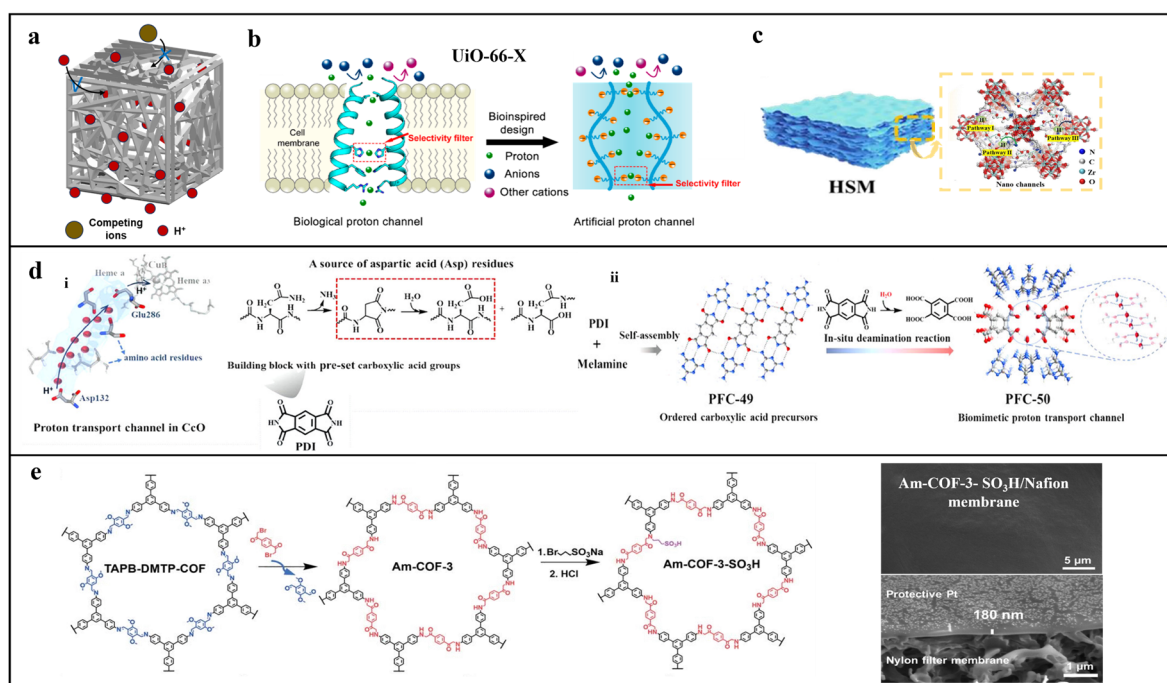


Figure 4. 3D biomimetic channels in membranes. (a) Schematic representation of 3D biomimetic materials. (b) Biomimetic construction of proton-selective MOF channels [45]. Copyright 2020, American Chemical Society. (c) Schematic illustration of proton conduction pathways composed of nanoscale hierarchical channels in the hydrogels self-standing membrane (HSM) [7]. Copyright 2025, Wiley-VCH. (d) (i): The structure of proton transport D-channel in CcO; (ii): the schematic illustration of the synthesis and structural transformation process of PFC-49 and biomimetic proton channel PFC-50 [47]. Copyright 2025, Wiley-VCH. (e) Structure of COF-based ionomers linked by α -aminoketone bonds and the surface and cross-section SEM images of Am-COF-3- SO₃H/Nafion membrane [48]. Copyright 2024, American Association for the Advancement of Science.

4. Applications

Integrating the ultrafast conduction and high selectivity of biological proton channels into artificial membrane materials provides a novel pathway for addressing key bottlenecks in energy conversion and environmental remediation. This section highlights research progress in the application of biomimetic proton channel materials within the fields of energy and environment, such as fuel cells, osmotic energy harvesting, and resource recovery.

4.1. Energy Conversion and Harvesting

The commercialization of hydrogen fuel cells has long been hindered by the dehydration-induced failure of proton exchange membranes (PEMs) under high-temperature operating conditions. Inspired by the osmoregulation mechanisms of hyperthermophilic organisms, in Wang' research [48], they constructed 3D open-framework ionic polymers with water locking capabilities, maintaining efficient proton conduction in high temperature, non-humidified environments (Figure 5a). In a complementary study, Mao et al. [7] designed biomimetic MOF membranes mimicking the hierarchical pore structures of plant vascular bundles. Leveraging their superior water encapsulation, these membranes exhibited superprotonic conductivity across a wide humidity range, effectively overcoming the water dependency of traditional PEMs (Figure 5b).

In the field of osmotic energy (blue energy) conversion, mimicking the unidirectional rectification characteristics of biological electric organs (e.g., electric eels) is central to enhancing conversion efficiency. Wang et al. [46] constructed MOF heterojunction channels that utilize sub-nanometer confinement to induce the orderly arrangement of water, achieving high ratio unidirectional proton rectification similar to biological channels (Figure 5c). Furthermore, Zhu and her coworkers [50] simulated the chloride-assisted mechanism of the ClC-ec1 protein, achieving synergistic kinetic enhancement of protons and auxiliary ions in acidic wastewater environments, which significantly boosted energy harvesting efficiency. Therefore, even a very low concentration of Cl^- can significantly increase the proton permeation ($9.8 \text{ mol m}^{-2} \text{ h}^{-1}$), and the output power density achieves 434.8 W m^{-2} under simulated acidic wastewater conditions with a 50-fold concentration gradient (Figure 5d). To strengthen operational robustness, Lei et al. [51] utilized the mechanical toughness of aramid nanofibers (ANFs) to achieve high power output under realistic operating conditions. The optimized commercial Nafion membranes through biomimetic environment tuning, demonstrating that conventional materials can also surpass the commercial power density threshold of 5.0 W m^{-2} in Xia' work [52] (Figure 5e). This suggests that the future of osmotic energy harvesting lies in the deep integration of biomimetic mechanisms with high-stability substrates.

Notably, while current research focuses heavily on organic supramolecular systems, the extreme confined conduction characteristics of inorganic 2D materials offer significant reference value. Mogg et al. [53] utilized atomic scale confined channels constructed from natural mica flakes to demonstrate exceptional proton conductivity in the mid-to-high temperature range ($100\text{--}500^\circ\text{C}$) (Figure 5f). This discovery implies that a precise confinement environment and continuous hydrogen bonding sites are universal principles for achieving unconventional proton transport, whether in biological protein pores or inorganic layered materials.

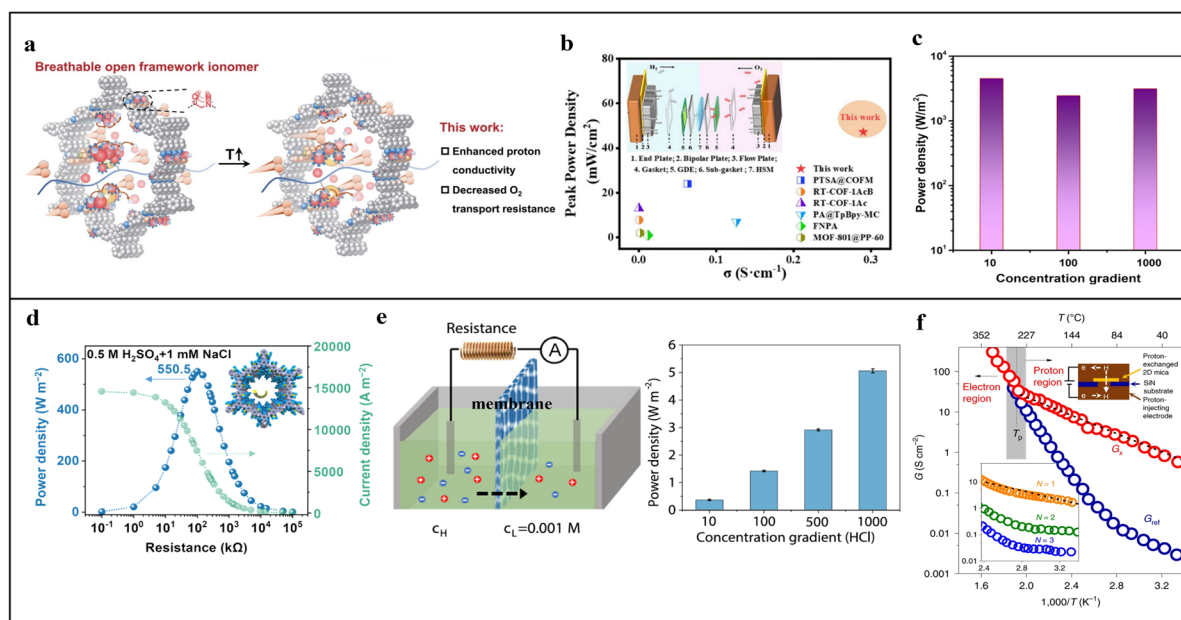


Figure 5. Energy applications. (a) Schematic diagram of the structure of a 3D open frame ionic polymer [48]. Copyright 2024, American Association for the Advancement of Science. (b) Comparative analysis of H_2/O_2 fuel cell peak power density and conductivity between homogeneous self-standing MOF membrane and reported self-standing proton-conducting materials [7]. Copyright 2025, Wiley-VCH. (c) Power density as a function of concentration gradient with the HCl concentration of the base side set as 1.0 M for PET/MIL-53-COOH NC [46]. Copyright 2022, American Association for the Advancement of Science. (d) Output power density and current density of the ANF/COF membrane in a $0.5 \text{ M H}_2\text{SO}_4 + 1 \text{ mM NaCl}/0.01 \text{ M H}_2\text{SO}_4$ gradient [50]. Copyright 2025,

American Chemical Society. (e) Schematic of osmotic energy harvesting device and power density across the Nafion membrane, the membrane test area is 0.2 mm^2 [52]. Copyright 2024, American Chemical Society. (f) G_x and G_{ref} of bilayer muscovite, G is the areal conductivity ($G = 1/R$) [53]. Copyright 2019, Springer Nature.

4.2. Resources and Environment

In typical industrial waste acid recovery processes, an ideal semi-permeable membrane must permit rapid proton diffusion while simultaneously achieving high rejection of heavy metal ions. However, conventional diffusion dialysis (DD) membranes generally suffer from low selectivity, where heavy metal ion leakage compromises recovered acid purity and increases the risk of secondary pollution. So, the near-perfect selectivity exhibited by biological proton channels provides critical inspiration for developing high performance acid recovery membranes.

Drawing inspiration from the dynamic charge-shielding effect and abundant proton-donating groups in biological channels, Jian et al. [40] engineered COF membranes with self-amplified selectivity. Compared to traditional non-biomimetic DD membranes, this material maintains high proton flux while leveraging the electronegative nature of functional groups to construct a potent electrostatic barrier against metal ions. This bifunctional design achieves efficient waste acid recovery and simultaneous electrical power output, in terms of selectivity, the $\text{H}^+/\text{Fe}^{3+}$ and $\text{H}^+/\text{Cu}^{2+}$ ratios reached 22,347 and 8915, and the selectivity against V^{5+} and Co^{2+} was almost perfect, demonstrating a sustainable approach to industrial wastewater treatment (Figure 6a). Furthermore, in Sun's research [54], he utilized charge assisted hydrogen bonds within guanidinium-based COF membranes to achieve highly selective separation of HCl from metal ions, further validating the importance of precise chemical microenvironment design in complex ionic separations (Figure 6b). The long term chemical robustness of biomimetic membranes is a prerequisite for their industrial implementation in harsh acidic environments. Jian et al. [40] verified the exceptional reusability of their membrane through multiple acid recovery cycles, while Sun et al. [54] confirmed that the TpTag-COF/PAN membrane could maintain stable permeance and high selectivity (e.g., $\text{P}(\text{HCl})/\text{P}(\text{H}_2\text{SO}_4)$ selectivity of up to 149) during a continuous over 200-h operational test. These findings highlight the structural integrity and functional reliability of biomimetic frameworks under sustained acidic exposure.

Leveraging the environmental sensitivity of biomimetic channels can enable high-sensitivity environmental monitoring. So, a proton gating membrane based on HOF composites was developed by Lei et al. [42]. By mimicking the open/closed states of biological channels, they achieved intelligent sensing of ambient humidity (Figure 6c). This gating mechanism does not rely on traditional physical occlusion, instead, it offers a new paradigm for developing high performance chemical sensors by switching proton transport modes.

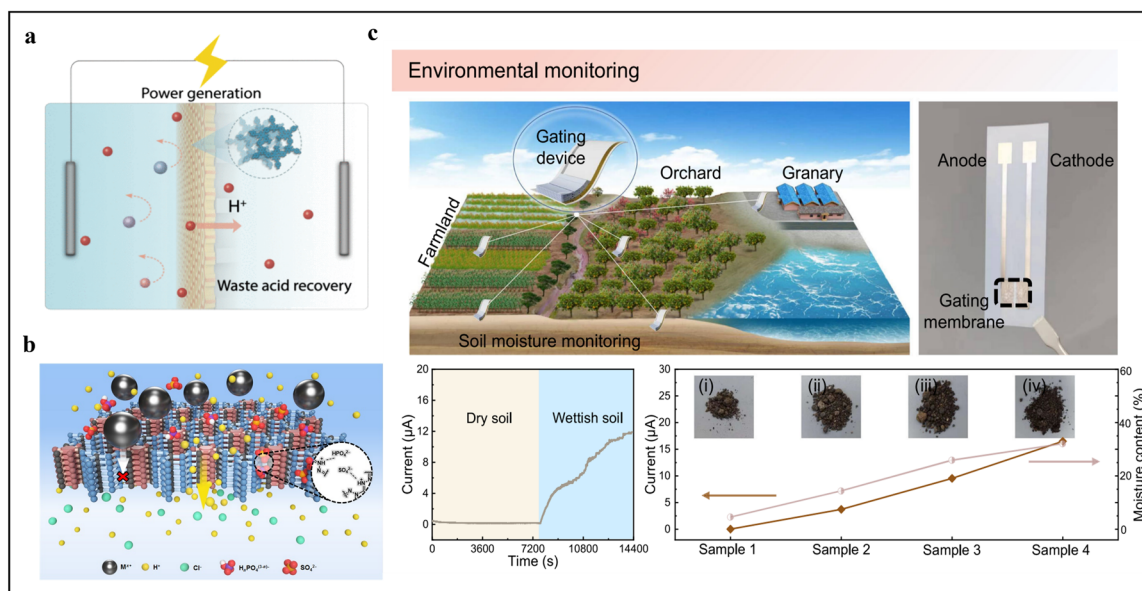


Figure 6. Resource and environment applications. (a) Schematic diagram of biomimetic proton channel membranes for waste acid recovery and power generation processes [40]. Copyright 2025, American Chemical Society. (b) Multifunctional COF membrane for HCl extraction [54]. Copyright 2023, American Association for the Advancement of Science. (c) Schematic of the moisture contents monitoring in both the storing environment and the nurturing soil, such as farmland, orchard, and granary. The optical photograph of the gating membrane device [42]. Copyright 2025, Springer Nature.

5. Conclusions and Perspectives

Biomimetic design provides innovative strategies for breaking the intrinsic trade-off between conductivity and selectivity in proton transport. By integrating 1D, 2D, and 3D building blocks into functional membrane platforms, researchers have preliminarily validated the potential of these bio-inspired architectures in fuel cells, osmotic energy harvesting, and industrial resource recovery. Despite rapid advancements in molecular synthesis and nanofabrication, transitioning from laboratory-scale prototypes to industrial-grade biomimetic membranes remains a formidable challenge.

First, achieving the near-perfect selectivity of biological channels within macroscopic membranes is still difficult. While individual nanochannels show promise, maintaining this precision across large area membrane surfaces requires unprecedented control over pore size distribution and chemical environment uniformity. Second, there remains significant room to optimize areal proton flux. The focus must shift from the intrinsic conductivity of nanomaterials to the effective density of active transport pathways within the membrane.

Most critically, the large scale fabrication of defect-free biomimetic membranes that simultaneously possess chemical durability and mechanical robustness is the core technical bottleneck. Strategies such as interfacial engineering and advanced processing technologies are essential to eliminate micro-voids and ensure structural integrity under harsh operating conditions, such as extreme pH or high temperatures. This gap in manufacturing and stability largely explains why biomimetic proton-conductive materials have yet to achieve widespread commercial applications.

Looking ahead, overcoming these obstacles requires a deep synergy between fundamental transport theory and membrane engineering. Most importantly, the transition from laboratory-scale prototypes to industrial-grade membranes remains a formidable challenge. Current mainstream laboratory processes, such as vacuum filtration, spin-coating, and *in-situ* growth, are highly effective for producing small-scale samples with precise channel architectures. However, these batch-wise methods encounter significant hurdles in maintaining orientation uniformity and structural consistency across large area membrane surfaces. In particular, vacuum filtration is inherently a batch process with low production efficiency, and when applied to large areas, non-uniform pressure distribution often leads to local defects or uneven thickness, compromising the integrity of the biomimetic channels. Similarly, while interfacial polymerization and *in-situ* growth can create dense selective layers, controlling the nucleation density and growth orientation at a macroscopic scale remains technically demanding, often resulting in localized defects or disordered domains.

To bridge this gap, future efforts must focus on developing scalable assembly techniques with molecular level precision. Potential solutions include the adoption of roll-to-roll processing combined with external field induced assembly (e.g., magnetic, electric, or shear force fields) to force the alignment of 1D/2D building blocks during large scale casting. Additionally, advanced manufacturing paradigms such as 3D printing or slot-die coating could provide more uniform control over the chemical environment and nanostructure deposition, enabling continuous production with improved structural fidelity. By bridging the gap between microscopic channel design and macroscopic membrane performance, the immense potential of biomimetic systems will be fully unleashed, laying a solid foundation for next-generation sustainable energy and environmental technologies.

Author Contributions

M.J.: investigation, software, writing original draft and editing; G.L. (Guozhen Liu): reviewing, data curation and investigation; J.G.: conceptualization, methodology and reviewing; G.L. (Gongping Liu): supervision, conceptualization, methodology and reviewing; W.J.: supervision, visualization, conceptualization. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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