Review

A Mini-Review of Ion Exchange Membranes for Capacitive Deionization: Research Progress, Commercialization, and Patent Trends

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Abstract: With global water scarcity worsening, improving water treatment efficiency and sustainability has become a priority for governments worldwide. Ion exchange membranes (IEMs) in capacitive deionization (CDI) are regarded as a promising water treatment technology, capable of meeting the urgent demand for sustainable water resource utilization. In this mini-review, we have provided an overview of the research progress made in IEM-assisted CDI (MCDI), focusing on membrane materials, system configurations, patent analysis, and commercialization. Bibliometric and citation analyses reveal a surge in research and patent activity related to MCDI over the past five years, highlighting their growing global interest. The commercialization of MCDI is accelerating, driven by government funding in Europe, the U.S., Japan, and South Korea, alongside industry innovations improving efficiency and scalability. Patent analysis identifies dominant technical topics, patent strength, and the evolving patent numbers and expiration patterns of MCDI. Although challenges remain regarding cost, membrane durability, and scalability, MCDI is set to be a transformative technology in next-generation water purification and electrochemical separation systems. This review examines the current state of MCDI across various countries, offering insights into its role in advancing sustainable water resource management and enhancing water treatment technologies.

Keywords: ion exchange membranes; capacitive deionization; water treatment; commercialization; patent analysis

1. Ion Exchange Membranes

1.1. Overview and Bibliometric Analysis of IEMs

To comprehensively examine the research landscape of ion exchange membranes (IEMs), a bibliometric analysis is conducted using VOSviewer. This tool facilitates the construction and visualization of bibliometric networks, enabling researchers to systematically examine relationships among publication information and keywords in a structured graphical format [1–3]. Figure 1a illustrates a keyword co-occurrence network, where distinct research domains are represented as color-coded clusters. The red cluster primarily pertains to studies on anion exchange membranes, particularly in the context of alkaline environments and fuel cell applications. The green cluster focuses on ion transport mechanisms and membrane performance optimization. The blue cluster highlights topics such as proton conductivity, polymer chemistry, and nanocomposite development. Meanwhile, the yellow cluster encompasses research on electrodialysis, adsorption processes, and membrane-based water purification technologies. These thematic clusters underscore the interdisciplinary nature of IEM research, bridging fields such as energy storage, fuel conversion, water treatment, and environmental remediation. The dense interconnections within and between clusters reflect the growing complexity and integration of IEMs-related studies. Figure 1b illustrates the citation network analyzed using Litmaps, showcasing the interconnected relationships within academic literature. Litmaps is a platform that simplifies literature management and visualization, enabling researchers to track advancements in their fields while constructing citation networks that illuminate the relationships among scholarly works. In 2021, Jiang et al. [4] published an article titled "A comprehensive review on the synthesis and applications of ion exchange membranes," which provides a comprehensive overview of the synthesis of IEMs, their structural characteristics, and their diverse applications, with a particular focus on advancing the adaptability of membrane materials. In this study, conventional methods such as solution casting and phase inversion, achieved membranes with high permselectivity, low electrical resistance, and improved ion exchange capacity, indicating the effectiveness of structural tuning and functional group modification in enhancing membrane performance, emphasized the importance of green synthesis approaches to address environmental concerns, and echoed the growing demand for next-generation IEMs in applications such as fuel cells, and redox flow batteries. This study serves as a pivotal reference point for research on IEMs. The interconnected citation pathways extending outward from the network reveal derivative studies that expand upon the original classifications, offering fresh insights into sustainable polymer development, hybrid membrane structures, ion-specific separations, as well as emerging applications such as redox-coupled electrodialysis and electrochemical energy recovery. Figure 1c presents the research conducted by Alkhadra et al. [5] in 2022 on the topic of Electrochemical methods for water purification, ion separations, and energy conversion, which has emerged as one of the most highly cited papers in recent years. This comprehensive review summarizes electrochemical strategies for water purification, ion separation, and energy conversion, emphasizing the primary advantages of electrochemical systems, including compact device design, high chemical selectivity, and minimal generation of secondary waste. Notably, this study advocates for the direct removal of contaminants from water rather than extracting water from contaminants. Additionally, it highlights advanced techniques such as shock electrodialysis and Faradaic deionization, establishing electrochemical membrane systems as essential tools for sustainable water and energy technologies in the future. The node located in the bottom-right corner of Figure 1c represents the latest research on IEMs published by Zhang et al. [6] in 2025. This study developed porous ion-exchange membranes by optimizing the ratio of sulfonated polyethersulfone, membrane porosity, and the density of active sites, thereby enhancing the selective transport of dye molecules. The results demonstrated outstanding water-dye separation performance, achieving a removal efficiency of up to 97.1%. Figure 1d depicts a time-resolved citation network, with the central green node representing a pivotal review [4]. The outward-extending green links indicate direct citation relationships with several influential works published between 2017 and 2021, focusing on topics such as enhancing membrane selectivity, diversifying applications, and integrating electrochemical processes. The dense clustering of blue nodes illustrates the concentrated activity in derivative studies, while the vertical arrangement of nodes reflects the chronological progression of scholarly contributions.

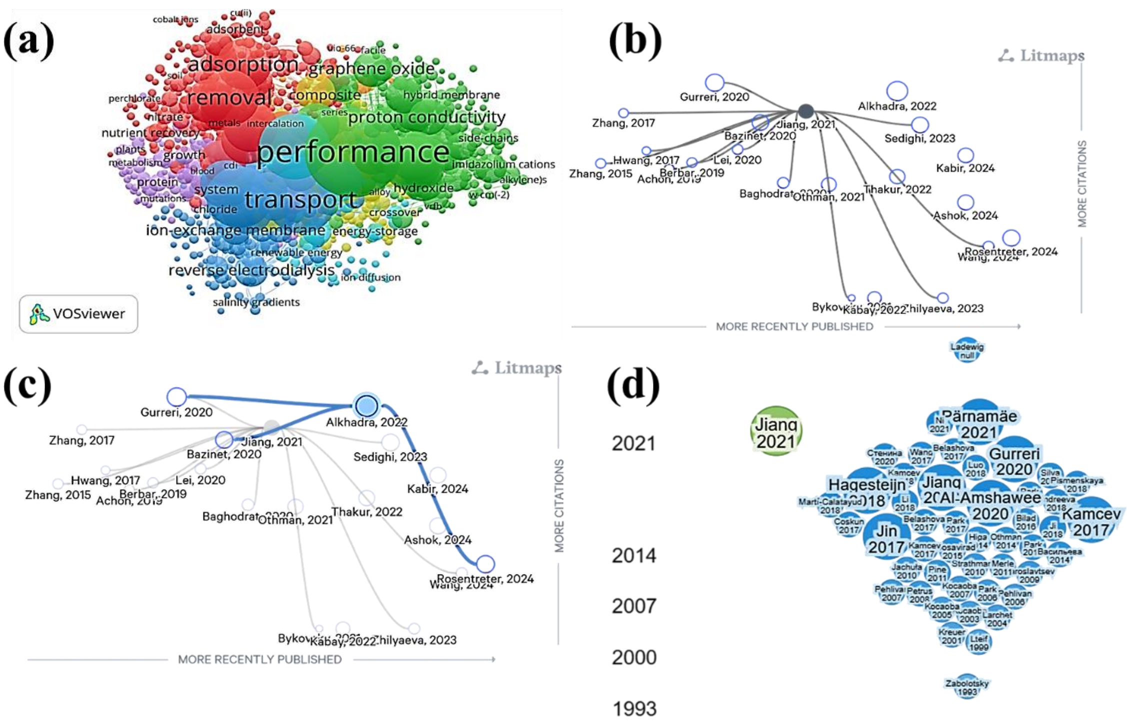

Figure 1. A bibliometric and citation-based analysis of research on ion-exchange membranes (IEMs). (**a**) A keyword co-occurrence map highlighting the primary thematic clusters. (**b**,**c**) Citation networks outlining the trajectory of core concepts related to IEMs. (**d**) Time-resolved citation clusters arranged chronologically.

1.2. IEMs Materials and Fabrication

As the research focus and interdisciplinary applications of IEMs expand, the materials have undergone significant evolution in chemistry and fabrication processes. Early-generation membranes are largely based on perfluorosulfonic acid (PFSA) structures, such as Nafion, valued for their high proton conductivity and electrochemical stability [7]. However, these materials are limited by their high cost and limited performance under elevated temperatures or alkaline environments. Consequently, the development of alternative materials to overcome these limitations has emerged as a critical challenge in advancing IEM technology. Recently, materials such as sulfonated polyetheretherketone (SPEEK), sulfonated aromatic polymers, sulfonated polyphenylene oxide biphenyl (sPPB), and proton-conductive multi-block copolymers have attracted significant attention due to their outstanding mechanical properties, chemical resistance, and tunable ion transport characteristics [8–10]. Notably, SPEEK membranes demonstrate remarkable proton conductivity and dimensional stability in PEMFCs, particularly under high-temperature and low-humidity conditions [11]. By fine-tuning their degree of sulfonation (DS), SPEEK serves as an effective, cost-efficient replacement for traditional, expensive PFSA membranes, while retaining sufficient electrochemical performance and chemical stability [12]. According to comparative membrane performance data (Table 1), PFSA membranes such as Nafion offer high proton conductivity (0.1–0.2 S/cm) and excellent chemical stability in both acidic and alkaline media, but suffer from moderate mechanical strength and thermal limits (≤363 K), with extremely high production costs [4,11]. In contrast, SPEEK provides adjustable conductivity (0.01–0.1 S/cm) and high thermal tolerance (up to 393 K), supported by a rigid backbone that enhances mechanical strength [10]. Other sulfonated polymers can be tailored for specific ion selectivity (e.g., Li^+/Mg^{2+}), and exhibit high thermal stability (up to 423 K), although their long-term stability remains environment-dependent [8,13].

In addition, recent advances in bioinspired membrane design have demonstrated how mimicking biological ion channels, such as those found in cell membranes, can significantly enhance ion selectivity, water permeability, and energy efficiency [14]. These membranes are typically engineered with nanopores or nanochannels that replicate the structural and electrostatic characteristics of natural transport proteins, enabling precise control over ion transport at the molecular level. For instance, a recent study developed a nanofluidic membrane that emulates charge-selective transport, achieving both high monovalent/divalent ion separation performance and reduced energy consumption [15]. This approach not only overcomes key limitations of conventional polymer membranes but also aligns with the broader movement toward sustainable and high-efficiency separation technologies. Bioinspired design thus offers a promising pathway for the development of next-generation IEMs that are more selective, durable, and compatible with low-energy desalination and resource recovery systems [15].

Table 1. Comparison of properties for ion exchange applications [4,8,10,11,13].

Property	Nafion (PFSA)	SPEEK	Other Sulfonated Polymers
Proton Conductivity	High (0.1–0.2 S/cm, high humidity)	Moderate (0.01–0.1 S/cm, tunable by DS)	Moderate-high (0.05–0.15 S/cm, structure-dependent)
Ion Selectivity	Low-moderate (monovalent ions)	Moderate-high (adjustable via DS)	High (tailorable for specific ions, e.g., Li^+/Mg^{2+})
Chemical Stability	Excellent (stable in strong acid/alkali)	Good (acid-stable, degrades in alkali)	Moderate-good (depends on chemistry)
Mechanical Strength	Moderate (often requires reinforcement)	High (rigid backbone)	High (aromatic backbone enhances strength)
Thermal Stability	Moderate (≤ 363 K)	High (up to 393 K)	High (up to 423 K, crosslinking-dependent)
Cost	Very high (perfluorinated synthesis)	Low-moderate (non-fluorinated)	Moderate (scalable but process-sensitive)
Lifetime	Long (5–10 years, fuel cell-validated)	Moderate (3–5 years, DS optimization needed)	Moderate (3–7 years, environment-dependent)
Primary Applications	PEM fuel cells, electrolyzes	MCDI, electrodialysis, high-T PEMFCs	Ion separation, Li recovery, acid/alkali treatment

1.3. Ion Transport Mechanisms and Developing Strategies for IEMs

IEMs have been widely and maturely employed in seawater desalination, wastewater treatment, and food-grade separations. However, limited research outcomes are available in lithium recovery, acid-base separation, and selective electrodialysis. The primary challenge lies in the need to further enhance the ion selectivity, mechanical stability, and chemical compatibility of IEMs in these applications [16–20]. Recent research findings indicate that the integration of nanoscale architectures, topological layer-by-layer assembly, and surface functionalization plays a crucial role in enhancing IEMs' selectivity and fouling resistance [21–23]. Multi-topological and hierarchical membrane structures enhance the interface interactions between membranes and the electrolyte environment by precisely regulating ion-specific transport pathways [24,25]. Moreover, as manufacturing complexity and cost remain critical barriers to the commercial application of IEMs, achieving a balance between functionality and economic feasibility continues to be a significant challenge for materials scientists and engineers [26]. In addition to structural improvements, understanding the fundamental mechanisms of ion transport is crucial for rational membrane design. Ion movement within IEMs is primarily governed by the Donnan exclusion principle, where fixed charged groups embedded in the polymer matrix repel co-ions and facilitate counter-ion conduction [27]. The efficiency of this process is influenced by charge density, hydration enthalpy, and polymer segment mobility. Interestingly, optimizing the spatial distribution and chemical nature of fixed charge groups can significantly enhance counter-ion selectivity while suppressing undesired co-ion leakage [28]. In addition, polymer microstructure such as free volume, crosslinking density, and backbone rigidity plays a critical role in determining ion diffusion behavior and electrostatic interactions within the membrane phase [29].

Developing strategies to streamline synthesis processes, enhance reproducibility, and integrate membrane technologies into broader energy-water frameworks may provide effective solutions. Notably, integrating IEMs into CDI systems offers promising opportunities to improve ion removal efficiency, reduce energy consumption, and expand the functional versatility of membrane-based water treatment systems [27]. Furthermore, the application of artificial intelligence (AI) in membrane material discovery and structural optimization is emerging as a transformative approach to accelerate the development of high-performance IEMs. AI-driven strategies leverage machine learning algorithms to predict material properties, identify optimal polymer compositions, and simulate membrane behaviors under various operating conditions. These tools enable researchers to drastically reduce experimental workload by narrowing down candidate materials through data-informed models and high-throughput screening techniques. The use of AI frameworks in membrane design workflows has enabled the integration of molecular descriptors, physicochemical databases, and performance benchmarks to identify promising membrane formulations with enhanced ion conductivity and mechanical stability [28]. The incorporation of AI not only expedites the material discovery process but also facilitates the development of tailor-made membranes for specific applications such as lithium recovery, nutrient separation, and electrochemical desalination. As such, AI serves as a critical enabler for next-generation IEM design, supporting the convergence of data science and materials engineering to meet emerging water treatment demands [28].

2. Membrane Capacitive Deionization

Capacitive deionization (CDI) is a technology that applies a low voltage of less than 1.2 V across porous electrodes [29]. Owing to its low energy consumption, minimal chemical usage, and strong regeneration capabilities, it has emerged as a promising electrochemical method for water treatment [30]. Co-ion repulsion, limited ion selectivity, and low charge efficiency are notable drawbacks of conventional CDI systems. Particularly in high-salinity or complex water matrices, these issues become more pronounced [31]. To address the limitations of conventional CDI systems, the integration of IEMs has emerged as a promising strategy [32]. The membrane capacitive deionization (MCDI) is a system in which cation exchange membranes (CEMs) and anion exchange membranes (AEMs) are strategically placed near the electrodes. This configuration allows counter-ions to pass through while effectively blocking co-ions [31,33]. This configuration significantly enhances charge efficiency, reduces ion back-diffusion, and improves ion selectivity [34]. Recent research has focused on tailoring the microstructure and surface properties of IEMs, including porosity, functional group density, and hydrophilicity, to enhance ion transport kinetics and overall electrochemical performance [35]. This advancement has enabled MCDI to more efficiently treat high-salinity water, recover lithium, and selectively remove contaminants [36–39].

Figure 2 provides an overview of research advancements in MCDI over the past decade. Notably, since 2017, the number of published articles has increased substantially and has remained stable at approximately 50 to 55 publications per year. These records were retrieved from the Web of Science Core Collection using the keywords "capacitive deionization" and "ion exchange membrane," covering the period from 2010 to 2024. This growth is largely attributed to the substantial potential for ion-selective transport in MCDI systems. By positioning CEM and AEM layers between the feed solution and electrodes, MCDI achieves ion-selective mobility. This structural arrangement facilitates the formation of a more stable electric double layer while minimizing parasitic energy losses, thereby enhancing overall system performance. The lower section of Figure 2 illustrates the evolution of the MCDI module architecture. Early designs were based on a traditional layered configuration, consisting of current collectors, porous carbon electrodes, IEMs, and spacers, forming a foundational platform for ion removal through electrosorption. This architecture established a solid basis for subsequent technological advancements and broader applications.

Recent advances in materials engineering have led to more sophisticated configurations that incorporate quaternized polymer-blend AEMs and high-surface-area activated carbon electrodes, contributing to enhanced ion selectivity, mechanical durability, and operational efficiency [40,41]. Concurrently, increasing attention has been given to the optimization of IEM microstructural properties such as porosity, water uptake, ion exchange capacity, and surface charge density, which govern deionization kinetics and system capacitance [27,31]. Building on these material and structural innovations, recent studies have further explored hybrid ion storage mechanisms, such as ion capacitive potential and pseudocapacitive behavior, to improve ion-specific removal rates and reduce energy consumption [30]. Novel membrane materials, including nanoporous ceramics, ionomer-based composites, and surface-functionalized polymers, have demonstrated promising results in improving electrosorption performance and operational stability [42,43]. Beyond technical improvements, the integration of IEMs has broadened the application scope of CDI systems. MCDI has proven effective not only for brackish water and ultrapure water production but also for lithium recovery, nutrient removal, and selective contaminant separation [31,38,39]. Its modular architecture, low energy requirements, and compatibility with renewable energy sources make MCDI a viable technology for decentralized and sustainable water treatment applications. In addition to material and structural innovations, recent research has increasingly focused on the integration of AI to further optimize the performance of MCDI systems. By leveraging machine learning algorithms, such as random forest and artificial neural networks, researchers have developed predictive models capable of estimating effluent ion concentrations with high accuracy [44]. These models enable real-time system adjustments, improving process control and overall operational stability. Through these applications, AI enhances not only ion selectivity and energy efficiency but also system adaptability in treating complex and dynamic water matrices. This data-driven approach represents a promising direction for the intelligent design and automation of next-generation MCDI technologies.

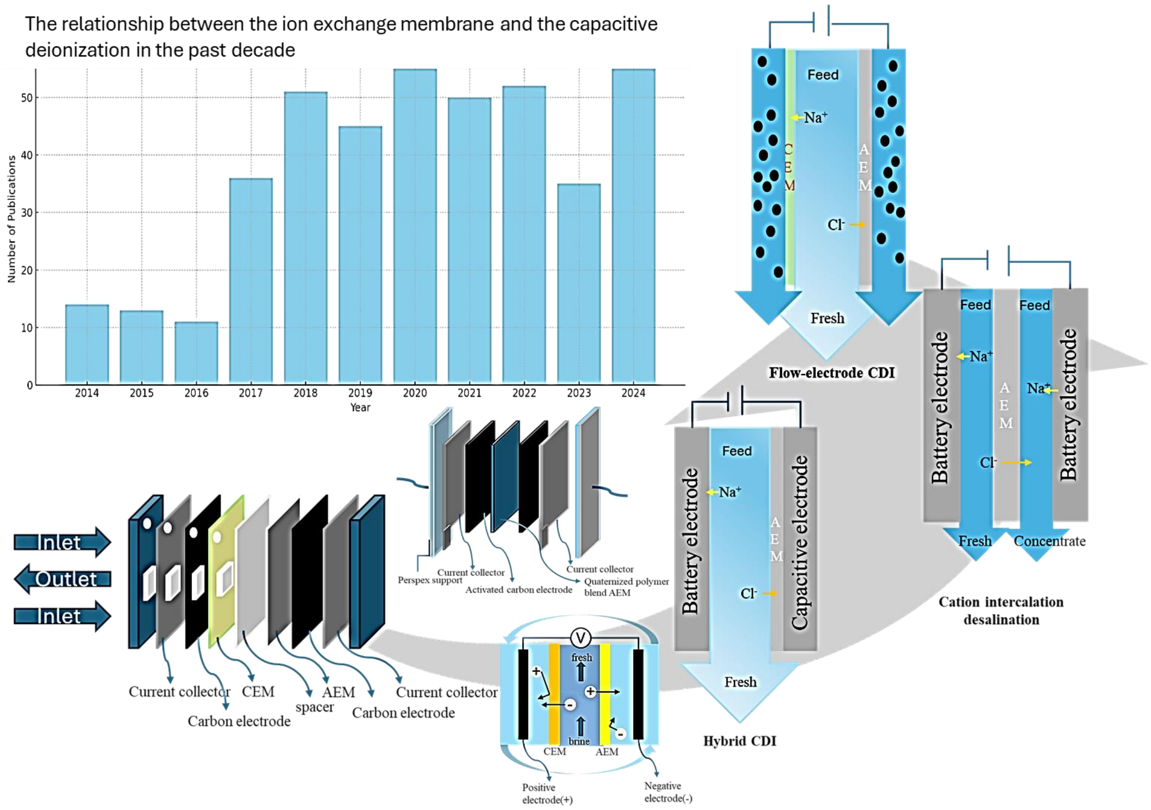

Figure 2. Research trends and system configurations of MCDI over the past decade.

3. Commercialization

Wastewater treatment methods include physical adsorption [45], electrochemistry [46] advanced oxidation [47,48], and biological treatment [49]. The intensifying global demand for clean and reliable water resources has driven growing attention toward MCDI as a next-generation desalination technology. According to the United Nations, nearly half of the world's population faces severe water scarcity during at least part of the year, highlighting the urgency for scalable, energy-efficient water treatment solutions [50]. In response, national governments and international organizations have increased their support for advanced desalination research and infrastructure, with MCDI emerging as a promising candidate. The convergence of public-sector funding, regulatory initiatives, and private-sector innovation is accelerating the advancement and commercialization of MCDI systems [51]. As a result, MCDI is increasingly viewed as a critical enabler in the global effort to secure water sustainability, particularly in regions burdened by resource limitations and environmental stressors.

3.1. Europe

Europe has spearheaded approximately 60% of global MCDI pilot projects. Notably, the Netherlands-based Wettsus research center and Voltea collaboratively developed a flow-electrode CDI (FCDI) system, achieving a water recovery rate of up to 80%, which has been successfully applied in purifying agricultural irrigation water [52]. Additionally, Germany's Fraunhofer Institute, in partnership with FuMA-Tech (Bietigheim-Bissingen, Germany), utilized polyelectrolyte multilayer membranes (PEMs) to modify IEMs, significantly enhancing the selectivity of MCDI systems for monovalent and divalent ions, such as Na^+ and Ca^{2+} [52,53]. This technology has been employed in industrial cooling water recycling, effectively reducing chemical reagent usage by up to 80% [54].

3.2. United States

Since 2010, the U.S. Department of Energy (DOE) and the National Science Foundation (NSF) have been major supporters of research on CDI, with a particular focus on advancing low-cost carbon-based electrodes and functionalized IEMs [13,52]. These efforts aim to improve the system performance, energy efficiency, and cost-effectiveness of CDI in practical desalination applications. Evoqua Water Technologies has reportedly developed an MCDI system successfully applied to groundwater desalination in California. This achieves a salt adsorption capacity of approximately 18.5 mg/g, significantly higher than the typical value of 12 mg/g for conventional CDI systems [52]. Meanwhile, U.S.-based research teams are investigating SPEEK membranes, which exhibit a high ion exchange capacity (approximately 3.5 meq/g) and superior antifouling properties. These materials are being evaluated for their potential applications in greenhouse irrigation [13]. Furthermore, SPEEK's hydrophilicity and structural stability make it a promising candidate for prolonged electrochemical cycling, especially when combined with advanced porous electrodes [13]. MCDI has garnered significant attention in the United States for its high energy efficiency and modular design, making it a viable option for low-salinity water treatment [13,55]. However, the technology still faces several critical challenges, particularly in enhancing membrane durability and reducing system integration costs. However, the technology still faces several critical challenges, particularly in enhancing membrane durability and reducing system integration costs. In 2022, the Office of Naval Research and the U.S. Marine Corps highlighted that MCDI systems exhibit significant performance decline when applied to high-salinity waters. Such conditions are common in real-world applications and are not easily addressed through pilot-scale optimization. This situation raises practical concerns regarding energy efficiency and system scalability [56].

3.3. Japan

Japan has maintained a leading position in the production of IEMs, with companies such as Asahi Glass and ASTOM renowned for their Neosepta IEMs, celebrated for their exceptional chemical stability. These membranes are widely used in MCDI systems due to their superior durability and performance [13,57]. Furthermore, the Japanese government has set ambitious goals to integrate MCDI technology into 60% of industrial wastewater recovery projects by 2030 and reduce IEM production costs by 40% from current levels. Despite Japan's excellence in membrane manufacturing technologies, challenges persist in scaling up electrode production to meet industrial demands [55].

3.4. South Korea

In 2016, South Korea incorporated MCDI into its water technology innovation program, initially focusing on wastewater treatment in the electronics industry. Researchers have explored the potential of graphene oxide (GO)-based IEMs for MCDI applications. These membranes exhibit high water absorption capacity and ion exchange properties, significantly enhancing desalination performance. However, challenges remain in optimizing membrane thickness to balance mechanical stability and ion transport efficiency [58]. Leading South Korean companies, including Samsung (Suwon-si, Republic of Korea) and LG Chem (Seoul, Republic of Korea), are actively driving the commercialization of MCDI technology, aiming to process up to 8 million cubic meters of water annually by 2030 [59]. Despite these efforts, South Korea faces challenges in scaling up practical applications and strengthening its competitiveness in international markets [60].

Driven by global policy support, industrial investment, and successful pilot-scale implementations, MCDI technology is steadily transitioning from laboratory research to commercial applications. As illustrated in Figure 3, the evolution of MCDI has followed a multi-phase trajectory, beginning with advancements in ion exchange membrane manufacturing and electrode material development. Subsequent efforts have focused on integrating hybrid ion storage mechanisms, optimizing system performance, and reducing energy consumption. These technological milestones have significantly improved system stability and efficiency, paving the way for commercial deployment. However, to fully realize MCDI's market potential, further research must address challenges such as membrane fouling, ion selectivity, cost reduction, and system scalability. Recent techno-economic analyses estimate that the levelized cost of water for full-scale MCDI systems ranges from 0.6 to 1.2 USD/m^3, depending on feedwater salinity and energy input. Which consisted of 10 pairs of activated carbon electrodes with a total effective surface area of 8000 cm^2. This remains significantly higher than the 0.3–0.6 USD/m^3 typically reported for mature reverse osmosis systems operating under similar conditions. Additionally, limited membrane lifetimes and modular integration constraints further elevate capital and maintenance costs, highlighting scalability as a persistent barrier to commercial competitiveness [26]. With the intensifying global water crisis, MCDI is increasingly recognized as a viable and sustainable solution for low-salinity desalination, resource recovery, and decentralized water treatment applications.

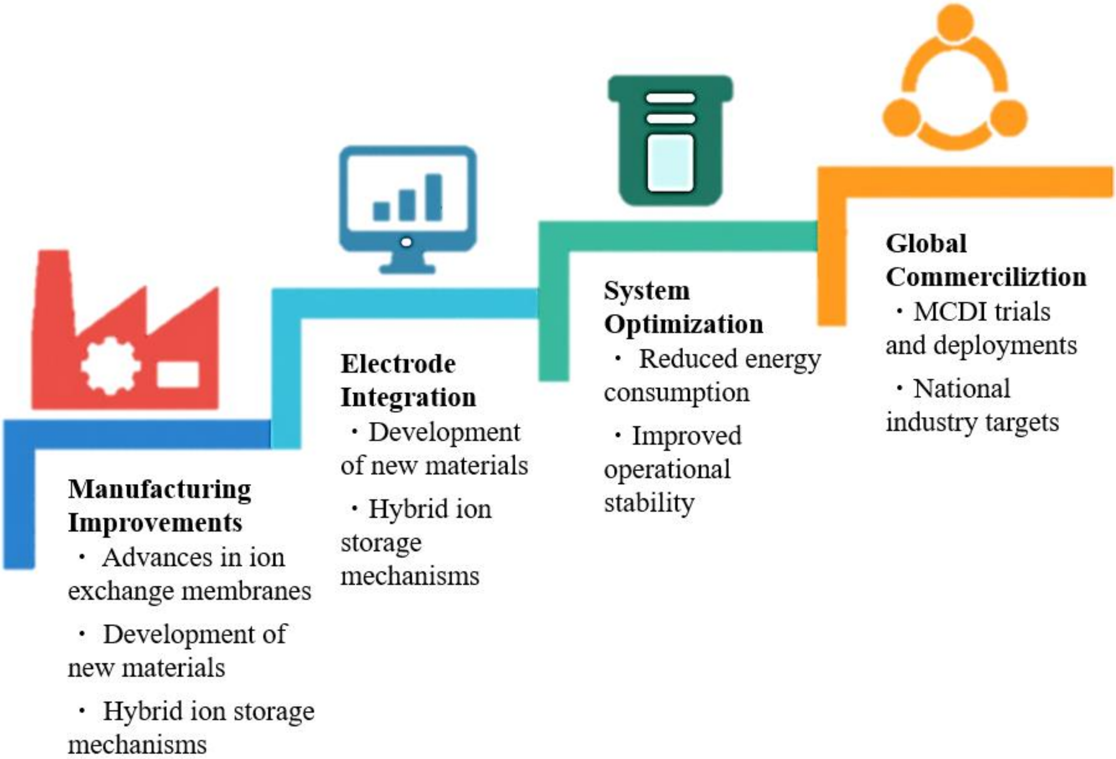

Figure 3. Technological evolution and commercialization pathway of MCDI.

4. Patent Analysis

This study primarily analyzes patents on the application of ion exchange membranes in capacitive deionization systems. The patent analysis was conducted using Innography, a patent analytics tool provided by Clarivate. Using the keywords 'Ion Exchange Membranes' and 'Capacitive Deionization,' approximately 500 active patents under protection have been identified, covering the period from 2002 to 2024. Notably, 78% of these patents were filed between 2015 and 2024, reflecting a significant increase in interest in applying ion exchange MCDI. Figure 4b,c present the distribution of these patents among various countries and institutions. The United States holds the largest share, comprising 32.70% of the total patents, followed by China (29.83%), South Korea (26.49%), EPO (5.97%), and India (5.01%). In terms of institutional distributions, the top five institutions ranked by the number of patents are Kraton Corporation (Houston, TX, USA) and Xylem Inc. (Washington, DC, USA) in the United States, Fujifilm Holding Corp. (Tokyo, Japan), Clariant AG (Muttenz, Switzerland), and Korea Institute of Energy Research (Daejeon, Republic of Korea). The number of patents held by these top five institutions accounts for about 43% of the total patents. This study conducted a detailed analysis of its active patents utilizing patent hotspots. The results reveal that these patents can be categorized into five primary technical areas including deionization, desalination, exchange membrane, ion exchange, and water treatment. These five topics are deemed critical technological factors for the potential commercialization of MCDI systems in the future.

The United States utility patent US11261109B2, owned by Deutsches Wollforschungsinstitut (Aachen, Germany), was filed on 15 January 2016, granted on 1 March 2022, and is set to expire on 10 January 2037. This patent addresses critical limitations of conventional CDI, including low electrode regeneration efficiency and challenges in achieving continuous operation. It introduces a groundbreaking flow electrode capacitive deionization (FCDI) technique with a single-module continuous desalination system, thereby revolutionizing the fields of seawater desalination and ion separation. The FCDI system employs flow electrodes composed of activated carbon, graphene, and carbon nanotubes (CNTs), enabling dynamic ion adsorption and desorption. The ion-exchange membranes (IEMs) utilized in this technology range from 0.01 to 1 mm in thickness, with options for both anion-exchange membranes (AEMs) and cation-exchange membranes (CEMs). These components work in concert to optimize ion transport and separation efficiency. Notably, the patent demonstrates remarkable performance metrics: when treating a 1 g/L sodium chloride (NaCl) solution, the system achieves a desalination rate of 70% and a maximum water recovery rate of 80%. These results underscore the FCDI system's superior efficiency compared to traditional CDI methods. US11261109B2 facilitates applications in multiple sectors, including seawater desalination, industrial wastewater treatment for ion separation, recovery of valuable ions from process streams, and removal of contaminants such as nitrate and ammonium from potable water sources. By overcoming the limitations of conventional CDI, this patent paves the way for more sustainable and efficient water treatment solutions.

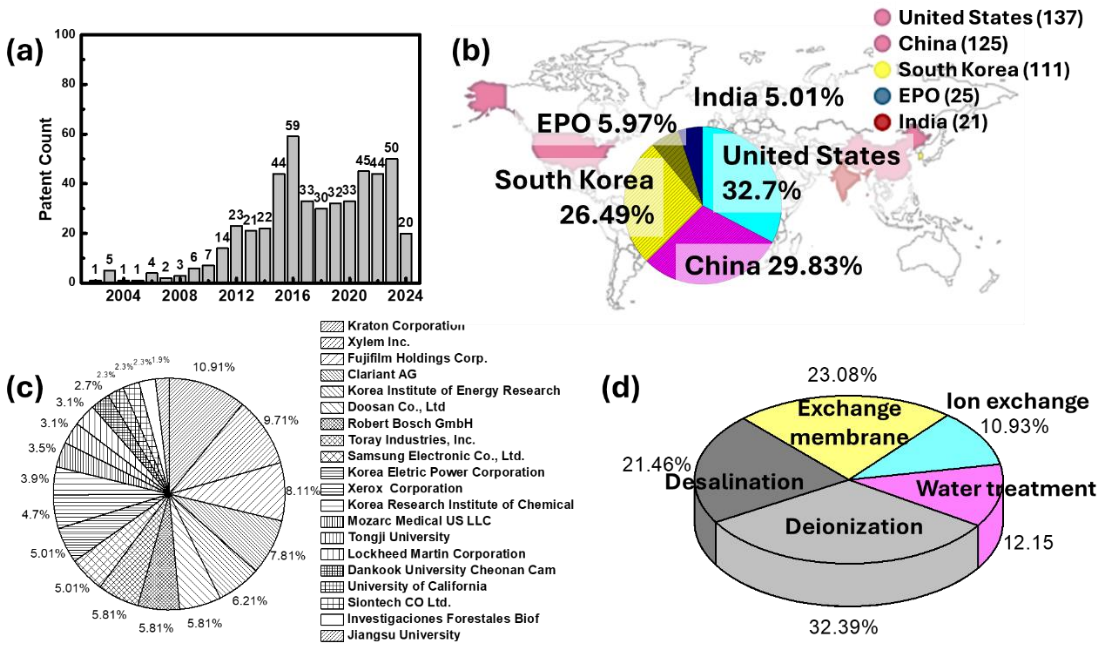

Figure 4. (**a**) Annual patent count from 2002 to 2024, (**b**) Global patent distribution and proportion, (**c**) Institutional distribution of patent ownership, (**d**) Distribution of patent topics.

Figure 5a presents the patent statistics in the United States, China, South Korea, and India from 2021 to 2024. Statistical results indicate that before 2023, the number of patents in various countries showed steady growth. Notably, in 2024, patent numbers across all countries experienced a significant decline, averaging a drop of more than 70%. This sharp decrease in patent filings may be related to the global focus on carbon reduction. Figure 5b presents the distribution of patent strength for MCDI between 2020 and 2024. Patent strength serves as a key metric for assessing the value and influence of patents, offering a thorough evaluation of their role in technological advancement, legal coverage, and market positioning. The assessment of patent strength typically incorporates factors like citation frequency, the breadth of the patent family, the number of claims, remaining patent lifespan, and the competitiveness of the relevant technical domain. Except for exchange membranes and water treatment, the patent strength of other topics has declined since 2023, likely due to the increasing focus on water resource issues. Around 2022, desalination-related patents demonstrated particularly strong patent strength. Meanwhile, the patent strength of ion exchange technologies has remained below 5 since 2021, possibly due to the maturation of CDI technology.

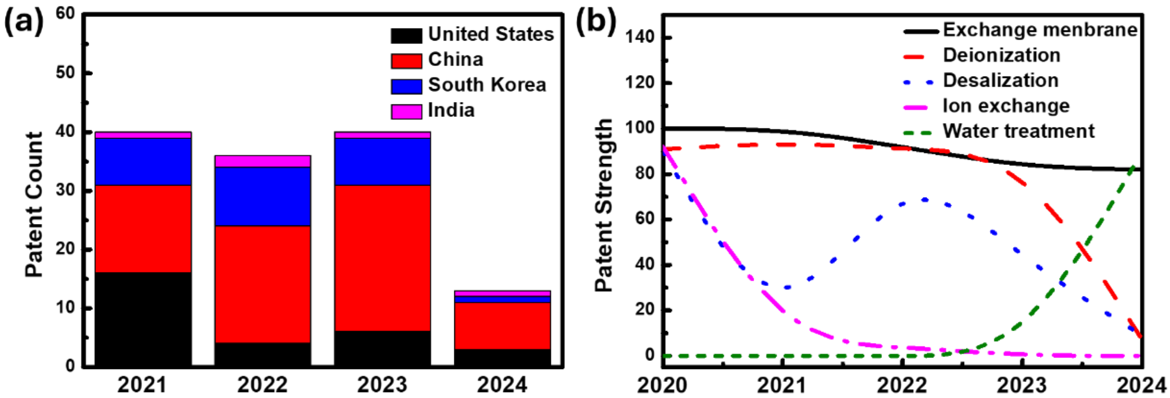

Figure 5. (**a**) Patent Statistics in the United States, China, South Korea, and India from 2021 to 2024, (**b**) Patent strength distribution of patent topics in the past five years.

Figure 6 illustrates the distribution of patents published, prioritized, and expired from 2001 to 2044. Statistical analysis indicates that the publication and priority year distributions of MCDI are quite similar. With respect to patent expiration, statistical data reveals that expired patents begin to emerge starting in 2025. Furthermore, projections indicate that approximately 51% of currently valid patents are expected to reach the end of their legal protection period between 2036 and 2042. The expiration of a patent marks the conclusion of its legally sanctioned exclusivity, whereby the patent holder's rights to restrict usage and commercialization cease to be enforceable. Typically, invention patents are granted a protection period of 20 years from the date of issuance, during which the patent holder retains the sole authority to regulate access, licensing, and implementation of the patented technology. Throughout this duration, third parties must obtain formal authorization to employ the innovation in any capacity. Upon expiration, the patented technology transitions into the public domain, permitting unrestricted utilization, modification, and further development by any entity, thereby fostering open innovation and technological dissemination. In order to conduct a more comprehensive analysis of the distribution of expired patents across various countries over the next four years, Figure 6b illustrates the distribution of expired patents in the United States, China, South Korea, and India from 2025 to 2029. Given the substantial patent holdings of the United States, it is expected that expiration will exhibit the highest volume of expired patents. In contrast, the number of expiration-related patents in China and South Korea is projected to peak around 2028, reflecting trends in technological development and intellectual property cycles within these jurisdictions.

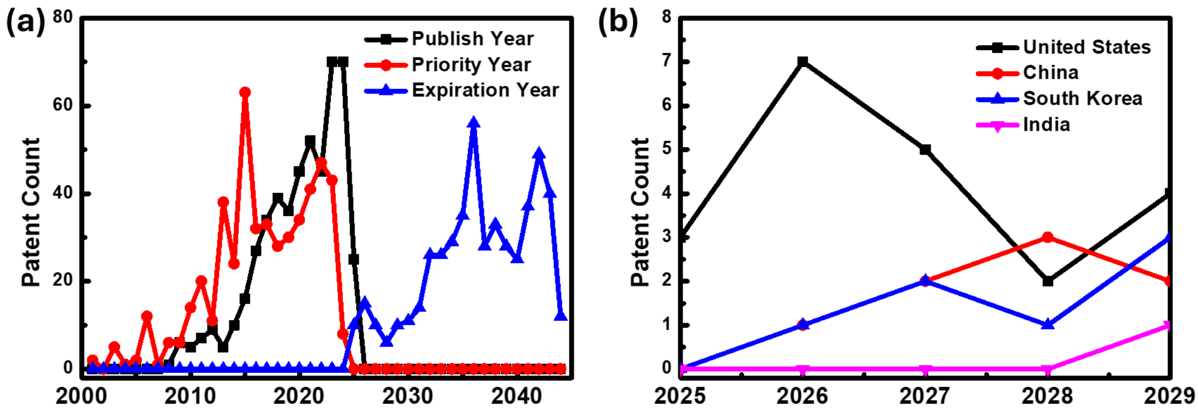

Figure 6. (**a**) Distribution of Patents Published, Prioritized, and Expired from 2001 to 2044, (**b**) Distribution of Expired Patents in the United States, China, South Korea, and India from 2025 to 2029.

5. Conclusions

The integration of IEMs has significantly improved the performance of CDI systems, particularly in applications such as brackish water treatment, ultrapure water production, and resource recovery. By advancing membrane materials, system architectures, and functional mechanisms, MCDI has emerged as a scalable and energy-efficient water treatment technology. Bibliometric and patent analyses over the past five years demonstrate a substantial global increase in research and patent activity related to MCDI. Notably, governmental funding from regions such as Europe, the United States, Japan, and South Korea, alongside industry-driven innovations, has accelerated the commercialization of this technology. Although challenges remain, including membrane fouling, limited-service life, and high production costs, recent advances in polymer chemistry, nanostructured membrane design, and hybrid charge storage have shown strong potential to address these issues. To further bridge the gap between laboratory advances and practical deployment, future research should prioritize integrative strategies. The application of AI can improve real-time system optimization, predictive maintenance, and adaptive control. At the same time, incorporating circular economy principles such as component reuse, energy recovery, and life-cycle-based system design can enhance both environmental and economic sustainability. Building upon these integrative strategies, continued collaboration between public institutions and private industry will be essential to drive real-world adoption of MCDI technologies. By fostering interdisciplinary research and strengthening international partnerships, the development and deployment of MCDI can be accelerated, enabling its broader application in decentralized water treatment and its long-term contribution to global water sustainability and environmental innovation.

Author Contributions: P.-A.C.: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing—review & editing. K.-T.L.: Conceptualization, Formal analysis, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing—review & editing. J.-L.C.: Investigation, Methodology, Validation, Formal analysis, Writing—original draft. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: This manuscript uses the Web of Science database as the retrieval tool for journal literature, with the search time range set from 2010 to 2024. The search formula is “capacitive deionization” AND “ion exchange membrane”. The patent analysis employs Clarivate’s Innography tool, a paid platform. Using the keywords “ion exchange membranes” and “capacitive deionization”, active patents in the status of “Active” between 2002 and 2024 were retrieved, with approximately 500 relevant patents ultimately included. Due to the commercial license agreement governing Innography data, this study only provides aggregated statistical results.

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