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Review

# Carbon-based electrode materials for sustainable capacitive deionization: Energy efficiency, performance metrics, and scalability challenges

Robel Ahmed[a], S.M Saklain Mostak Saumik[b], Md Rasel Ahmed[c], Md Yeanur Rahman[b], Md Abdullah Al Shahil[b], Monjur Mourshed[c,*]

[a] Institute of Energy & Environmental Studies, Rajshahi University of Engineering & Technology, Rajshahi, 6204, Bangladesh
[b] Department of Mechanical Engineering, Hajee Mohammad Danesh Science & Technology University, Dinajpur, 5200, Bangladesh
[c] Department of Mechanical Engineering, Rajshahi University of Engineering & Technology (RUET), Rajshahi, 6204, Bangladesh

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ABSTRACT

Growing freshwater scarcity, rapid industrialization, population growth, and climate change have intensified the demand for sustainable and energy-efficient desalination technologies. Among emerging electrochemical water-treatment approaches, capacitive deionization (CDI) and flow-electrode capacitive deionization (FCDI) have attracted significant attention because of their low operating voltage, modular design, operational flexibility, and potential for resource recovery. Despite substantial progress, a comprehensive understanding of how electrode materials, charge-storage mechanisms, system configurations, and operational parameters collectively influence desalination performance and scalability remains fragmented across the literature. This review critically examines the development of CDI and FCDI technologies, with particular emphasis on carbon-based electrode materials and their role in electrochemical desalination. The fundamental mechanisms governing ion removal, including electric double-layer formation, co-ion effects, and Faradaic charge storage, are discussed alongside the evolution of major CDI architectures, such as membrane CDI, inverted CDI, hybrid CDI, desalination batteries, and FCDI. Recent advances in carbon-based electrodes, flow-electrode materials, membrane integration, reactor design, and process optimization are systematically evaluated in relation to desalination efficiency, ion selectivity, energy consumption, and operational stability. Emerging applications in wastewater treatment, selective ion separation, nutrient recovery, and resource recovery are also highlighted. Current challenges associated with electrode degradation, membrane fouling, flow-electrode conductivity, process standardization, scale-up, and commercialization are critically discussed. Finally, future research directions involving advanced material design, intelligent process optimization, renewable-energy integration, and hybrid treatment systems are identified to support the practical deployment of CDI and FCDI technologies for sustainable water treatment and resource management.

## 1. Introduction

Climate change, resource depletion, population increase, and environmental degradation pose unprecedented challenges to the supply of water and energy, which are essential foundations of contemporary society. According to forecasts, the world's water delivery system would need to serve an extra 2 to 2.5 billion people by 2050 due to the sharp increase in water shortages (World Water Assessment Programme, 2019). According to the International Desalination Association, the world's desalination capacity reached about 3.7 million cubic meters per day in 2016, with 41% going toward brackish and river water desalination and 59% going toward saltwater treatment (International Desalination Association, 2017). However, energy consumption, which accounts for 35% of all desalination plant expenses and 65% of operational costs, represents a significant constraint. Significant environmental problems are raised by the primary dependence on non-renewable energy sources, which produce large greenhouse gas emissions (Elimelech and Phillip, 2011).

Sea level rise, drought intensification, ecological disturbance, and increased saline intrusion into upstream rivers and coastal groundwater reserves are some of the ways that climate change exacerbates water shortage (Ferguson and Gleeson, 2012; Werner et al., 2013). Saline

* Corresponding author.
*E-mail address:* monjurmourshed@me.ruet.ac.bd (M. Mourshed).

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intrusion into freshwater aquifers is accelerated by the building of hydroelectric dams and excessive groundwater extraction that exceeds natural replenishment rates (Gleeson et al., 2012; Taylor et al., 2013). The development of energy-efficient, economical desalination systems with high water recovery capacities that can treat a variety of water sources, from brackish groundwater to extremely saline saltwater, is required due to these combined demands. Reverse osmosis (RO), multistage flash distillation (MSF), and multi-effect desalination (MED) are examples of conventional desalination systems that have significant limitations in terms of energy consumption, capital expenditures, operational complexity, and environmental impact (Mezher et al., 2011; Shatat et al., 2013). These systems create problems with concentrated brine disposal and need large energy inputs. Alternative methods that selectively remove ions instead of collecting water molecules provide better energy efficiency and economic feasibility for brackish water applications with modest salt concentrations.

With significant benefits such as low energy consumption, no secondary pollution, economic effectiveness, and easy electrode regeneration, CDI has become a promising electrochemical water treatment technique (Porada et al., 2013; Suss et al., 2015). Although the idea of CDI was first presented in the 1960s, Farmer et al. officially coined the term in 1996 (Farmer et al., 1996). Research on CDI has grown exponentially in recent decades because of advancements in new electrode materials, creative cell designs, and a better comprehension of ion electrosorption principles (Oladunni et al., 2018; Tang et al., 2019). In order to cause electrostatic adsorption of charged species inside electrical double layers created at the electrode solution interface, CDI applies tiny electrical potentials (usually less than 1.5 V) between porous carbon electrodes. Short-circuiting or polarity reversal releases trapped ions at electrode saturation, enabling electrode regeneration and producing concentrated brine streams.

Despite its advantages, traditional CDI has significant drawbacks, including faradaic reactions that jeopardize long-term electrode durability, electrode saturation that limits continuous operation, and co-ion repulsion that decreases charge efficiency (Biesheuvel et al., 2011; Zhao et al., 2012). By incorporating ion exchange membranes (IEMs) in front of electrodes to stop co-ion ejection and inhibit unwanted faradaic reactions, MCDI greatly improves desalination performance and charge efficiency (Li et al., 2008; Kim and Choi, 2010). Nevertheless, successive adsorption and desorption operations are still required for static electrode designs in MCDI, which restricts throughput and necessitates periodic system stoppage for regeneration. A revolutionary development that gets over the basic drawbacks of static electrode CDI systems is FCDI, which was first presented by Jeon et al., in 2013, allowing for continuous desalination operation without system stoppage for regeneration by substituting constantly flowing suspensions of conductive carbon particles in aqueous or organic electrolytes for fixed electrodes (Jeon et al., 2013). The ground-breaking FCDI demonstration established FCDI as a viable method for treating fluids unsuitable for traditional CDI by achieving 95% salt removal efficiency from high salinity brine (32.1 g/L NaCl) (Jeon et al., 2013). Because desalinated and brine streams are produced in different chambers, FCDI achieves very high flow efficiencies that are close to 100% by continually replacing electrode chambers with fresh or regenerated particle suspensions. FCDI is especially appealing for remote off-grid applications, as this architecture enables integration with renewable energy sources such as solar, wind, tidal, and geothermal systems (Hatzell et al., 2015; Doornbusch et al., 2016). Because FCDI uses flowable electrodes made of active materials, conductive additives, and electrolyte solutions, its working mechanism blends capacitive adsorption principles with electrodialysis effects. Due to their improved ion-capture capacity and adjustable ion selectivity, charge-transfer materials such as sodium manganese oxide, sodium iron phosphate, sodium vanadium phosphate, molybdenum disulphide, and bismuth oxychloride have attracted increasing attention as components of flow electrodes (Halder et al., 2025). By enabling faradaic charge storage processes in addition to conventional electrostatic adsorption, these pseudocapacitive materials significantly enhance desalination performance.

Since its launch, FCDI technology has rapidly evolved in a number of research areas, including advanced material development, environmental applications, and theoretical investigations. The goal of theoretical research has been to clarify intricate charge transport mechanisms that include ion migration and electron transfer in flowing electrode suspensions (Liang et al., 2017; Mourshed et al., 2023). System configuration design, operating mode optimization, energy and water recovery rate assessment, and electrode material innovation have all been thoroughly investigated in experimental research (Zhang et al., 2021; Shajid et al., 2025). Beyond desalination, FCDI is now used in resource recovery, heavy metal removal, water softening, nutrient recovery (phosphate and nitrate), organic pollutant treatment, and water disinfection (Yang et al., 2021; Shajid et al., 2025). The CDI electrode compositions have the ability of higher capacitance, conductivity, and stability (Gao et al., 2024). Though scientific and technical challenges are available for developing (Gao et al., 2023). But the boosting with CDI or FCDI found in sodium adsorption (Gao et al., 2024). The nanomaterial application with the fundamental utilized as electrospinning in industrial sectors (Yang et al., 2023). Prussian Blue (PB) and its analogues (PBAs) have become an economic, effective, open arrangement structure and a modifiable synthesis (Gao et al., 2024). The authors introduce the effect of combining electrospinning and carbonizing with nanoparticles for better desalination (Gao et al., 2024). The experimental and mathematical investigation has been introduced for the modified model and improving properties of desalination (Miao et al., 2024). Comparative experiments investigation for the illustration of the synthesis found for better microstructure study (Liu et al., 2026). The optimal results for SPFA-70 ionomer demonstrate a different pattern of characteristics, finding $Na^+$ conductivity of 43.1 $mS{\cdot}cm^{-1}$ under fully hydrated conditions (Jiang et al., 2026).

This comprehensive review examines recent advances in CDI and FCDI technologies, focusing on their operating principles, material developments, system configurations, and emerging applications. Unlike many previous reviews that primarily emphasize either electrode-material development, specific CDI configurations, or desalination performance independently, the present work provides an integrated assessment of the fundamental mechanisms, carbon-based electrode materials, membrane technologies, reactor architectures, performance metrics, energy considerations, and scalability challenges associated with both CDI and FCDI systems. Key factors governing desalination performance, including cell design, electrode materials (activated carbon, carbon nanotubes, graphene derivatives, and metal oxides), ion-exchange membranes, flow-channel geometry, and regeneration strategies, are systematically evaluated. A comparative analysis of CDI and FCDI is presented to highlight their respective advantages, limitations, and suitable application domains. In addition, recent developments in hybrid capacitive–Faradaic systems, advanced electrode engineering, selective ion separation, resource recovery, and renewable-energy integration are critically discussed. By consolidating these diverse aspects within a single framework, this review not only summarizes the current state of the art but also identifies critical research gaps, technological barriers, and future development pathways necessary for the large-scale commercialization of CDI and FCDI technologies to address global water scarcity challenges.

## 2. State of the art: capacitive and flow-electrode capacitive deionization technologies

### 2.1. Capacitive deionization technologies

#### 2.1.1. Fundamental principles and structure of CDI

CDI is an electrochemical method for removing salts from water by applying a small electrical potential across porous electrodes. Over the past decade, CDI has advanced well beyond the traditional configuration

based on two carbon electrodes. Modern CDI architectures aim to achieve higher salt adsorption capacity, improved charge efficiency, enhanced ion selectivity, and more practical operating modes (Mourshed et al., 2021). These developments include membrane-assisted CDI systems that regulate ion transport, surface-modified electrodes that tailor adsorption behavior, and hybrid or battery-like CDI concepts that incorporate Faradaic or intercalation-based ion storage to overcome the intrinsic limitations of purely electric double-layer (EDL) mechanisms (Mourshed et al., 2024; Shajid et al., 2025). Fig. 1 provides an overview of the main CDI-related architectures, ranging from conventional and membrane or flow-through CDI designs to flow-electrode and hybrid or battery-like systems, illustrating the technological evolution toward improved performance and more continuous operation (Mourshed et al., 2024; Robin et al., 2025).

In parallel, FCDI has been developed to address a key limitation of conventional fixed-electrode CDI, namely the need for intermittent operation due to electrode saturation and regeneration. FCDI employs flowable carbon slurry electrodes that can be continuously circulated through the cell and regenerated externally, enabling quasi-continuous or fully continuous desalination. This approach offers the potential for higher salt removal rates and improved operational flexibility (Yang et al., 2021). Current research in FCDI focuses on optimizing the composition and rheological properties of the slurry electrodes, reducing pumping and electrical losses, enhancing ionic and electronic transport within the flow electrodes, and improving cell and module designs, with or without ion-exchange membranes, to ensure scalable and stable operation (Mourshed et al., 2022, Mourshed et al., 2023). Taken together, the transition from CDI to FCDI reflects a broader shift in the field from proof-of-concept demonstrations toward practically viable systems, including opportunities for energy recovery during discharge and for harvesting salinity-gradient energy using capacitive technologies (Yang et al., 2021).

CDI is an electrochemical water treatment process in which dissolved ions are removed by applying a voltage across porous electrodes. It is widely studied for energy-efficient brackish water desalination and for the selective removal or recovery of salts, nutrients, and metal ions. In conventional fixed-electrode CDI, the cell comprises two oppositely polarized porous electrodes typically made of carbon, each connected to a current collector, and separated by a spacer channel through which feedwater flows (Akbarzadeh et al., 2025). This causes cations in the feed to migrate toward the negatively charged electrode and anions toward the positively charged electrode, as depicted in Fig. 2. These ions

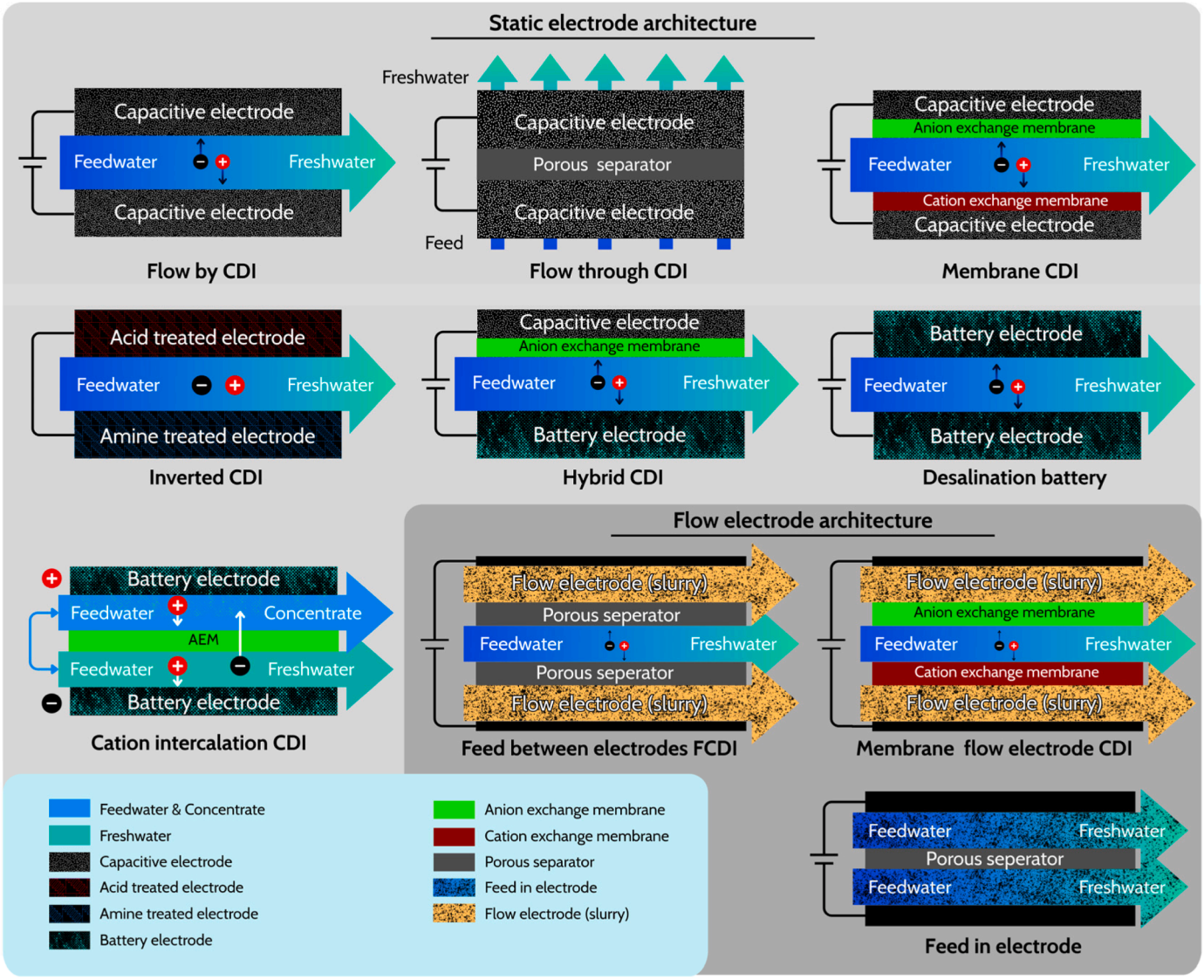



**Fig. 1.** Overview of major CDI-based architectures, illustrating the evolution from conventional designs to advanced configurations (Suss et al., 2015; Tang et al., 2019).

are stored primarily by electrosorption within the electrodes: ions enter the porous network and are electrostatically immobilized in electrical double layers (EDLs) formed at internal pore surfaces. As feedwater passes through the cell during the charging step, its ionic concentration decreases, producing a desalinated effluent (Akbarzadeh et al., 2025). Fig. 2 shows the schematic of CDI operation. During charging (adsorption), an applied voltage attracts cations to the cathode and anions to the anode, forming EDLs and removing salt from the flowing feed. During discharging (desorption), the cell is short-circuited, the voltage is removed, or polarity is reversed, releasing ions into a concentrate/brine stream and regenerating the electrodes for the next cycle (Akbarzadeh et al., 2025). During charging, ions are removed from the water, so the outlet becomes low-salinity (fresh) water. When the electrodes become full, the voltage is removed or reversed to release the stored ions. This produces a concentrated brine. Thus, CDI works in cycles, giving fresh water during charging and brine during discharge, either in batch or continuous flow mode.

While CDI is often described as a purely capacitive (non-Faradaic) EDL-based process, in practice Faradaic side reactions can occur concurrently, especially at higher cell voltages, in the presence of dissolved oxygen, or due to electrode surface chemistry (Mourshed et al., 2022). These reactions (e.g., oxygen reduction at the cathode, carbon oxidation or other anodic processes) consume charge without contributing to salt removal, reduce charge efficiency, and may degrade electrode performance over time, an important practical consideration emphasized in recent reviews of fixed-electrode CDI (Wu et al., 2022). Consequently, CDI operation commonly balances salt removal performance against the need to suppress parasitic reactions through conservative voltage windows, appropriate electrode materials, and careful cell design. CDI architectures can also differ in hydraulic configuration. In flow-by CDI, feedwater passes through the spacer channel between the electrodes without penetrating deeply into the electrode matrix, yielding relatively low pressure drop and straightforward implementation (Halder et al., 2025). In flow-through CDI, feedwater is forced through permeable porous electrodes before exiting the cell (Suss et al., 2015). Flow-through designs can enhance water-electrode contact and accelerate electrosorption kinetics (higher salt adsorption rate), but they typically impose higher pressure drop and may increase exposure to parasitic reactions due to more intimate electrolyte-electrode interaction. Thus, the selection of flow arrangement involves a trade-off between desalination kinetics/performance and hydraulic/pumping energy (Suss et al., 2015). CDI removes salt by storing ions on the surfaces of porous electrodes, similar to how a supercapacitor stores charge, allowing desalination at low voltage without high pressure (Mourshed et al., 2022; Rimon et al., 2025). However, its performance is limited by side reactions and limited ion storage, so advanced designs like membrane-assisted, battery-type CDI, and continuous systems such as FCDI have been developed.

### 2.1.2. *Ion adsorption and charge storage mechanisms*

*2.1.2.1. Electric double-layer formation.* Ion adsorption and charge storage are the core mechanisms that enable CDI to remove dissolved salts under an applied electric field. During operation, ions migrate into porous electrodes and are retained by charge-compensating storage, mainly through EDL formation and, in some designs, additional Faradaic or pseudocapacitive contributions (Mourshed et al., 2022; Rimon et al., 2025). These pathways directly govern salt adsorption capacity, charge efficiency, selectivity, and long-term stability, and they explain why CDI performance varies across electrode materials, pore structures, and operating conditions. Fig. 3 summarizes the key mechanisms and non-ideal effects of EDL formation, co-ion expulsion, pore-size dependent transport limitations, parasitic side reactions, and the role of pseudocapacitive/intercalation electrodes, which are discussed in detail in the following subsections.

In CDI, salt is removed from water mainly through the formation of an electric double layer (EDL) on the surface of porous electrodes. When

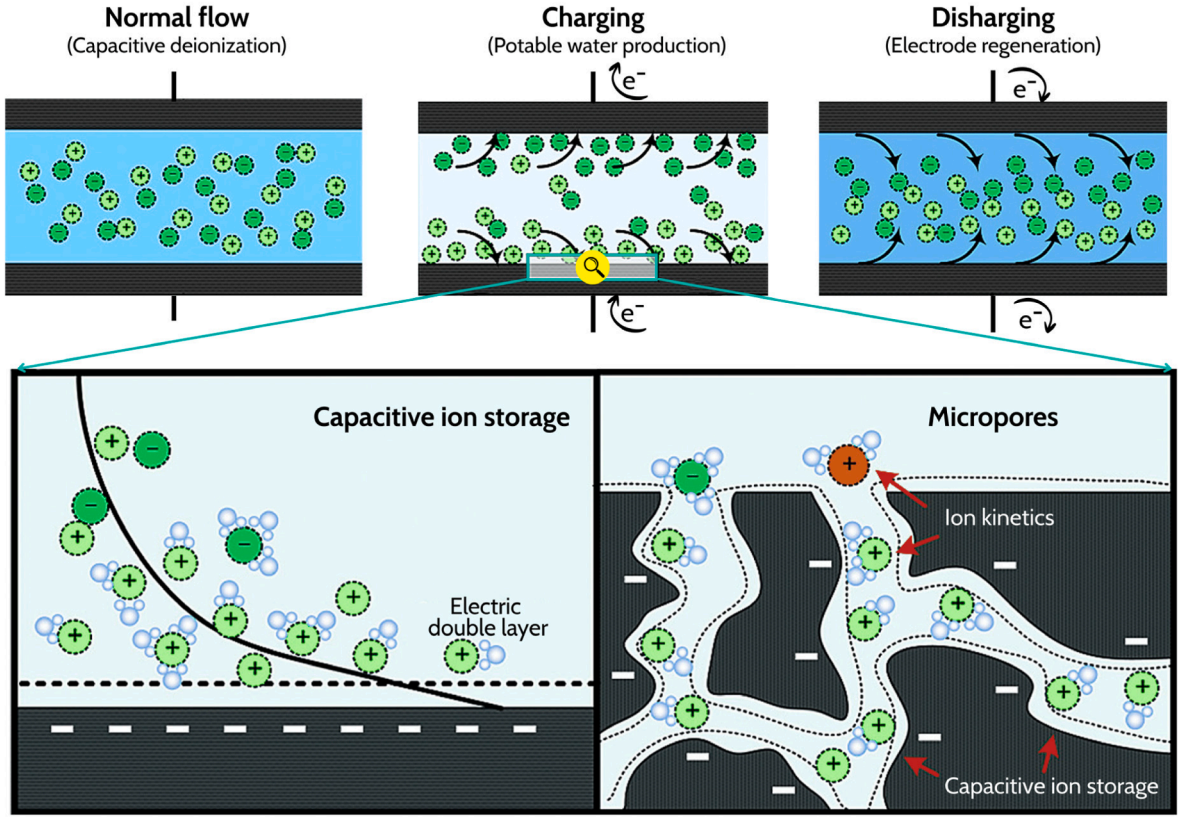



**Fig. 2.** Schematic diagram of CDI showing EDL-based ion adsorption in porous carbon electrodes and micropores during cell charging (Zhang et al., 2018)

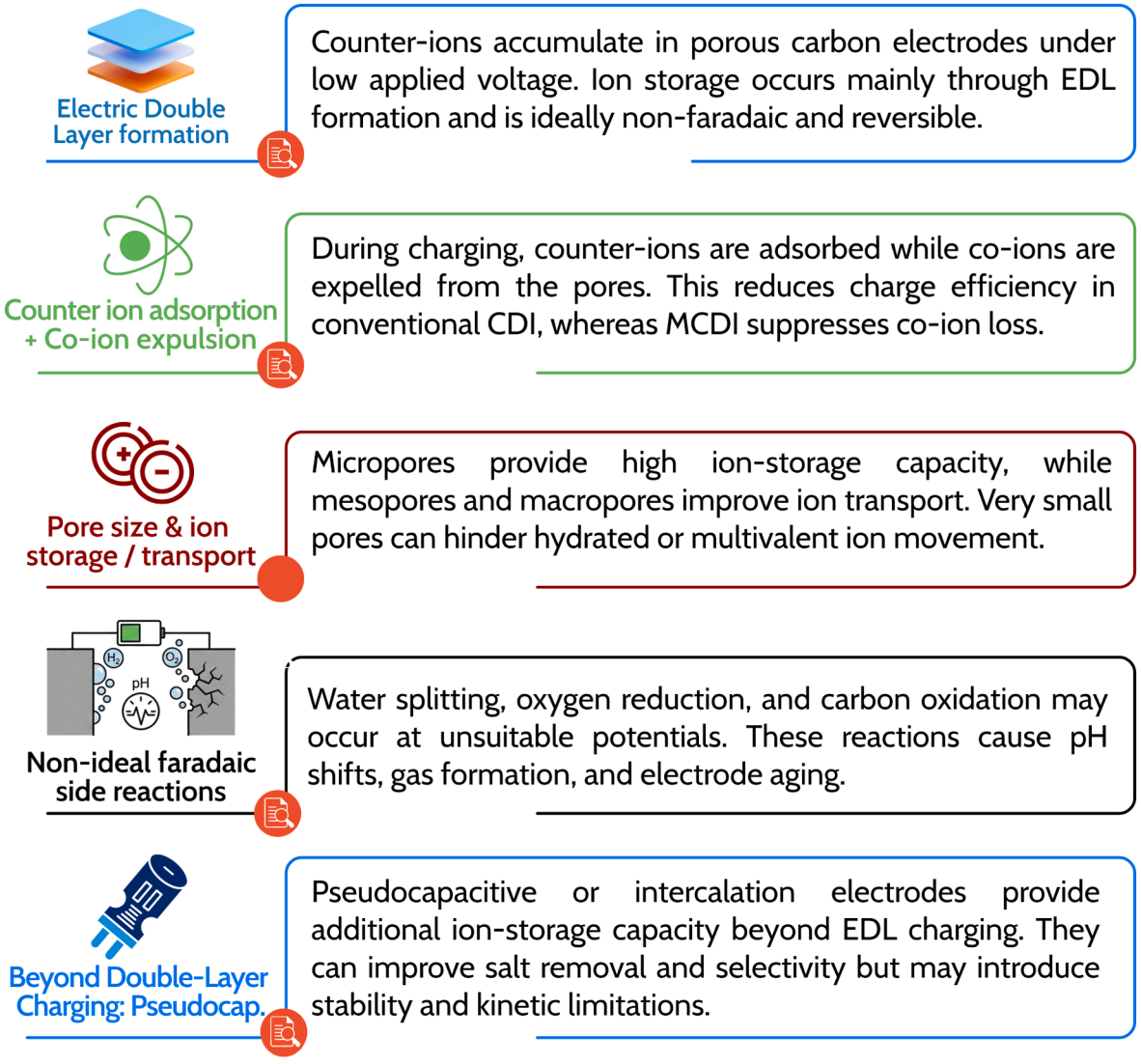



**Fig. 3.** Conceptual overview of CDI ion adsorption and charge storage, encompassing EDL formation, co-ion expulsion, pore-size dependent transport and storage limitations, parasitic Faradaic side reactions, and pseudocapacitive/intercalation-based charge storage.

a small voltage is applied, the carbon electrode becomes electrically charged. As a result, oppositely charged ions from the water move into the tiny pores of the electrode and stick to its surface to balance that charge (Porada et al., 2013; Mourshed et al., 2021). According to the Gouy-Chapman-Stern model, this EDL has two parts: a compact layer of ions attached directly to the surface (Stern layer) and a more spread-out layer of ions in the nearby solution (diffuse layer) (Biesheuvel and Bazant, 2010; Chowdhury et al., 2025). Because materials like activated carbon, carbon nanotubes, and graphene have a very large internal surface area, they can store many ions inside their pores. In the ideal case, ion storage can occur without Faradaic (redox) reactions, making the process largely reversible and energy-efficient (Biesheuvel and Bazant, 2010).

*2.1.2.2. Counter-ion adsorption and Co-ion expulsion.* In an ideal CDI system, each electron transferred through the external circuit would ultimately correspond to removing one monovalent salt ion pair from solution (one cation stored at the cathode and one anion stored at the anode), giving a charge efficiency of $\Lambda = 1$. In practice, however, porous carbon electrodes already contain electrolyte in their pores before charging, including ions that have the same sign as the electrode charge (co-ions). When a voltage is applied, EDLs form in the pores by a combination of counter-ion adsorption and co-ion expulsion (desorption); co-ions are pushed out of the pores as like charges repel (Zhao et al., 2010). Because some of the injected charge is associated with expelling co-ions rather than bringing additional counter-ions in from the bulk, the net salt removal is lower than the total ionic charge stored (Zhao et al., 2010). This is quantified by the charge efficiency $\Lambda$, commonly defined as the ratio of moles of salt removed (ion pairs) to Faraday equivalents of electronic charge passed (Zhao et al., 2010). In conventional CDI without membranes, $\Lambda$ is therefore typically below 1; literature and reviews commonly report values below ~0.8, and values on the order of ~0.6-0.8 are often observed under typical operating conditions, while some studies report ~0.5-0.8 depending on conditions. Importantly, $\Lambda$ generally decreases with increasing feed salt concentration (Kim et al., 2015). Co-ion expulsion is often more pronounced in microporous carbons, where double layers can strongly overlap (conceptually when the Debye length is not small compared to pore size), making co-ion desorption a significant part of charge compensation (Biesheuvel et al., 2014).

A common way to reduce co-ion loss is to use MCDI. In this method, special ion-exchange membranes are placed in front of the electrodes so that unwanted co-ions cannot easily leave the electrode region (Biesheuvel et al., 2011). This forces more useful counter-ions to enter and

be stored in the electrodes, which improves salt removal. Because of this, MCDI usually has a higher charge efficiency (Λ) than normal CDI, although it is still not perfectly 100% in real systems (Zhao et al., 2013). Overall, co-ion expulsion is one of the main reasons why conventional CDI is less efficient, and this is why membrane-based and improved CDI designs are widely used.

*2.1.2.3. Pore size and ion storage.* The pore size of CDI electrodes strongly affects how ions are stored and transported. Micropores (≤2 nm) provide most of the internal surface area, so they are mainly responsible for holding electrical charge and removing salt. However, when these pores become similar in size to hydrated ions, the ions face space limitations and partial loss of their water shell, which can slow their movement and influence which ions can enter the pores. In such very small pores, the EDLs from opposite pore walls overlap, so the classical diffuse-layer theory no longer applies. To describe ion behavior in these tiny pores, Donnan-type models are used. These models treat each micropore as a region with a nearly uniform electrical potential, where ions distribute themselves according to the Donnan potential between the pore and the bulk solution. This approach helps predict how many counter-ions are stored and how many co-ions are expelled during CDI operation (Liu et al., 2022). In practical CDI electrodes, a hierarchical pore structure is preferred. Micropores provide high salt storage capacity, while mesopores and macropores act as fast "ion highways" that allow ions to move quickly into and out of the electrode. This improves both capacity and desalination rate. Also, larger or multivalent ions (such as $Ca^{2+}$ or $Mg^{2+}$) move more slowly and are more strongly hindered in small pores, making pore design very important for selective ion removal and water softening (Zhang et al., 2022).

*2.1.2.4. Non-ideal faradaic reactions.* Although CDI is intended to rely on electrostatic (non-faradaic) EDL charging, real cells often exhibit some faradaic side reactions. When the applied cell voltage approaches or exceeds the aqueous water stability window (~1.23 V), water splitting reactions can occur, leading to $H_2$ evolution at the cathode and $O_2$ evolution (or water oxidation) at the anode (Lu et al., 2017). Even below this nominal limit, dissolved oxygen reduction at the cathode and carbon electrode oxidation (and other surface redox processes) can generate parasitic currents. These reactions are widely reported to cause pH fluctuations, gas bubble formation, and gradual electrode aging/-performance decay during repeated cycling (Zhang et al., 2018). Because this charge is consumed by redox processes rather than ion electrosorption, faradaic reactions lower Coulombic/charge efficiency and can accelerate electrode degradation. Strategies commonly discussed to mitigate these effects include operating within a safer voltage window (often using asymmetric charging/discharging to reduce anode oxidation), improving electrode stability, and controlling oxygen exposure; long-term studies show that improper voltage windows (e.g., symmetric operation around ~1.2 V) can strongly degrade performance (Algurainy and Call, 2021).

*2.1.2.5. Beyond double-layer charging- pseudocapacitance.* While classical CDI is designed to rely mainly on EDL charging (ideally avoiding Faradaic chemistry), many advanced hybrid/Faradaic CDI concepts intentionally introduce pseudocapacitive or intercalation-type electrodes to increase ion storage beyond what porous carbon EDLs can typically provide (Mourshed et al., 2021; Mourshed et al., 2022). Pseudocapacitance refers to fast, reversible surface or near-surface redox reactions (sometimes including near-surface ion insertion) that exhibit a capacitor-like response but still involve Faradaic charge transfer. For example, $MnO_x/MnO_2$-based components are widely explored because Mn redox can contribute additional charge storage and therefore improve desalination performance compared with purely carbon electrodes under similar operating windows (Sun et al., 2023). In fact, several CDI studies and reviews point out that the salt adsorption capacity (SAC) of conventional carbon-EDL CDI is often constrained by surface area and pore structure, with many reports clustering around ~10–15 $mg \cdot g^{-1}$ under common test conditions, motivating the use of intercalation-type pseudocapacitive or other Faradaic materials to overcome this ceiling (Zhang et al., 2018; Sun et al., 2023).

The main trade-off is that Faradaic storage introduces additional constraints on kinetics and durability. Because these materials rely on redox and ion transport within (or into) solids, they can show capacity fade, dissolution/leaching, or parasitic side reactions over long cycling if the chemistry is not well controlled. Also, electrode redox potentials must remain compatible with the aqueous stability window to limit water electrolysis; the thermodynamic decomposition threshold of water is ~1.23 V, so CDI systems commonly manage operating voltage/current to avoid triggering excessive gas evolution and related inefficiencies (practical limits depend on overpotentials and electrode chemistry) (Zhang et al., 2018).

### 2.1.3. Evolution of CDI configurations

*2.1.3.1. Conventional CDI.* CDI has evolved from a simple two-electrode desalination concept into a diverse family of cell configurations designed to overcome the limitations of early systems. As research progressed, challenges such as low charge efficiency, electrode saturation, co-ion expulsion, and limited salt storage motivated the development of new architectures. These innovations aimed to improve ion selectivity, energy efficiency, operational stability, and continuous water production. As a result, CDI now includes several advanced configurations that combine electrostatic, membrane-assisted, and faradaic mechanisms (Halder et al., 2025; Shajid et al., 2025). The following sections review the major CDI variants and explain how each addresses specific performance bottlenecks of conventional CDI.

CDI is commonly introduced through the classic (symmetric) CDI cell**:** two identical porous carbon electrodes separated by a flow channel, without ion-exchange membranes, where ions are removed mainly by EDL electrosorption under a low applied voltage (typically ≤ ~1.2 V to limit parasitic Faradaic reactions) (Zhao et al., 2025). The technology's roots trace back to early work around the 1960s, followed by major growth as high–surface area carbon materials and improved cell engineering became available; modern reviews summarize this historical timeline and its key milestones (Akbarzadeh et al., 2025). Conventional CDI is attractive because it is mechanically simple, modular, and membrane-free, which can reduce cost and simplify maintenance. Reviews also emphasize that CDI is most competitive in a design-specific operating window favoring low-to-moderate salinity waters (e.g., brackish water) rather than high-salinity feeds (Akbarzadeh et al., 2025). The same baseline design has well-known limitations. Co-ion expulsion and other non-idealities reduce the fraction of electrical charge that actually contributes to salt removal; this is one major reason membrane-assisted variants (MCDI) can improve "useful" charge by blocking co-ions. Conventional CDI is also often operated in cyclic (batch) mode, and its performance typically degrades as feed salinity increases because electrodes saturate faster and energy efficiency drops (Porada et al., 2013; Akbarzadeh et al., 2025). Within conventional CDI, flow-by (water between electrodes) is the most common architecture, while flow-through (water forced through porous electrodes) can increase adsorption rate but often shows lower charge efficiency and more side reactions under comparable conditions (Zhang et al., 2019).

*2.1.3.2. Membrane CDI.* MCDI is a practical upgrade of conventional CDI that adds ion-exchange membranes (IEMs) to make ion removal more efficient and more controllable. The term and concept are widely traced to the 2006 demonstration by Lee et al., and recent reviews describe MCDI as a key milestone that helped CDI move from a "membrane-free" concept to a higher-performance architecture used for desalination, softening, and selective separations (Xiao et al., 2024). In a

standard MCDI cell, a cation-exchange membrane (CEM) is placed in front of the cathode, and an anion-exchange membrane (AEM) is placed in front of the anode, so the feed spacer channel is effectively sandwiched between an AEM and a CEM (Xiao et al., 2024; Akbarzadeh et al., 2025). The membranes are "one-way gates" for ions: they mainly allow counter-ions to move toward the oppositely charged electrode region while suppressing co-ion transport in the undesired direction. This directly reduces the co-ion expulsion problem that wastes charge in conventional CDI, so a larger fraction of the applied electrical charge contributes to salt removal (Li et al., 2020). Because of this, MCDI typically shows higher charge efficiency and salt adsorption per cycle than membrane-free CDI under comparable conditions. For example, Zhao et al. experimentally compared CDI and MCDI using graphite-cloth electrodes in 400 ppm NaCl solution and reported that the average charge efficiency increased from 16.33% for CDI to 70.15% for MCDI after incorporating ion-exchange membranes; this result was also summarized in the 2022 energy-focused review (Zhao et al., 2013). However, this improvement should be interpreted as condition-specific, since charge efficiency depends strongly on electrode material, feed salinity, applied voltage, and operating mode. In practice, MCDI is commonly operated in the "safe" CDI voltage window, often around ~1.2 V for carbon-electrode systems to limit parasitic Faradaic reactions and water splitting; this guideline is repeatedly stated in recent CDI/MCDI literature and reviews (Zhang et al., 2019).

For regeneration (desorption), MCDI can be discharged at 0 V/short-circuit (ions diffuse back) or run with polarity reversal (reverse voltage) to actively push ions out. Both theory and experiments show that reverse-voltage discharge can improve regeneration speed/completeness in many cases, although very strong reversal can also cause "re-adsorption" effects that need to be managed by choosing an appropriate discharge strategy (Biesheuvel et al., 2011). Another practical advantage is that MCDI integrates well with constant-current control and even energy-recovery strategies; a classic MCDI energy-recovery study reported up to 83% recovery of charging energy during regeneration under specific operating conditions (Długołecki and van der Wal, 2013). At the same time, membranes add cost and assembly complexity, introduce extra resistance (voltage loss), and can be affected by fouling/scaling (e.g., hardness and organics), which can reduce performance if pretreatment and cleaning are not addressed (Oh et al., 2024). MCDI is therefore widely used when higher efficiency and better ion control are needed, while ongoing work focuses on lowering membrane resistance and improving long-term robustness in real waters (Xiao et al., 2024).

*2.1.3.3. Inverted CDI (i-CDI).* Inverted capacitive deionization (i-CDI) is a newer way to operate CDI, where the usual adsorption/desorption pattern is flipped: the cell can release salt during the charging step and remove salt during the discharge (or low-voltage) step (Xu and Pan, 2023). This inversion happens because at least one porous carbon electrode is chemically modified so it carries a built-in (fixed) surface charge, or its potential of zero charge (PZC) is shifted. Typical modifications include introducing acidic/basic functional groups, surfactant layers, or polyelectrolyte coatings that create a permanent preference for counter-ions inside the pores (Orozco-Barrera et al., 2023). A common i-CDI strategy uses two electrodes with different surface chemistries (for example, one made more negatively charged and the other less so). At open circuit or low voltage, the fixed charges attract counter-ions into the pores, so the outlet becomes less salty (a diluate). When a normal cell voltage is applied, the electrode potentials shift relative to their zero-charge states and the stored ions are pushed back out, creating a concentrated stream. Because the "dilute" and "concentrate" periods happen at opposite electrical steps compared with standard CDI, i-CDI can be useful when you want a stable long-term operation strategy (for example, pairing two cells out of phase to approximate continuous product) (Xu and Pan, 2023). One widely cited demonstration reported stable i-CDI operation for roughly 600 h at a cell voltage of about 0.8 V, and later discussions point out that the electrode potential distribution in i-CDI can help mitigate carbon oxidation compared with some conventional operating windows (Gao et al., 2020). At the same time, the low voltage window often used in that early work can limit salt adsorption capacity, so later designs try to balance stability with capacity by tuning the surface charge and operating voltage (Taha et al., 2021).

Surface-charge control can also support selectivity in mixed-ion waters. For instance, a recent CDI review discusses i-CDI designs for nitrate-focused operation using tailored functionalization, and reports nitrate-over-chloride selectivity gains on the order of several-fold (about 6.5× in one configuration) (Pang et al., 2024). Recent broader reviews of fixed-electrode CDI also keep i-CDI in the list of important architectures and materials directions, alongside membrane CDI and Faradaic/battery-type variants (Song et al., 2023). Overall, i-CDI is promising but not a free upgrade: it needs extra electrode-modification steps, careful voltage-window control to avoid side reactions, and most systems still run adsorption/regeneration phases, so truly continuous product water usually requires multiple cells or smart flow management.

*2.1.3.4. Hybrid and asymmetric CDI.* Hybrid or asymmetric CDI is a key step in CDI evolution because it combines two different ion-storage mechanisms in one cell. Instead of using two identical porous carbon electrodes (pure EDL, storage), a hybrid CDI (HCDI) cell keeps one electrode as a normal carbon "capacitor" and replaces the other with a battery-type (Faradaic or pseudocapacitive) electrode that stores ions through reversible redox reactions or ion insertion. Recent reviews highlight hybrid configurations as an important strategy to overcome the limited capacity of EDL-only CDI (Akbarzadeh et al., 2025). Faradaic ion-storage processes (intercalation/conversion) are also widely discussed as a "positive" use of Faradaic reactions in CDI architectures (Zhang et al., 2018).

The main motivation is higher salt removal per cycle. In a representative high-performance carbon-only CDI study, the salt electrosorption capacity reached about 15 mg NaCl per gram of porous carbon (both electrodes) at 1.2 V, showing the practical limit of EDL storage even with optimized pore structures (Porada et al., 2013). By adding a Faradaic electrode, the cell can store more ionic charge (often in the bulk of the material), which can translate into higher desalination capacity and sometimes higher charge efficiency. A common example is pairing a carbon electrode with an Ag/AgCl conversion electrode, where chloride is captured via $Ag + Cl^- \rightleftharpoons AgCl + e^-$; one study reported that Ag-coating in a hybrid setup increased deionization capacity (reported as 88% more) and improved charge efficiency from 76% to 92% (Yoon et al., 2017). If both electrodes are Faradaic (often called "desalination batteries" or dual-ion systems), even larger capacities are possible, for example, an AgCl–$Na_{0.44}MnO_2$ dual-ion system reported 57.4 $mg \cdot g^{-1}$ reversible salt absorption/desorption over 100 cycles with charge efficiency close to 1.0 (Chen et al., 2017). Recent literature also emphasizes that choosing ion-selective intercalation hosts (including Prussian blue analogues) can make asymmetric systems useful for targeted ion separations (Younes et al., 2024). Hybrid CDI also brings battery-like challenges: solid-state ion diffusion can slow the rate, Faradaic materials may fade over long cycling, and operation needs careful voltage control so the Faradaic electrode is not overcharged. Still, it is a practical route when higher capacity or selective ion removal is needed beyond standard carbon–carbon CDI (Shajid et al., 2025).

*2.1.3.5. Intercalation-based CDI.* Intercalation-based CDI, often called desalination batteries (DBs), is an advanced CDI concept where both electrodes store salt ions through battery-like (Faradaic) reactions, not mainly by EDL adsorption on carbon. The core idea is simple: one electrode is a cation host (it intercalates or inserts $Na^+$ or other cations), while the other electrode is an anion host (it captures $Cl^-$ or other anions

through a reversible conversion/insertion reaction). This makes the device behave like a rechargeable "NaCl battery," where desalination happens because ions are pulled out of water and locked into solid electrodes during one step, then released back during the regeneration step (Santos and La Mantia, 2023). A classic example is the desalination battery introduced by the author, which used a sodium-insertion manganese oxide electrode ($Na_{2-x}Mn_5O_{10}$) and an Ag/AgCl electrode to capture chloride (Santos and La Mantia, 2023). Later "dual-ion" systems have used AgCl-$Na_{0.44}MnO_2$ electrodes, where $Na^+$ and $Cl^-$ are removed simultaneously to their respective electrodes under the appropriate current direction and released during the reverse step (Pothanamkandathil et al., 2020). Because both ions can be stored in the bulk of redox-active materials (not just on surfaces), salt removal capacity can reach tens of mg per g of electrode material. For instance, the author reported a stable, reversible salt absorption/desorption capacity of 57.4 $mg{\cdot}g^{-1}$ over 100 cycles, along with reported charge efficiencies 0.979/0.956 (desorption/absorption) (Chen et al., 2017). Even higher capacities continue to appear in newer "rocking-chair" intercalation CDI designs; one report showed a desalination capacity around 123 $mg\cdot g^{-1}$ (Ahn et al., 2024).

These systems also blur the line between desalination and energy storage. The work explicitly frames the device as related to "mixing entropy batteries," and reports an energy consumption figure for partial salt removal under their protocol (Pasta et al., 2012). A more recent perspective explains DB operation as a multi-step cycle and notes that net energy use depends on the voltage–charge path across the cycle, meaning some steps can be energy-releasing while the full cycle still has a net cost (or, in special cases, different energy behavior depending on electrode choices and electrolyte exchange strategy) (Santos and La Mantia, 2023). The main practical challenges are battery-like: material stability in aqueous media, possible dissolution/structural degradation, and slower kinetics due to solid-state ion transport (Mahima et al., 2025). Operation is also constrained by water's electrochemical stability (thermodynamically ~1.23 V), so many systems aim to keep cell voltages near ~1.2 V to limit water splitting and leakage currents, which restricts useable redox couples (Kim et al., 2015). Many DB designs also require separators or membranes/compartments to prevent cross-contamination and keep electrode reactions stable, adding complexity (Santos and La Mantia, 2023). Overall, desalination batteries can deliver very high salt-removal capacity and new energy-aware operating possibilities, but long-term electrode durability and practical cell design remain the main hurdles. CDI has developed into several advanced forms as researchers worked to overcome the limits of the original carbon–carbon system.

Table 1 summarizes these CDI variants and their key features. Membrane CDI improved efficiency by reducing unwanted ion loss, inverted CDI improved stability through surface-charged electrodes, and hybrid and intercalation-based CDI increased salt removal by using battery-type materials. Today, CDI follows two main directions: improving fixed-electrode cells for better efficiency and selectivity, and developing FCDI for continuous operation.

#### 2.1.4. Limitations of fixed-electrode CDI

FCDI was developed mainly because conventional CDI with fixed (static) electrodes has practical limits when it is used for long-term, steady water treatment. In a standard CDI cell, ions are stored inside the pores of two solid electrodes during the charging step (Halder et al., 2025). Once those pores become filled (saturated), desalination must pause, and the cell must be regenerated to release the stored ions. This naturally creates intermittent (cyclic) operation, where the outlet

**Table 1**
Summarizes these CDI variants and their key features.

| CDI variant | Key concept | Main advantages | Main limitations | Typical operating mode | Typical Performance Range | Refs |
|---|---|---|---|---|---|---|
| Conventional CDI | Two porous carbon electrodes storing ions by EDL formation | Simple design; low cost; membrane-free; suitable for low-salinity brackish water | Co-ion expulsion lowers charge efficiency; limited salt storage; usually cyclic operation; performance decreases at higher salinity | Batch or semi-batch charge–discharge cycles | Salt adsorption capacity typically ~5–15 $mg{\cdot}g^{-1}$ for carbon electrodes under low-salinity conditions; charge efficiency well below unity | Suss et al. (2015) |
| Membrane CDI (MCDI) | Addition of cation- and anion-exchange membranes to suppress co-ion loss | Higher charge efficiency; improved salt removal per cycle; steadier effluent possible under constant-current operation | Added cost and complexity; membrane fouling/scaling; additional ohmic resistance | Cyclic operation with zero-voltage or reverse-voltage regeneration; constant-current driving possible | Charge efficiency can approach unity (≈1.0) under optimized low-to-moderate salinity conditions; higher SAC than conventional CDI | McNair et al. (2020) |
| Inverted CDI (i-CDI) | Fixed chemical charge on electrode surfaces inverts adsorption/desorption behavior | Improved operational stability; reduced performance decay during long operation | Requires surface-modified electrodes; sensitive to surface chemistry; limited commercial maturity | Often constant-voltage operation with inverted desalination step | Stable operation demonstrated for hundreds of hours (≈600 h reported) at moderate voltages (~0.8 V); per-cycle SAC typically lower than MCDI | Gao et al. (2015); He et al. (2023) |
| Hybrid/Asymmetric CDI | One capacitive carbon electrode paired with one Faradaic (battery-type) electrode | Higher salt removal capacity; improved charge efficiency; potential ion selectivity via electrode choice | Slower kinetics than EDL storage; possible capacity fade of Faradaic electrode; careful voltage control required | Cyclic charge–discharge operation | Salt adsorption capacities commonly >20–30 $mg{\cdot}g^{-1}$, depending on Faradaic material and operating conditions | Yoon et al. (2017); Pang et al. (2024) |
| Intercalation-based CDI (Desalination batteries) | Both electrodes are Faradaic, storing cations and anions through reversible redox or intercalation reactions | Highest salt storage per cycle; strong link between desalination and energy storage/recovery; high ion selectivity possible | Complex cell design; stability issues in aqueous media; limited voltage window (~1.2 V); slower solid-state ion diffusion | Battery-like galvanostatic cycling | Reported salt adsorption capacities often >50 $mg{\cdot}g^{-1}$ (e.g., ~57–60 $mg\cdot g^{-1}$) with high charge efficiency under controlled conditions | Suss et al. (2015); Chen et al. (2017a) |
| Flow-electrode capacitive deionization (FCDI) | Flowable carbon slurry electrodes enabling continuous adsorption and external regeneration | Truly continuous desalination; avoids electrode saturation; capable of handling high salinity feeds | System complexity; pumping and slurry handling losses; high resistive losses; membranes often required | Continuous steady-state operation | Continuous desalination demonstrated up to seawater-level salinity (~35 $g{\cdot}L^{-1}$); efficiency depends on slurry conductivity and system design | Cho et al. (2019); Zhang et al. (2021); Tauk et al. (2025) |

quality changes with time and a single cell cannot continuously deliver a steady stream of desalinated water without extra plumbing, valves, or multiple cells operating out-of-phase. Reviews of CDI and FCDI repeatedly highlight this "saturation → regeneration" bottleneck as a central motivation for moving toward flowable electrodes and continuous operation (Gendel et al., 2014; Rommerskirchen et al., 2020).

A second driver is capacity limitation at higher salinity. Conventional CDI is most attractive for low to moderate salinity waters (typical brackish ranges), because energy efficiency and charge efficiency degrade as salinity increases and the electrodes saturate more quickly. Classic and widely cited CDI reviews describe CDI as most energy-efficient below roughly ~10 g/L salt concentration (order-of-magnitude guidance), and more recent analyses similarly show performance and efficiency challenges as feed salinity rises into higher ranges (Porada et al., 2013; Suss et al., 2015). In practical terms, trying to remove a large fraction of salt from seawater-level feeds (about 35 g/L NaCl equivalent) would require either extremely short cycles (because the electrodes fill rapidly) or very large electrode masses, while also facing transport limits inside thick electrodes. This is why fixed-electrode CDI is generally discussed as a brackish-water technology rather than a direct seawater desalination approach (Patel et al., 2020).

FCDI tackles these issues by replacing solid electrodes with pumpable carbon slurry electrodes that continuously circulate through the cell. Instead of relying on a fixed amount of adsorption capacity stored in stationary plates, the system effectively "refreshes" the active electrode material in real time and can store salt in the external slurry volume. Early demonstrations reported both batch and continuous operation using flowing carbon suspensions, and later work showed that FCDI can operate at elevated salinities (Rommerskirchen et al., 2020). Importantly, seawater-relevant tests have been reported in the FCDI literature; for example, a Water Research study explicitly evaluated FCDI at 35 g/L (equivalent to seawater) and reported high salt removal rates under its conditions (Cho et al., 2019).

Scale-up and throughput also motivate FCDI. With static CDI, higher treatment flow typically means stacking many modules in parallel, which increases manifold complexity, electrical connections, and maintenance effort. FCDI can be designed for continuous steady-state operation, and it decouples "salt storage capacity" from the physical size of the electrode plates because storage can be expanded by increasing slurry inventory or reservoir volume. Reviews describe this as a key engineering advantage of flow electrodes when targeting larger throughputs or longer continuous runs (Tauk et al., 2025).

Finally, energy and regeneration considerations encouraged FCDI development. In fixed-electrode CDI, energy recovery is possible but often requires added circuitry and careful operation; in flow-electrode systems, regeneration can be handled in a dedicated loop, and some studies explicitly analyze process design and energy recovery options in continuous FCDI configurations (Rommerskirchen et al., 2020; Ma et al., 2023). Overall, these motivations, intermittent output from saturation/regeneration, limited practicality at higher salinity, scale-up complexity, and the desire for more flexible regeneration/energy handling collectively explain why the field moved toward the flow-electrode concept, which the next section describes in detail.

### 2.2. Fundamental principles and structure of FCDI

#### 2.2.1. An overview

FCDI is an extension of conventional CDI that was developed to overcome the limitations of fixed, solid electrodes and to enable truly continuous desalination. In FCDI, the rigid carbon electrodes used in standard CDI are replaced by flowable electrodes, which are suspensions of electrically conductive carbon particles dispersed in water. Because these electrodes are liquid-like and can be pumped, the system no longer relies on a fixed adsorption capacity within stationary plates. Instead, ion storage and regeneration take place continuously as the carbon slurry circulates through the system (Tauk et al., 2025). At the heart of FCDI is the carbon slurry flow-electrode. This slurry typically consists of micron-scale carbon materials such as activated carbon or carbon black mixed with water and a small amount of supporting electrolyte. The carbon particles act as mobile adsorption sites, storing ions in their EDLs, just like solid carbon electrodes in conventional CDI. However, unlike static electrodes, these particles are constantly moving. The slurry is pumped through electrode chambers located on both sides of a central feedwater channel, allowing fresh, unsaturated carbon to continuously enter the desalination zone (Tauk et al., 2025). Fig. 4 illustrates a typical FCDI cell. Structurally, FCDI has a central feedwater channel (the stream to be desalinated) and two electrode channels on the sides that carry the carbon slurries. The feed channel is separated from the cathode-slurry channel by a CEM and from the anode-slurry channel by an AEM. The outer sides of the slurry channels touch current collectors (graphite plates/meshes or other conductive collectors) that apply the electrical potential to the flowing slurries (Zhang et al., 2021; Tauk et al., 2025).

When a voltage is applied across the two slurry electrodes, the carbon particles near the cathode become negatively polarized and adsorb cations; the carbon particles near the anode become positively polarized and adsorb anions. At the same time, ions from the feed stream migrate through the membranes: Cations pass through the CEM into the cathode slurry, Anions pass through the AEM into the anode slurry (Tauk et al., 2025). Unlike a solid electrode, where electrons move through a fixed carbon network, the slurry needs frequent particle-particle contact to carry electrons from the current collector into the bulk of the flow channel. Many studies describe this as an electronic percolation network formed by collisions and temporary chains of particles. Practically, this is why carbon concentration matters: increasing carbon loading usually improves electronic pathways (and often improves desalination performance), but it also increases viscosity and pressure drop. Reviews and experimental studies commonly report that flow-electrode slurries are often used in the range of ~5wt%-20 wt% carbon as a compromise between conductivity and pumpability; going much above ~20 wt% can risk clogging or unstable flow in conventional channel designs (Zhang et al., 2021; Kim et al., 2023).

The key difference from fixed-electrode CDI is that the carbon particles do not stay in the cell until they saturate. After picking up ions, the loaded slurry leaves the cell and is refreshed outside the desalination channel, then returned. This is why FCDI can run continuously: while some slurry is adsorbing ions inside the cell, another portion is being regenerated elsewhere in the loop. Recent overviews emphasize that this external regeneration step is the defining feature that turns CDI from a cyclic/batch process into a continuous one (Tauk et al., 2025). In practice, regeneration is implemented through a limited number of established approaches. One approach involves short-circuiting or chemical neutralization in a regeneration tank, allowing adsorbed ions to desorb into a concentrated brine stream. A second approach uses a dedicated regeneration cell, where a reverse potential or controlled current drives ion release into a separate concentrate stream. A third approach employs loop-based configurations, in which the slurry is sequentially exposed to different electrical conditions, enabling alternating adsorption and desorption. These strategies are described in foundational flow-electrode studies and later process-design work on continuous desalination and brine concentration (Porada et al., 2014). Most modern FCDI systems use IEMs because the membranes act as both an ion-selective pathway and a physical barrier that prevents carbon particles from entering the product stream. Reviews often describe the separator/membrane as a key component for stable operation, because without it the risk of particle crossover, product contamination, and uncontrolled ion transport becomes high. Membrane-less concepts exist in research, but they are generally more difficult to implement reliably at scale (Zhang et al., 2021).

Fixed-electrode CDI is usually most effective at low-to-moderate salinity, but FCDI has been demonstrated in conditions as high as seawater-level salinity (~35 g/L NaCl) by using continuously circulating flow electrodes and optimized cell designs/materials. This does not

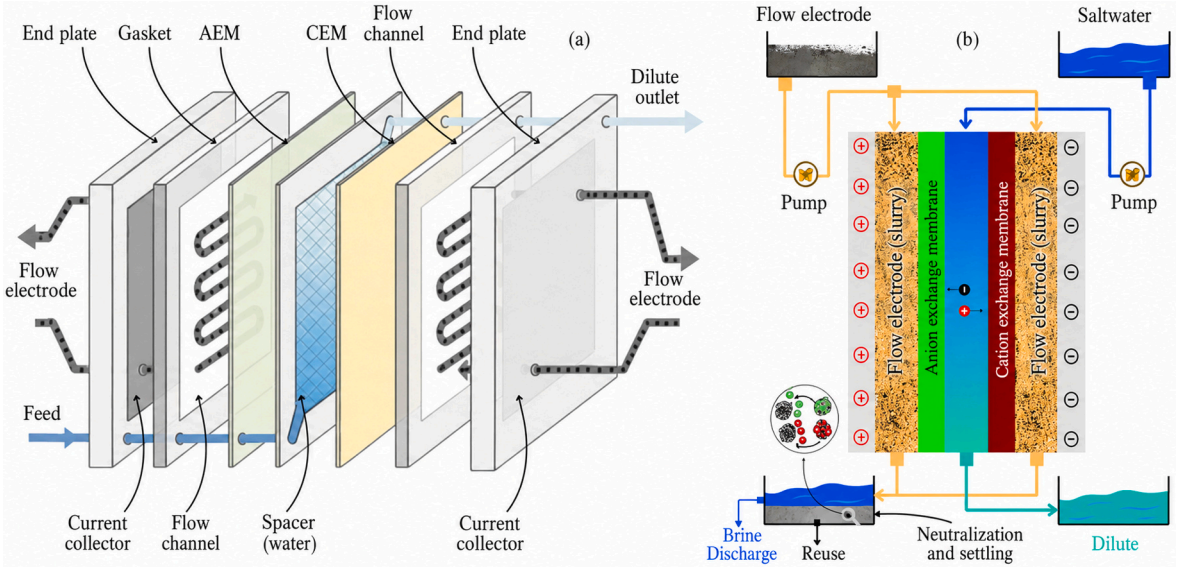



**Fig. 4.** Schematic illustration of (a) a typical FCDI cell geometry and (b) continuous operation with fresh carbon slurry inflow, desalinated water production, and downstream electrode regeneration via slurry mixing and settling (He et al., 2018).

mean seawater desalination is always energy-optimal in FCDI, but it shows that the "electrode saturation" limitation can be strongly reduced by the flow-electrode approach (Ma et al., 2023). FCDI can run in single-pass mode (feed goes through once and exits as dilute) or recirculation mode (feed is recycled until a target salinity is reached). Under stable flow rates and applied voltage/current, many systems approach a steady operating condition, where the rate of ion removal from the feed balances the rate at which ions are released from the slurry during regeneration. This steady-state idea is central in modern FCDI process modeling and scale-up discussions (Rommerskirchen et al., 2020; Ma et al., 2023; Lim et al., 2024). In summary, FCDI transforms CDI from a batch process into a continuous desalination technology by replacing fixed electrodes with regenerable, flowing carbon slurries. Although the system requires additional components such as pumps, membranes, and reservoirs, it offers continuous operation, higher effective salt capacity, and improved suitability for higher salinity feeds.

### 2.2.2. *Developments in FCDI configurations and operation*

Since the first experimental demonstration of FCDI, the technology has evolved significantly through improvements in cell design, materials, and operating strategies. Early FCDI systems mainly focused on proving the concept of continuous desalination, but more recent research has aimed at improving efficiency, scalability, and practical operation. This section summarizes the major developments that have shaped modern FCDI systems, using simple language while highlighting the key technical ideas.

Advances in cell and module design have been one of the most important areas of progress in FCDI. Early FCDI studies commonly used simple flat, parallel-plate channels, but later work showed that non-uniform slurry distribution and stagnant regions in straight channels can reduce effective electrode utilization and limit desalination performance (Zhang et al., 2021). To address this, recent studies increasingly apply engineered flow-field designs (similar to approaches used in electrochemical flow systems such as flow batteries and fuel cells), including serpentine- and interdigitated-type channel concepts, to improve slurry distribution and reduce dead zones (Tauk et al., 2025). For example, a recent study specifically focused on optimizing flow-field distribution to enhance desalination performance and electrode utilization by redesigning channel structures and evaluating flow uniformity effects (Liu et al., 2024). Overall, both experimental and review literature emphasize that improved flow patterns can lead to more uniform slurry contact, better utilization of active carbon, and more stable performance across the cell (Tauk et al., 2025). In contrast to solid-electrode CDI, flow-through architectures are generally less common/practical in FCDI, because pushing dense carbon slurries through porous structures increases hydraulic resistance and complicates stable operation; therefore, most FCDI systems rely on flow-by channel configurations for the slurry electrodes (Ma et al., 2023).

Advances in cell and module design have been one of the most important areas of progress. Initial FCDI cells used simple flat, parallel-plate flow channels, similar to early CDI designs. However, researchers soon realized that poor slurry distribution and stagnant regions inside straight channels could limit salt removal (Saif et al., 2024). To address this, later studies adopted flow-field designs inspired by redox flow batteries and fuel cells, such as serpentine and interdigitated channels (Liu et al., 2024). These designs help distribute the carbon slurry more uniformly across the electrode area and reduce dead zones where little desalination occurs. Modeling and experimental studies showed that improved flow patterns lead to better utilization of the carbon particles and more consistent performance across the cell (Liu et al., 2024). In contrast to solid-electrode CDI, flow-through designs are generally not practical for FCDI because dense carbon slurries are difficult to push through porous structures; therefore, most FCDI systems rely on flow-by channel configurations (Zhang et al., 2021).

Scaling up FCDI systems has also received considerable attention. A single FCDI cell can treat water continuously, but its throughput is limited by channel size and operating current. To increase capacity, researchers have developed multi-cell stacks, similar to electrodialysis stacks, where several FCDI cell pairs are arranged in series or parallel (Rimon et al., 2025; Shajid et al., 2025). Stacking allows higher flow rates or higher operating voltages without changing the basic cell design. Pilot-scale demonstrations have shown that stacked FCDI systems can treat brackish water continuously, indicating that scale-up beyond laboratory devices is feasible (Köller et al., 2024; Tauk et al., 2025). Because FCDI already operates continuously, additional modules are mainly used for increasing throughput or enabling energy-recovery strategies rather than simply smoothing batch operation (Zhang et al., 2021).

A major focus of research has been on optimizing the flow-electrode slurry itself. The performance of FCDI depends strongly on slurry properties such as carbon particle size, concentration, electrical conductivity, and stability (Tauk et al., 2025). Smaller particles provide a

higher surface area for ion adsorption, but also increase slurry viscosity and the risk of aggregation (Folaranmi et al., 2022). To maintain stable suspensions, researchers have explored surface-functionalized carbons, dispersants, and polymer additives that prevent particle clumping and settling. In addition to conventional activated carbon, advanced carbon materials such as graphene, carbon nanotubes, and hybrid composites have been tested to improve electronic connectivity within the slurry (Caalim et al., 2025). Some studies have even added pseudocapacitive or redox-active particles to the slurry to increase salt storage capacity. However, a persistent challenge is the relatively low electrical conductivity of dilute slurries compared to solid electrodes, which can increase internal resistance and limit current density. Approaches such as increasing the slurry flow rate or adding soluble redox couples have been investigated, though these solutions add complexity (Zhang et al., 2021). Another important development concerns the use of ion-exchange membranes (IEMs) versus membrane-less designs. In most modern FCDI cells, a CEM and an AEM are placed on the two sides of the feed channel so that cations and anions are driven into the correct slurry-electrode compartments, while the membranes also act as a physical barrier that helps prevent carbon particles from entering the product stream (Jeon et al., 2013). Because IEMs suppress uncontrolled ion back-transport and improve directional ion migration, membrane-based FCDI generally shows higher charge efficiency and more stable continuous desalination performance than comparable membrane-less concepts (Rommerskirchen et al., 2020). At the same time, membranes add cost and can foul, so researchers have explored membrane-less (or diaphragm/separator-based) FCDI where IEMs are replaced by a porous separator and the process relies more on hydrodynamics and downstream separation (e.g., filtration/settling) to avoid slurry carryover. These membrane-less approaches can work in principle, but they typically face lower efficiency (more co-ion leakage/less ion directionality) and greater operational challenges, which is why IEM-based FCDI remains the dominant and most practical approach in current research (Hatzell et al., 2014).

Regeneration and circulation strategies in FCDI have evolved from simple approaches to more engineered process layouts. Early systems commonly regenerated the carbon slurry in an external tank, where the charged particles were discharged and released ions to form a brine stream. A well-known fully continuous concept combined slurry mixing with an overflow section so the brine could be removed while carbon particles were retained, using gravity/stagnant-flow separation in a vertical tube (Doornbusch et al., 2016). More advanced schemes have also been reported in which regeneration is assisted by dedicated regeneration compartments or module-level process designs, aiming to sustain steady operation while controlling energy loss and salt back-mixing (Zhang et al., 2021). From a performance perspective, FCDI's key advantage, continuous desalination without fixed-electrode saturation, is now well demonstrated. For example, Jeon et al. reported 95% NaCl removal from a near-seawater solution (32.1 g/L NaCl), highlighting how flow electrodes can overcome the short-cycle limitation of conventional CDI at high salinity (Jeon et al., 2013). Scale-up studies also show that stacking and module design can push FCDI beyond lab devices; a membrane-stack configuration study reported productivity $>100\ \mathrm{L{\cdot}m^{-2}{\cdot}h^{-1}}$ (with the note that adding many membrane pairs can shift behavior toward electrodialysis-like transport) (Ma et al., 2020). These results are why FCDI is increasingly explored for continuous brackish-water desalination, brine management/concentration, and high-recovery process trains (Zhang et al., 2021). At the same time, several practical challenges remain active research topics. Pumping energy can become significant because slurry viscosity and pressure drop rise with carbon loading and particle interactions; recent work explicitly analyzes slurry morphology/rheology alongside electrochemical performance, reflecting the need to optimize conductivity without excessive hydraulic losses (Said et al., 2022). Particle aggregation, settling, and channel dead zones can reduce effective electrode utilization and contribute to clogging risks, making flow-field design and slurry stabilization important. Finally, membrane-related issues (fouling/scaling and carbon deposition at the membrane interface) can degrade long-term performance, so many studies emphasize operating-condition control and module design strategies to limit particle–membrane contact and maintain stable resistance (Zhang et al., 2021). Table 2 represents recent CDI/FCDI performance metrics.

Overall, recent developments show that FCDI has progressed from a laboratory curiosity to a flexible and continuously operating desalination platform. With improved cell designs, better slurry formulations, and smarter operating strategies, many of the early limitations of FCDI are being addressed. As the technology matures, FCDI is emerging as a promising option for continuous desalination, brine management, and high-recovery water treatment systems.

### 2.3. Energy recovery and generation in CDI and FCDI

#### 2.3.1. Technical framework and energy dynamics of CDI and FCDI

Water scarcity and the high energy demand of conventional desalination technologies have catalyzed the development of sustainable and energy-efficient water treatment solutions. CDI and its advanced variant, FCDI, have emerged as promising electrochemical technologies for water desalination and ion removal. They offer distinct advantages over traditional methods, including lower energy consumption, operational flexibility, and a reduced environmental footprint, primarily due to their low-pressure, chemical-free operation (Said et al., 2022). A pivotal aspect of their development and broader adoption lies in understanding and optimizing energy consumption and, crucially, harnessing energy recovery mechanisms to further reduce operational costs and enhance sustainability. This section delves into the technical specifications, comparative energy analysis, mechanisms of energy recovery and generation, recent advancements, and future outlook for both CDI and FCDI systems. Fig. 5 shows the general method for energy recovery from different CDI system.

CDI operates on the principle of electro-sorption, where ions are removed from water by applying a low electric potential (typically 1.0-1.4 V) across two porous carbon electrodes (Folaranmi et al., 2020; Bao et al., 2023). During the deionization (charging) cycle, ions migrate toward the oppositely charged electrodes and are stored within the EDLs formed at the electrode-solution interface. This process is analogous to charging a supercapacitor, where electrical energy is stored (Said et al., 2022). Once the electrodes reach saturation, the potential is typically removed (short-circuited) or reversed to release the adsorbed ions, regenerating the electrodes and producing a concentrated brine stream (Al Radi et al., 2021b; Bao et al., 2023). However, conventional CDI is a batch process, leading to discontinuous desalination, which can limit its large-scale applicability due to electrode saturation and frequent regeneration cycles (Liu et al., 2020). FCDI was developed to overcome the batch nature of conventional CDI. In FCDI, the static electrodes are replaced by a continuous flow of a carbon slurry (flow electrodes) that can be regenerated outside the main desalination cell (Dahiya and Mishra, 2020). This continuous flow enables uninterrupted desalination and offers greater flexibility in managing the concentrated brine stream. The fundamental difference in electrode configuration significantly impacts energy dynamics. While CDI's energy storage is primarily within the static EDLs, FCDI involves additional energy considerations related to pumping the conductive slurry and the electron transfer resistance within the flow electrode itself (Dahiya and Mishra, 2020; He et al., 2023).

A number of key parameters affect the energy efficiency of both CDI and FCDI systems. These include the applied potential and current, as optimal control can significantly impact charge efficiency and minimize parasitic reactions (Tang et al., 2020). Electrode material properties such as high salt adsorption capacity (SAC), excellent electrical conductivity, and suitable pore structures are crucial for efficient ion storage and low energy dissipation (Jiang et al., 2022; Tauk et al., 2023). Feedwater salinity also plays a major role, as energy consumption

**Table 2**
Impact of recent innovations on CDI/FCDI performance metrics.

| Innovation | Technology type | Key performance | Reported improvement | Remarks | Refs |
|---|---|---|---|---|---|
| $K_2Ti_2O_5$-AC Flow Electrode | FCDI | $NH_4^+$ Selectivity | Increased from 2.3 to 31 over $Na^+$ | Selective ammonium removal from synthetic wastewater | Lin et al. (2020) |
| $K_2Ti_2O_5$-AC Flow Electrode | FCDI | $NH_4^+$ Desorption Efficiency | Increased from 35.6% to >80% | Selective ammonium removal from synthetic wastewater | Lin et al. (2020) |
| Fiber-structured Biocarbons (FBCs) | FCDI | Salt Adsorption Rate (SAR) | 1.26–5.92 mM/($m^2$·s) (vs. 0.09–2.58 mM/($m^2$·s) for AC) | Saline water (1.01-35.00 g/L) at 1.8 V | Li et al. (2024) |
| CNT-enhanced slurry electrodes | FCDI | Energy Recovery | 60% increase | Conductive agent in slurry electrode | Chu et al. (2022) |
| PEC-FCDI Dual System | FCDI | Specific Energy Consumption | 0.031 kWh·$g^{-1}$ ion removal | Photoelectrochemical oxidation coupled with FCDI | Lim et al. (2022) |
| Strategically Operated FC-FCDI | FCDI | P Removal Rate and Concentration Factor | 0.22 μmol/($cm^2$·min) and 17.2 | Selective phosphorus extraction as vivianite | He et al. (2022) |
| Optimized CC CDI | CDI | Energy Consumption Reduction | 93.9% reduction | Single-objective optimization using GA/PSO | Naveed et al. (2021) |

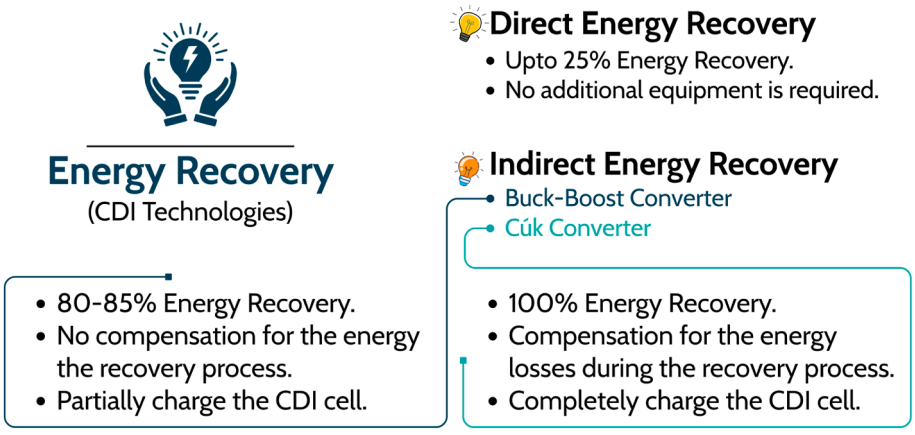



**Fig. 5.** General methods of energy recovery in capacitive deionization systems.

generally increases with higher salt concentrations 8. Other important factors include flow rate, cell architecture (flow-by vs. flow-through), charging/discharging mode (constant current vs. constant voltage), and the use of ion-exchange membranes (IEMs), which can improve charge efficiency but may add resistance (Bao et al., 2023; He et al., 2023).

### 2.3.2. *Comparative analysis of energy consumption*

The specific energy consumption (SEC) is a critical metric for evaluating the economic viability and environmental footprint of desalination technologies, often expressed in units like Wh·g$NaCl^{-1}$ or kWh·$m^{-3}$ (Lim et al., 2022). While CDI is generally energy-efficient for low-salinity brackish water, its energy consumption increases significantly with higher salt concentrations (Zhou et al., 2023). In contrast, FCDI, with its continuous operation, is better suited for treating higher salinity waters and for brine concentration applications (Rommerskirchen et al., 2020). However, FCDI systems face challenges with the electrical conductivity of the flow electrode slurry and the energy required for pumping, which can lead to higher electron transfer resistance compared to static CDI/MCDI electrodes (Dahiya and Mishra, 2020; He et al., 2023).

A comparative study on phosphorus recovery ranked the energy consumption of various electro-driven technologies as ED > FCDI > CDI ≈ MCDI. FCDI's energy consumption was below 30 kWh $kgP^{-1}$, while CDI and MCDI were below 4 kWh $kgP^{-1}$(He et al., 2023). In another study focused on ammonia removal, a pure activated carbon (AC) FCDI system consumed 6.62 kWh $kgN^{-1}$, which was significantly reduced to 2.49 kWh $kgN^{-1}$ by using an innovative $K_2Ti_2O_5$-AC composite electrode (Lin et al., 2020). For general desalination, CDI energy consumption has been reported as low as 0.0089 Wh g$NaCl^{-1}$ with energy recovery, which is significantly lower than RO at high salinity (Jiang et al., 2022). Table 3 presents the comparative energy performance of CDI and FCDI Systems. Recent advancements in FCDI design, such as the use of multiple cell pairs, have demonstrated the potential to reduce energy demand by more than 70% in brine concentration applications under specific operating conditions, making FCDI promising for continuous desalination and brine-management applications (Al Radi et al., 2021). Optimization of operational parameters is also crucial. For FCDI, optimal conditions of 1.6 V applied potential and 0.2 M initial salt concentration have been identified to prevent energy-wasting Faradaic reactions and minimize concentration polarization, leading to more efficient desalination (Tang et al., 2020).

### 2.3.3. *Mechanisms and theoretical basis of energy recovery*

Energy recovery is a key route to reducing the net energy footprint of CDI and FCDI by leveraging their supercapacitor-like behavior. During ion adsorption, electrical energy is stored as ions form EDLs within porous electrodes. During regeneration, part of that stored energy can be returned to the circuit instead of being dissipated as heat. In this sense, CDI/FCDI behaves as a low-voltage electrochemical system in which a fraction of the electrical work invested in ion separation is theoretically reversible (Lin et al., 2020). When an electric potential is applied, counter-ions accumulate near the charged electrode surface while co-ions are repelled, creating EDLs and storing electrical energy. This stored energy corresponds to the reversible electrical work associated with separating ions from the bulk solution and confining them near the electrode interface (Said et al., 2022).

**Table 3**
Comparative energy performance of CDI and FCDI systems.

| Technology | Operational Mode | Salinity Range | Typical Energy Consumption | Energy Recovery (%) | Key Factors Influencing Performance | Refs |
|---|---|---|---|---|---|---|
| CDI | Batch/ Cyclical | Low-Brackish | 0.0089 - 1.57 (Wh $gNaCl^{-1}$) | Up to 84% | Electrode material, charging mode, feed flow rate, salinity, applied voltage | Al Radi et al. (2021); Naveed et al. (2021); Jiang et al. (2022) |
| FCDI | Continuous | Brackish-High | <30 kWh $kgP^{-1}$(P recovery); 2.49-6.62 kWh $kgN^{-1}$(N recovery) | 20-60% | Flow electrode conductivity, pumping energy, cell architecture, applied potential | Al Radi et al. (2021); Chu et al. (2022); He et al. (2023) |
| MCDI | Batch/ Cyclical | Low-Brackish | 0.87-2.10 kWh $kgP^{-1}$ (P recovery); 0.1-0.85 kWh $m^{-3}$ | Up to 83% | Ion-exchange membranes, electrode material, charging mode | Said et al. (2022) |
| ICDI | Batch/ Cyclical | Low-Brackish | 0.01 - 0.464 Wh $gNaCl^{-1}$ | 39-71.9% | Intercalation materials, constant voltage operation | Wang and Lin (2020); Jiang et al. (2022) |
| Redox Flow Desalination | Continuous | High | 0.034 - 0.49 Wh $gNaCl^{-1}$ | 52.4-85% | Liquid redox electrolytes, high charge efficiency, fast ion diffusion | Jiang et al. (2022) |

A simple approach is direct energy recovery, where a charged CDI cell is connected directly to an uncharged cell or an external capacitor so the discharging cell transfers energy passively. Because the cell voltage drops continuously during discharge and the transfer is not actively regulated, energy capture is limited. For two identical cells, the theoretical maximum recovery for direct transfer is 25% (Said et al., 2022). However, higher recovery can be achieved by configuring multiple CDI stacks in sequence, so energy is transferred in stages with a smaller voltage mismatch. Using such multi-stack approaches, energy recovery up to ~70% has been demonstrated (Al Radi et al., 2021), indicating that system architecture alone can significantly reduce dissipation even without sophisticated control.

More advanced implementations use indirect energy recovery, employing DC/DC power converters such as buck-boost converters shown in Fig. 6 (Tang et al., 2019) or Ćuk converters to control the discharge pathway and route recovered energy efficiently to a DC bus, capacitor bank, or another stack (Pernía et al., 2011). Because these converters can regulate current and voltage profiles, they reduce resistive losses and enable higher recovery than passive charge transfer. Under optimized MCDI operating conditions, Długołęcki and van der Wal reported recovery of up to approximately 83% of the charging energy during regeneration (Długołecki, van der Wal et al., 2013). Recent reviews also indicate that CDI/MCDI energy recovery can approach approximately 83–84% when appropriate recovery circuits and controlled operating modes are used (Al Radi et al., 2021; Said et al., 2022). Therefore, these values should be interpreted as system-specific upper-range values rather than universal energy-recovery efficiencies for all CDI/FCDI systems.

Thermodynamically, an ideally reversible CDI cycle would consume energy equal to the Gibbs free energy of separation for the specific feed and recovery ratio. Practical cycles are irreversible, so net energy consumption exceeds this limit. The major loss mechanisms include ohmic drop (internal resistance across electrodes, electrolyte, membranes, and contacts), kinetic and mass-transfer overpotentials, and parasitic Faradaic reactions that convert electrical energy into unwanted chemical pathways (Jiang et al., 2022; Said et al., 2022). These losses not only raise energy consumption during charging but also reduce the electrical energy available to reclaim during discharge.

Consequently, the energy recovery ratio depends on both operating mode and cell properties. Constant-current (CC) operation is often more favorable than constant-voltage (CV) because CC can maintain controlled charge/discharge trajectories and avoid long periods at high overpotential. Lower applied voltage/current generally increases recoverability by reducing resistive heating and suppressing Faradaic side reactions. Feed salinity can also affect recovery: higher salinity typically increases conductivity, lowering ohmic losses and sometimes improving recovery. Electrode salt adsorption capacity and hydrodynamics matter as well, because higher useable capacity and reduced polarization support more reversible operation (Wang and Lin, 2020; Said et al., 2022). Energy recovery has also been demonstrated in FCDI, but typically at lower levels than in CDI/MCDI due to the higher internal resistance and charge-transport complexity of flowable slurries. In an isolated closed-cycle mode, ion-laden flow electrodes can be discharged in a controlled step to generate recoverable energy. Lim et al. (2020) reported a maximum recovery of about 25% at an optimal discharging current of 50 mA (He et al., 2023). They further showed that energy

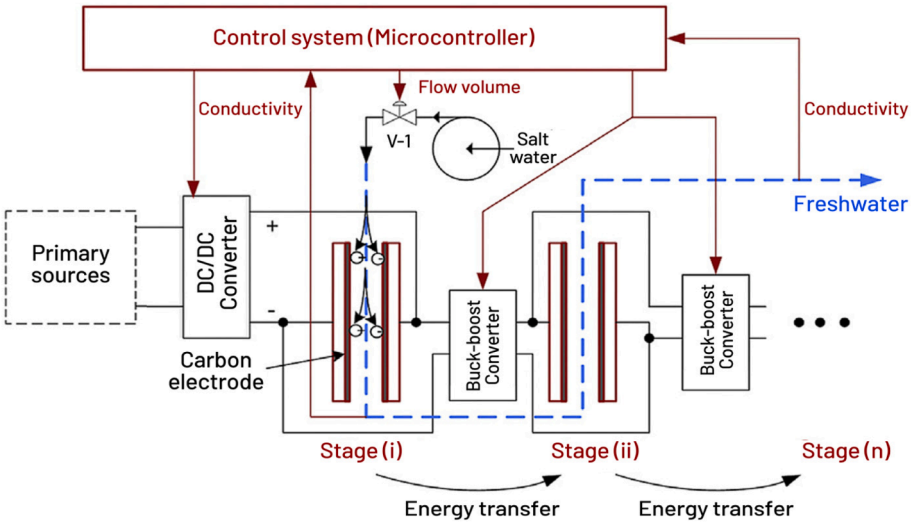



**Fig. 6.** Schematic of a CDI system with energy recovery control using a buck-boost converter (Tang et al., 2019).

storage/generation scales with the flow-electrode slurry volume and increases with higher feed salt concentration, consistent with increased effective capacity and conductivity effects (Lim et al., 2020). Overall, FCDI recovery is often reported in the 20–50% range, reflecting resistive losses, electronic percolation limitations in the slurry, and mixing-related inefficiencies (Al Radi et al., 2021).

### 2.3.4. Recent advances and innovations in energy recovery and generation

*2.3.4.1. Innovations in electrode materials and architectures.* Recent advances in CDI and FCDI increasingly focus on reducing net energy consumption, maximizing recoverable electrical energy, and extending the technology toward selective recovery and energy generation. Progress has been driven by coordinated developments in electrode materials, cell architectures, and system-level operation. Rather than treating desalination and energy recovery as separate goals, modern CDI/FCDI research approaches the system as a reversible electrochemical platform in which ion separation, charge storage, and energy flow are tightly coupled.

Electrodes are central to both ion removal and energy storage, making them the most influential component for improving energy recovery and efficiency. One major innovation is the transition from purely EDL carbon electrodes toward Faradaic and intercalation-based materials. Unlike conventional carbon electrodes that store ions electrostatically, Faradaic electrodes rely on reversible redox reactions, enabling higher ion storage capacity and often lower energy consumption by reducing co-ion expulsion and polarization losses (Jiang et al., 2022; Tauk et al., 2023). iCDI, which uses battery-like intercalation hosts, has demonstrated improved energy efficiency compared with traditional CDI under constant-voltage operation. In addition to energy benefits, intercalation materials allow selective ion uptake, opening new possibilities for targeted resource recovery rather than bulk salt removal (Bao et al., 2023).

Another important direction involves enhancing electrode conductivity and charge transport to reduce resistive energy losses. Graphene and carbon nanotube (CNT) composites have attracted strong interest due to their high electrical conductivity and large accessible surface area. When incorporated into CDI electrodes, graphene reduces electron-transfer resistance and improves charge efficiency, enabling reported energy recovery ratios as high as 83% (Al Radi et al., 2021). In FCDI, adding CNTs to carbon slurries improves electronic percolation within the flow electrode, leading to a 60% increase in energy recovery compared with conventional activated carbon slurries (Chu et al., 2022). These results highlight how improving internal conductivity directly translates into higher fractions of stored energy being recovered during discharge. In this context, carbon foam (CF) has recently been highlighted as a multifunctional porous electrode and three-dimensional current collector with ultra-high porosity (~97%-99%) and tunable hierarchical pore networks (Mourshed et al., 2023; Mourshed et al., 2024). Such structural features can simultaneously enhance electronic conductivity and mass transport, making CF-based architectures particularly attractive for slurry and flow-electrode configurations. A recent review suggests that carbon foam scaffolds can reduce resistive losses and improve operational stability in electrochemical systems, although practical challenges such as mechanical brittleness and energy-intensive fabrication remain important considerations for large-scale deployment (Mourshed et al., 2025).

Sustainability and cost considerations have further motivated the development of bio-based carbon materials. Biochar and other biomass-derived carbons provide low-cost, environmentally friendly alternatives to synthetic carbons. In FCDI systems, fiber-structured biocarbons (FBCs) have proven particularly effective as conductive additives. Their fibrous morphology forms interconnected conductive networks within the slurry, improving electrical conductivity and accelerating salt adsorption. For example, introducing 0.25 wt% carbonized bacterial cellulose into a 5 wt% activated carbon slurry increased the salt adsorption rate from 0.09 to 2.58 mM/($m^2$·s) to 1.26–5.92 mM/($m^2$·s) (Li et al., 2024). Faster adsorption kinetics and lower internal resistance contribute to reduced overpotentials and improved energy recovery.

Alongside material development, novel electrode and cell architectures are being explored to shorten ion and electron transport pathways. Flow-through electrode (FTE) CDI, in which water flows directly through porous electrodes rather than between them, offers improved mass transfer and structural simplicity. Advanced materials such as 3D $TiO_2$-encapsulated carbon nanofibers have shown promising performance in FTE-CDI configurations (Guo et al., 2020). In FCDI, tubular electrode designs arranged in shell-and-tube configurations have been proposed to facilitate scale-up while maintaining high salt removal rates (He et al., 2021). To address the inherently low conductivity of flowing slurries, membrane-assisted static mixers (MASMs) have been introduced to minimize charge transport distances. This approach achieved a salt removal rate of 4.424 μg NaCl $cm^{-2}$ ·$s^{-1}$ with a total energy consumption of 98.95 kJ ·$mol^{-1}$, demonstrating that architectural optimization can substantially lower energy demand (Ehring et al., 2023). Recent studies on dopant-engineered oxide materials further demonstrate that controlled compositional tuning can simultaneously modify microstructure, electrical conductivity, and mechanical stability. These structure property insights are relevant to CDI and FCDI electrode design, where balancing charge-transport efficiency with structural robustness is essential for long-term and energy-efficient operation (Daud et al., 2025).

*2.3.4.2. System-level optimization and advanced operational modes.* Beyond materials and geometry, system-level design and operating strategies strongly influence overall energy recovery and generation in CDI and FCDI. One important advance is the use of multi-cell pair configurations in continuous FCDI. By distributing current across multiple cell pairs, polarization losses are reduced, and flow-electrode utilization is improved. In brine concentration applications, such systems have demonstrated energy demand reductions exceeding 70%, suggesting that optimized FCDI could become competitive with established high-energy technologies such as mechanical vapor compression (Rommerskirchen et al., 2020).

Integration of CDI/FCDI with complementary processes has also emerged as an effective strategy for improving overall energy efficiency. Hybrid systems combine desalination with additional treatment functions, allowing shared electrical infrastructure and synergistic operation. For instance, coupling photoelectrochemical (PEC) oxidation with FCDI enables simultaneous removal of salts and degradation of organic pollutants, achieving an optimized total specific energy consumption of 0.031 kWh·$g^{-1}$ of ion removed (Lim et al., 2022). Such multifunctional systems are particularly attractive for complex wastewaters where desalination alone is insufficient.

A rapidly growing area is selective ion recovery, where energy efficiency is evaluated not only by energy per volume treated, but also by the value of recovered products. In ammonium-rich streams, a $K_2Ti_2O_5$-activated carbon (KTO-AC) flow electrode demonstrated strong selectivity for $NH_4^+$ over $Na^+$, increasing $NH_4^+$ removal from 28.5% to 64.8% and improving desorption efficiency from 35.6% to over 80% (Lin et al., 2020). Similarly, a strategically operated four-chamber FCDI (FC-FCDI) system enabled selective phosphorus recovery as solid vivianite, achieving a P removal rate of 0.22 μmol/($cm^2$·min), a concentration factor of 17.2, and the highest reported selectivity for P over $SO_4^{2-}$ (4.4) in CDI-based systems (He et al., 2022). These studies demonstrate how operational control and system design can transform CDI/FCDI into resource-recovery platforms rather than simple desalination units.

Finally, some advanced FCDI configurations explore energy generation from salinity gradients by operating under capacitive mixing principles. Systems incorporating cylindrical ion-exchange membranes (IEMs) have been proposed to continuously harvest energy from salinity

differences while maintaining flow-electrode operation (Honarparvar et al., 2021). Although still at an early stage, this approach illustrates the broader potential of CDI/FCDI to function as a reversible electrochemical technology capable of both desalination and power generation, depending on operating conditions.

## 3. Factors affecting capacitive and flow electrode capacitive deionization

### 3.1. Cell configuration and working principle

CDI operates based on the EDL adsorption mechanism, in which salt ions from a saline solution are electrostatically adsorbed onto the surface of porous carbon electrodes. When a constant voltage or current is applied across a pair of electrodes, cations migrate toward the negatively charged cathode and anions toward the positively charged anode, forming EDLs that store ions without involving chemical reactions, as depicted in Fig. 7 (a) (AlMarzooqi et al., 2014; Thu Tran et al., 2020). Once the electrodes become saturated, the applied voltage is either reversed or short-circuited to release the stored ions back into the flow channel, generating a concentrated brine stream. This cyclic process of adsorption and desorption enables repeated operation and partial energy recovery during the discharge stage, similar to supercapacitor behavior (Yin and Chen, 2003; Barcelos et al., 2020).

However, conventional CDI faces two primary challenges: (1) Co-ion repulsion, where ions of the same charge as the electrode are expelled into the solution, reducing desalination efficiency, and (2) Faradaic reactions, which can lead to electrode degradation, especially at the anode through oxidation or hydrogen peroxide formation (Kang et al., 2014; Liang et al., 2017; Baroud and Giannelis, 2018; Saleem et al., 2018). These issues result in reduced charge efficiency (CE), lower salt adsorption capacity (SAC), higher energy consumption, and pH fluctuations. To overcome these limitations, MCDI was developed by IEMs on each electrode surface (Zhao et al., 2013; Kim et al., 2016; Tang et al., 2017; Wang et al., 2022).Fig. 7(b)–a CEM covers the cathode, and an AEM covers the anode, effectively blocking co-ion movement and minimizing faradaic side reactions. This configuration significantly enhances CE, stabilizes pH, and improves salt removal efficiency. Despite being more effective, MCDI systems are constrained by the high expense of membranes and the extra resistance brought on by the IEMs' and electrodes' poor adhesion (Długołecki et al., 2013; Liu et al., 2016). Since the electrodes in the majority of setups are flat and fixed, two separate stages of operation, adsorption and desorption, are required (Wu et al., 2020). The structure of multichannel membrane CDI (MC-MCDI) consists of two independently controlled channels: the side channel (SC), which houses the electrodes, and the feed channel (FC), which is used for raw water. Because IEMs separate these channels, different electrolyte types or salinities can be used in each without mixing, increasing desalination performance and flexibility (Kim et al., 2017; Kim et al., 2020a).

In recent developments, hybrid capacitive deionization (HCDI) has emerged as an advanced configuration integrating both capacitive and faradaic processes (Erinmwingbovo et al., 2017). HCDI employs two types of electrodes: a carbon-based EDL electrode and a faradaic (redox-active) electrode capable of ion intercalation or redox reactions, as presented in Fig. 7(c). This hybrid mechanism enhances ion selectivity and increases removal capacity, though the limited amount of active material may restrict overall ion adsorption (Chen et al., 2017a; Divyapriya et al., 2019; Xu et al., 2020).

Another significant advancement is FCDI illustrated in Fig. 7(d), which combines the ideas of electrodialysis (ED) and CDI. Under an electric field, ions move across IEMs in FCDI, but they are subsequently trapped in charged flow electrodes made of carbon particles suspended in a conductive electrolyte (Lin, 2019; Yang et al., 2021). As the device works, activated carbon particles come into intermittent contact with current collectors, pick up charge, and adsorb ions. When the particles exit the contact region, charge neutralization returns the ions to the electrode electrolyte. Constant desalination is made possible by the circulating flow electrode's constant cycling between adsorption (in-cell) and desorption (out-cell) (Presser et al., 2012).

A typical laboratory-scale FCDI unit consists of current collectors, separators, and spacers, which define feedwater and electrode flow paths, as shown in Fig. 4 (Zhang et al., 2020; Mourshed et al., 2022; Mourshed et al., 2023a). Although FCDI shares similarities with

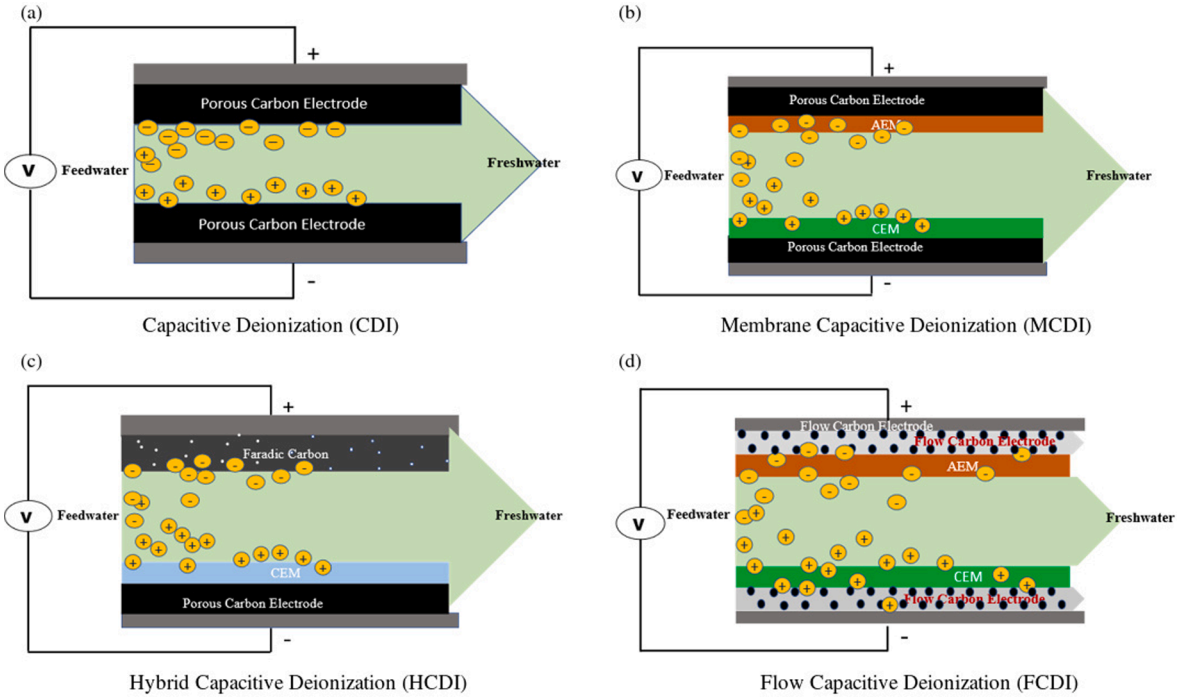



**Fig. 7.** Schematic illustration of CDI-based technology cell configurations: (a) Conventional CDI, (b) Membrane CDI (MCDI), (c) Hybrid CDI (HCDI), and (d) Flow-electrode capacitive deionization (FCDI).

electrodialysis in ion migration across IEMs, the captured ions are stored in flowable electrodes rather than static solids. Studies have revealed that a significant portion of potential drop occurs across the electrodes, consuming over 30% of the total applied voltage, indicating the need for improved electrode and membrane design for energy efficiency (Jeon et al., 2013; Rommerskirchen et al., 2020; Wang et al., 2020).

### 3.2. Material selection and properties

For CDI and FCDI systems, the electrode material selection is crucial since it has a direct impact on long-term stability, charge transfer, and ion adsorption capacity. High specific surface area, good electrical conductivity, and appropriate wettability are desirable characteristics of CDI electrodes because they function similarly to supercapacitor sb (Tu, Liu et al., 2023; Wang et al., 2023). AC, mesoporous carbon, CNTs, and graphene are carbon-based materials that have been thoroughly studied for CDI because of their low cost, chemical stability, and electrical conductivity. Generally speaking, flow electrodes with AC have a solid content of 15%-20%; higher concentrations can improve ion removal but also raise viscosity, which increases the possibility of channel clogging (Park et al., 2016; Yang et al., 2017). Notwithstanding these benefits, weak interparticle conductivity is a common problem with AC electrodes, especially when larger AC particles are used. Despite its high conductivity, carbon black (CB) is unable to effectively fill the spaces between AC granules due to its small particle size (~μm scale) (Parant et al., 2017). The low cost and environmental friendliness of activated carbons made from biomass waste have garnered attention (Rahman et al., 2025; Robin et al., 2025). SAC is normally limited by EDL-based adsorption to 10–15 $mg \cdot g^{-1}$, which is low in comparison to what is anticipated for large-scale desalination (Bharath et al., 2020). Both binder-assisted and binder-free electrode structures, such as carbon cloth, CNT sponges, and 3D graphene meshes, have been researched to improve performance (Huang et al., 2017; Wang et al., 2022; Matsumoto and Fukunishi, 2024).

The doctor-blading method uses common binders like PVDF or PTFE, but free-standing electrodes made of polyaniline or phenol resin have also been developed with moderate SAC (~8.9 $mg \cdot g^{-1}$), but improved conductivity (Barcelos, 2021). The mechanical strength, electrochemical stability, and one-dimensional structure of CNTs allow for electron bridging between AC granules, making them suitable as conductive additives or standalone electrodes (Xie et al., 2020; Gong et al., 2023). For CDI applications, Metal-Organic Framework (MOF)--derived carbons and Layered Double Hydroxides (LDHs) have recently attracted a lot of attention because of their superior charge storage behavior, high porosity, and tunable structures (Pan et al., 2017; Zhang et al., 2018; Wang et al., 2019; Zhang et al., 2019). Similarly, open frameworks for quick ion intercalation and storage of monovalent and multivalent cations, such as $Na^+$, $Mg^{2+}$, $Ca^{2+}$, and $Zn^{2+}$, are offered by prussian blue (PB) and prussian blue analogues (PBAs) (Nie et al., 2014; Hurlbutt et al., 2018; Wheeler et al., 2019). However, heteroatom doping (e.g., N, P, F) can effectively improve conductivity and electro-sorption performance, as pristine MOFs frequently exhibit limited ion diffusion due to their dense framework (Furukawa et al., 2013; Zhang et al., 2022; Gong et al., 2023). Table 4 comparison highlights the fundamental differences between MCDI and FCDI in terms of operation and desalination performance. MCDI systems rely on membrane integration to enhance ion selectivity and improve charge utilization, making them well-suited for the stable treatment of moderately saline water. Their overall efficiency largely depends on effective membrane–electrode coupling and thoughtful structural design. In contrast, FCDI offers greater operational flexibility, particularly for highly saline streams, because the use of flowable electrodes enables continuous desalination and reduces saturation limitations. Overall, system performance is shaped by membrane selectivity, electrode material properties, and overall configuration, with FCDI showing stronger potential for scalable treatment of concentrated solutions.

### 3.3. Membrane

In MCDI and FCDI systems, ion-exchange membranes are essential because they selectively allow counterions to pass through while obstructing co-ions when an electric field is applied. Several desalination and concentration compartments are created in an ED setup by sandwiching alternating CEMs and AEMs between the anode and cathode (Galama, 2015).

The membranes listed Table 5 represent recent developments in AEM and CEM materials tailored for MCDI applications:

Membranes with moderate to high IEC (1-3 $meq \cdot g^{-1}$) and low area resistance (<5 $\Omega\,cm^2$) are generally needed for optimal CDI/FCDI performance in order to maximize charge efficiency. The combination of mechanical robustness, ionic conductivity, and stable desalination efficiency makes PVDF-g-VBC and PE-CPS membranes unique among existing materials (Ding et al., 2025).

Based on the tabulated data from Table 5 and the preceding discussion, it can be inferred that the variations in ion-exchange capacity (IEC), area resistance, and water uptake between AEMs and CEMs primarily arise from differences in polymer backbone architecture, functional group concentration, membrane thickness, and degree of crosslinking. These structural parameters collectively govern ion transport kinetics, hydration behavior, and mechanical robustness. For optimal CDI/FCDI performance, enhancing a single property is insufficient; instead, a well-balanced integration of electrochemical and structural characteristics is required. In this regard, membranes exhibiting moderate-to-high IEC values (1-3 $meq \cdot g^{-1}$), low area resistance

**Table 4**
Comparison table for materials properties.

| Technology | Initial conc. (mg/L) | Electrode composition | Flow rate (mL/min) | Voltage (V) | SRE (%) | SAC/cSAC (mg/g) | Refs |
|---|---|---|---|---|---|---|---|
| **MCr-MCDI** | 585 (10 mM NaCl) | AC electrodes + IEM | 20 | +1.2/-1.2 | 96% | cSAC: 49 | Kim et al. (2021) |
| **MCDI** | 2000 | AC + novel liquid distributor | - | - | - | SAC: 23.8 | Ma and Wang (2021) |
| **FCDI** | Various | AC slurry flow electrode | Various | 1.0-2.0 | - | - | Zhang et al. (2021) |
| **FCDI** | Various | Flow electrode mechanisms | Various | - | - | - | Yang et al. (2021) |
| **FCDI** | 27-40 g/L NaCl | AC flow electrodes | - | Over limiting | - | High SRR | Tang and Zhou (2020) |
| **FCDI** | 1-5 g/L | AC-based with MF integration | - | - | - | - | Zhang et al. (2019) |
| **MCDI** | Various | HT-MT integrated membrane electrodes | - | - | 90.5% CE | SAC: 15.8 | Wu et al. (2021) |
| **FCDI** | Various | AC/Carbon Black comparison (~70 vs ~2000 $m^2/g$) | - | - | - | CB outperformed AC | Ma et al. (2020) |

**Table 5**
Summary of ion-exchange membrane properties developed for MCDI.

| Type | Membrane Designation | Thickness (μm) | IEC (mequiv $g^{-1}$) | $R_a$ (Ω $cm^2$) | WU (%) | Refs |
|---|---|---|---|---|---|---|
| AEM | QPPO | 62-70 | 1.3-2.6 | 1.0-9.0 | 10-90 | Chang et al. (2018) |
| AEM | QPVA | - | 1.2-2.8 | - | 7-31 | Tian et al. (2014) |
| AEM | VBC-EMA-St | - | 0.9-1.7 | 1.6-8.8 | 23-68 | Chang et al. (2018) |
| AEM | PE-CMS | 29 | 3.0 | 0.3 | 5 | ul Haq et al. (2018) |
| AEM | PVDF-g-VBC | - | 0.4-1.3 | 2.0-15 | 12-56 | Jeong et al. (2015) |
| CEM | sPEEK | 100 | 2.0-2.3 | 0.5-0.9 | 28-47 | Cha et al. (2018); ul Haq et al. (2018) |
| CEM | VBC-EMA-St | - | 0.5-1.0 | 0.6-2.8 | 76-121 | Koo et al. (2012) |
| CEM | PE-CSPS | 25 | 0.7-1.0 | 0.3-0.6 | 26-36 | Qiu et al. (2017) |
| CEM | sPBC | - | 1.0-2.0 | - | 40-200 | Jain et al. (2019) |
| CEM | PVDF-g-PSVBS | - | 0.1-1.1 | 2-60 | 7-61 | Kang et al. (2015) |

($<5\ \Omega\ cm^2$), and controlled water uptake are generally more favorable, as they ensure efficient ionic conductivity while maintaining the mechanical integrity necessary for long-term operational stability.

### *3.4. Flow channel geometry: Rheological properties of flow electrodes and their impact on performance*

In FCDI systems, the geometry of the flow channel plays a decisive role in regulating slurry distribution, ion transport pathways, current distribution, and overall desalination efficiency. Unlike conventional CDI architectures, FCDI relies on the continuous circulation of carbon slurry electrodes; therefore, hydrodynamic uniformity and effective electrical contact along the channel length are critical design considerations. Serpentine flow channel configurations are widely adopted because they promote extended residence time, improve mixing, and ensure more homogeneous utilization of the flowable electrodes. By guiding the slurry through a continuous, curved pathway, serpentine designs mitigate dead zones and reduce bypass flow, thereby enhancing charge transfer and salt removal efficiency (Gendel et al., 2014; Zhang et al., 2020). Several geometric variations have been reported, including cut-through, single-sided, and double-sided channel architectures. Cut-through channels allow full-depth penetration of the flow path, reducing flow resistance and facilitating better slurry renewal. Single-sided designs confine the channel to one face of the collector, whereas double-sided geometries enable symmetric flow distribution and improved current uniformity across the cell thickness. These geometric modifications directly influence pressure drop, shear rate, particle dispersion, and effective electroactive area, all of which govern ion adsorption dynamics and energy efficiency (Yang et al., 2016; Zhang et al., 2018). To further optimize channel performance while simplifying fabrication, the author introduced a laser-engraved serpentine microchannel configuration laminated onto a supporting substrate. This geometric approach reduced fabrication complexity while maintaining uniform slurry flow and effective electrical connectivity. The serpentine microchannels enhanced interparticle contact and ensured stable desalination performance even at relatively high carbon loadings (~10wt%), demonstrating that appropriate channel geometry can preserve electrochemical efficiency without compromising operational stability (Ma et al., 2018). A detailed investigation of geometric effects was conducted by H. M. Saif et al. (2024), who evaluated open, horizontal serpentine, and vertical serpentine channels using combined experimental methods and CFD simulations (Saif et al., 2024). The horizontal serpentine configuration demonstrated superior desalination performance and operational stability. Its short, winding paths generated frequent bends, increasing local shear rates. Since carbon slurry exhibits shear-thinning behavior, elevated shear reduces apparent viscosity, improves particle dispersion, and enhances electrical connectivity, resulting in more uniform ion transport and current distribution.

In contrast, the vertical serpentine channel, characterized by longer straight segments and fewer directional changes, produced extended low-shear regions. These zones encouraged particle agglomeration and localized clogging, leading to unstable flow conditions. The open channel configuration avoided severe blockage but suffered from uneven mixing and non-uniform current density, which ultimately reduced desalination efficiency. CFD analysis confirmed that channel curvature and flow-path complexity significantly influence viscosity gradients and shear distribution within the slurry, thereby directly impacting electrochemical performance (Saif et al., 2024). Recent geometric innovations further emphasize fabrication-efficient channel designs. For example, laser-engraved serpentine microchannels integrated onto supporting substrates have been introduced to maintain uniform flow while simplifying manufacturing processes. These microstructured pathways preserved effective slurry connectivity and stable desalination performance even at relatively high carbon loadings (~10wt%). The rheological behavior of carbon slurry electrodes is central to FCDI performance. At typical carbon loadings of 5wt%–20wt%, these suspensions display non-Newtonian, shear-thinning characteristics with a finite yield stress, behaving as colloidal gels. This shear-thinning property is advantageous in serpentine or interdigitated channels, where higher shear rates (induced by channel curvature or increased flow velocity) lower apparent viscosity, promote particle dispersion, and strengthen interparticle electrical contacts (Das et al., 2024; Said et al., 2022).

However, rheological challenges significantly affect scalability. Particle sedimentation occurs in low-shear or stagnant regions, leading to phase separation, uneven carbon distribution, increased internal resistance, and reduced effective electrode utilization. Sedimentation is especially pronounced in vertical or long straight channels and at higher carbon loadings, where gravitational settling competes with flow-driven mixing. Recent CFD modeling and in-situ studies show that dynamic bed formation can locally enhance charge transport in controlled cases, but uncontrolled sedimentation often causes channel clogging and performance decay (Hipp, 2020; Said et al., 2022). Carbon loading presents a critical trade-off: higher loadings (15wt%–20wt%) improve electronic conductivity and salt adsorption capacity through better percolation networks, yet they sharply increase viscosity and yield stress, raising pumping energy demands and the risk of agglomeration. Particle size distribution further modulates these effects-bimodal distributions can balance high surface area for ion adsorption with adequate transport channels. Additives such as non-ionic surfactants can mitigate viscosity issues by disrupting gel networks, although excessive dosing may eliminate yield stress and compromise electronic percolation (Das et al., 2024; Said et al., 2022).

Overall, rheological optimization through tailored channel geometry, carbon type, loading, particle size distribution, and additives-is essential for balancing mass transfer, energy efficiency, and long-term operational stability in FCDI systems. Recent geometric innovations, such as Archimedean spiral channels, further demonstrate the potential of advanced flow-field designs to achieve more uniform velocity fields and extended residence times while addressing non-Newtonian flow challenges (Zhang et al., 2022).

## 4. Applications

### 4.1. Water purification

Water scarcity has become one of the most pressing global challenges today. More than one-third of the world's population already lives in regions experiencing water stress, and this number is expected to rise to nearly two-thirds by 2025 (Elimelech and Phillip, 2011). Limited access to safe drinking water and proper sanitation remains a widespread problem affecting millions of people worldwide. Projections suggest that water shortages will continue to intensify in the coming decades, even in regions traditionally considered water-abundant. Addressing this challenge requires the development of new water treatment technologies that are reliable, energy-efficient, cost-effective, and environmentally sustainable, while also minimizing chemical usage (Shannon et al., 2008).CDI removes dissolved ions from saline water by applying a voltage typically between 1 and 1.6 V across two porous electrodes. Under this electric field, ions migrate toward oppositely charged electrodes and are stored through electro-adsorption (Robin et al., 2025; Shajid et al., 2025). The performance of the system strongly depends on the selection of electrode materials, as suitable materials can significantly enhance the electro-sorption capacity of the electrodes. The development of FCDI has further expanded the potential of CDI by enabling selective ion removal. This ion selectivity opens opportunities for various specialized applications beyond conventional desalination (Tauk et al., 2024). Recent research has examined three different FCDI operational modes: single-cycle with separate concentrate chamber (SCSC), isolated closed-cycle (ICC), and short-circuited closed-cycle (SCC). Among these configurations, the SCC mode has shown the best performance, achieving higher desalination efficiency, improved current efficiency, and lower specific energy consumption across different operating voltages (Saif et al., 2025).

CDI systems are capable of removing a wide range of contaminants, including dissolved salts, chloride ions, and heavy metals. In addition to desalination, CDI has also demonstrated potential for resource recovery. For example, solar-powered CDI systems have been used to extract rare earth elements (REEs) from geothermal brines while simultaneously removing common ions, highlighting the technology's dual capability for water purification and valuable material recovery (Bist et al., 2024). CDI can also remove organic pollutants, although the efficiency depends on factors such as molecular size, charge, and membrane characteristics. Recent studies have explored advanced membrane designs, including duplex-coated porous membranes made from materials such as polyether sulfone, polyamide, and modified polyacrylonitrile, to better understand and model the electro-adsorption and electro-desorption behavior of natural organic matter (Mantel et al., 2021; Usman et al., 2024).

Further improvements in electrode materials and system design have continued to enhance the desalination performance of CDI technologies. In particular, Faradaic electrode materials have demonstrated higher ion adsorption capacities compared with traditional activated carbon electrodes (Pang et al., 2024). For instance, FCDI systems employing nickel-foam-coated carbon electrodes have achieved salt removal efficiencies as high as 99.9% during real seawater desalination experiments (Zhang et al., 2022). These developments underscore the growing role of CDI and FCDI in sustainable water recovery and purification applications.

Fig. 8 illustrates the progressive improvement in salt removal efficiency of CDI and FCDI systems from 2018 to 2025. A clear upward trend is observed over the years, indicating continuous advancements in desalination performance. Notably, the highest efficiency is achieved in 2025, approaching nearly 100% salt removal (Yekun et al., 2025). This substantial enhancement reflects the significant progress made in electrode materials, system configuration, ion selectivity, and energy optimization. The near-complete desalination efficiency reported in recent studies represents a major milestone in the development of CDI technologies and highlights their growing potential as a competitive and sustainable alternative for advanced water desalination applications.

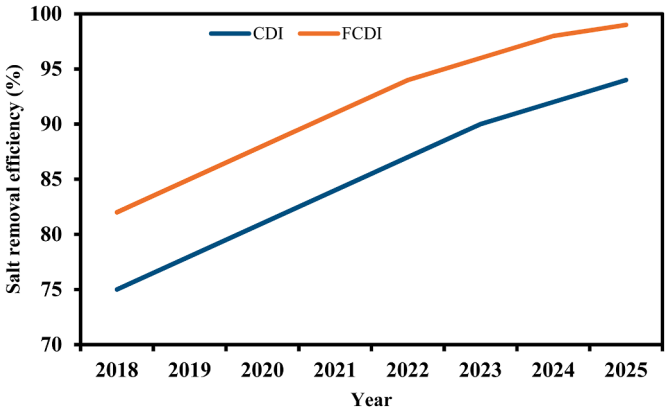



**Fig. 8.** Year-by-year evolution of salt removal efficiency in CDI and FCDI-based studies (2018–2025).

### 4.2. Nutrient recovery

The removal and recovery of nitrogen (N) and phosphorus (P) from wastewater are essential for preventing eutrophication and supporting sustainable water management (Rahman et al., 2025; Shajid et al., 2025). Excessive discharge of these nutrients into natural water bodies can lead to algal blooms and ecological imbalance. Among the emerging technologies for nutrient removal, FCDI has gained considerable attention as an electro-sorption technique capable of extracting and recovering charged species from wastewater streams (Song et al., 2025). In practical desalination environments such as brackish or seawater, the solution typically contains a complex mixture of ions. Common cations include $Na^+$, $K^+$, $Ca^{2+}$, and $Mg^{2+}$, while anions may include $Cl^-$, $F^-$, $NO_3^-$, $SO_4^{2-}$, and $CO_3^{2-}$ (Shajid et al., 2025). The coexistence and competition of these ions can significantly influence the desalination performance and ion-removal efficiency of electrochemical systems. Consequently, the selectivity of the process plays a critical role in determining the quality of the treated effluent. In addition to these common ions, wastewater may also contain hazardous heavy metals such as Cr, Cu, As, Pb, and Cd, which must be selectively removed to meet environmental discharge standards. Previous investigations into ion selectivity in CDI systems have shown that several factors govern the preferential adsorption of cations, including their valence, hydrated ionic radius, and initial molar concentration. Ions with higher charge and smaller hydrated radii generally exhibit stronger electrostatic interactions with the electrode surface and can more easily enter the microporous structure of the electrodes (Pang et al., 2024). These characteristics enable efficient separation of different ionic species during the desalination process.

FCDI provides an effective way to simultaneously remove salts and recover nutrient ions from wastewater by concentrating them in the flow-electrode slurry. Unlike conventional biological nutrient removal processes, this electrochemical approach takes advantage of the ionic nature of species such as $NH_4^+$-N, $NO_3^-$-N, and $PO_4^{3-}$-P, enabling simultaneous desalination and nutrient recovery. Experimental results indicate that when the electrode loading ranges from 5wt% to 15wt%, a separated flow-electrode configuration (FCDI-S) can achieve salinity removal of 70%–98.5%, phosphate removal of 49%–91%, ammonium removal of 89%–99%, and nitrate removal of 83%–99%. Furthermore, more than 80% of the captured nutrient ions can be recovered in the concentrate stream during the discharge stage by applying a reverse potential (Bian et al., 2019).

Performance improvements have also been observed when a connected flow-electrode configuration (FCDI-C) is used. In this

arrangement, external mixing of the flow electrodes provides additional adsorption sites, enhancing the overall removal efficiency. As a result, phosphate removal increased by approximately 43.5% ± 2.2%, while ammonium and nitrate removal improved by 12.3% ± 1.1% and 9.9 % ± 0.3%, respectively. These findings demonstrate that FCDI represents a promising alternative approach for nutrient recovery, particularly for decentralized or remote wastewater treatment applications (Bian et al., 2019), as illustrated in Fig. 9.

Further treatment steps can also be integrated with FCDI to improve nutrient recovery. For example, membrane CDI can be used to further reduce ammonia concentrations in the effluent while concentrating excess ammonia into a smaller stream. In addition, bipolar membrane electrodialysis can be applied to alkalize the wastewater, facilitating the precipitation of struvite and enabling phosphorus recovery. Studies have shown that this integrated electrochemical treatment process can recover nearly 81% of wastewater as high-quality effluent suitable for discharge or reuse, while removing approximately 89% of phosphorus and 77% of ammonia. Compared with other electrochemical nutrient-recovery techniques, this treatment strategy requires lower chemical input and consumes less energy, making it a more sustainable option for wastewater management.

### 4.3. Energy management and energy generation

Energy management and recovery are critical factors in evaluating the practical feasibility of FCDI and CDI systems. An investigation comparing isolated closed-cycle (ICC) and short-circuited closed-cycle (SCC) modes demonstrated that approximately 20% of the input energy could be recovered during the constant current discharge process (Jeon et al., 2014). Similarly, a systematic study examining the influence of flow-electrode slurry volume, feed concentration, and discharge rate reported that, at a maximum discharge current of 50 mA, nearly 25% of the energy consumed during desalination could be recovered (Lim et al., 2020). These findings highlight the growing potential of CDI-based systems not only for desalination but also for partial energy recuperation.

Energy consumption and efficiency remain fundamental performance indicators in CDI systems. Several parameters influence overall energy demand, including cell architecture, operating mode of the external power supply, and parasitic or faradaic reactions occurring within the electrodes (Pang et al., 2024). Optimization of cell configuration has been shown to reduce energy losses and improve charge efficiency. In particular, the integration of IEMs onto electrode surfaces can suppress co-ion repulsion during charging and discharging, thereby enhancing energy efficiency (Biesheuvel, 2016). From an economic perspective, material costs especially those associated with electrodes and ion-exchange membranes constitute the dominant portion of the overall CDI system cost. A comparative analysis of the levelized cost of water (LCOW) among CDI, membrane CDI (MCDI), and FCDI architectures relative to reverse osmosis (RO) for brackish water desalination indicates that CDI technologies remain less cost-competitive at feed concentrations exceeding 2 $g{\cdot}L^{-1}$ unless significant improvements are achieved in electrode durability, cost reduction, and operational efficiency (Liu et al., 2020). Operational conditions also strongly affect energy recovery performance. The energy recovery ratio increases with higher applied voltage and feed salinity, while shorter cycle times further enhance recovery efficiency. Although system size does not significantly alter the energy recovery ratio, larger-scale configurations may improve thermodynamic efficiency (Choi et al., 2019). Overall, CDI energy consumption is governed by multiple interrelated factors, including electric field mode, electrode material properties, electrode condition, and cell design. These mechanisms collectively determine system-level energy performance (Jiang et al., 2022).

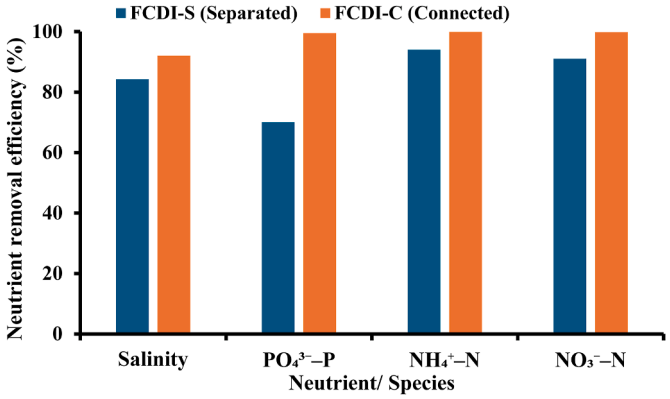



**Fig. 9.** Comparison of nutrient removal efficiency between FCDI-S and FCDI-C.

Comparative studies indicate that although the CC mode may exhibit slightly lower desalination capacity, it generally achieves superior energy efficiency compared to the CV mode (Choi et al., 2020). Electric field intensity plays a pivotal role in CDI operation. Increasing the applied voltage typically enhances salt removal capacity; however, this improvement is accompanied by increased energy consumption. From a thermodynamic standpoint, a trade-off exists between desalination efficiency and energy utilization, necessitating careful optimization of operating conditions (Wang et al., 2019).

## 5. Limitations

The performance of FCDI and CDI systems is strongly affected by several operational and structural factors. These include the particle size distribution of the carbon electrodes, the salt concentration present in the flow electrodes, the slurry flow rate, internal electrical resistance, and the geometry of the flow channels, as illustrated in Fig. 10. These parameters collectively influence ion transport behavior, charge efficiency, desalination capacity, and overall system performance. In addition, electrode stability remains a major challenge for long-term operation and commercial scalability. Repeated adsorption/desorption cycles can induce surface oxidation, corrosion, mechanical stress, and fouling, which progressively deteriorate electrode properties and reduce salt adsorption capacity and charge efficiency (Ming and Wenqing, 2024). The influence of these factors on system performance is discussed in the following sections.

### 5.1. Particle size distribution

In FCDI and CDI systems, ion transport within carbon pores is strongly influenced by the pore size relative to the ion hydration diameter. When the pore size approaches or falls below the hydrated ion diameter (<1 nm), phenomena such as ion dehydration and water–-water interactions, often neglected in classical electric double layer (EDL) theory, become significant. This can lead to anti-selectivity for divalent ions, primarily due to a sieving effect that hinders their access to micropores. The characteristics of conductive additives, including particle size, shape, conductivity, and porosity, also play a critical role in determining flow electrode performance (Wang et al., 2018). Proper management of these additives is essential: while they enhance slurry conductivity and reduce viscosity, excessive loading can lead to particle aggregation and potential cell blockage, which in turn limits ion transport and overall desalination efficiency (Park et al., 2016).

The electrochemical performance of CDI arrangements is strongly influenced by the PSD of the electrode's substrate. Larger specific surface area and improved ion adsorption capacity are provided by smaller particles; nevertheless, excessive decrease in PSD results in denser distribution, greater electrical resistance, and impeded ion transit. Larger PSD, on the other hand, have a lower salt adsorption capability because of their limited surface accessibility, which hinders ion movement due to decreased diffusion resistance. According to experimental research, salt

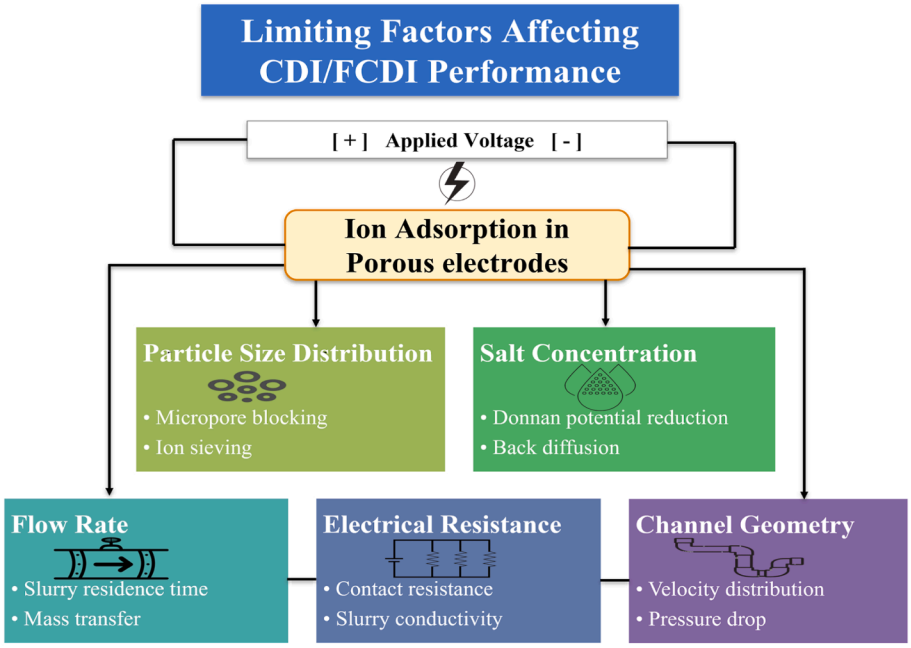



**Fig. 10.** Schematic representation of key limitations affecting CDI and FCDI systems.

adsorption ability can be decreased by around 20%–40% when PSD is increased from ~10 μm to ~100 μm. Higher salt adsorption capacity (~12–15 mg/g) and better charge efficiency (~35%–40%) result from a bimodal PSD, whereas tiny particles increase surface area but bigger particles preserve transport channels (Han et al., 2014; Jia and Zhang, 2016; Zhang et al., 2022; Käärik et al., 2023). Hierarchical porous architectures that combine micro-, meso-, and macropores, such as those in nitrogen-doped carbon nanofiber membranes, help mitigate these trade-offs by providing abundant active sites while maintaining efficient ion transport pathways and accommodating volume changes during cycling. This design contributes to superior long-term stability and high ion removal performance even for challenging contaminants like fluoride (Ming et al., 2025).

Furthermore, the electrostatic interactions within appropriately sized carbon pores influence ion selectivity, highlighting that pore architecture must be carefully tailored to balance ion accessibility with effective charge storage. Poorly optimized particle size distribution can therefore become a key limiting factor in FCDI performance.

### 5.2. Salt concentration

The salt concentration within the electrode chamber is another critical factor affecting FCDI efficiency. Higher local salt content can reduce the driving potential for ion transport by diminishing the Donnan potential across ion-exchange membranes, while also promoting back-diffusion of ions, which lowers charge efficiency and weakens desalination performance (Ma et al., 2019). Maintaining a stable salt concentration in the flow electrodes is therefore essential for continuous operation. Strategies such as using microfiltration membranes to remove concentrated water from the electrodes help to stabilize the electrode salt content over extended operation, mitigating the negative effects of concentration buildup (Zhang et al., 2020).

According to experimental investigations, the salt adsorption capacity (SAC) rises as the overall concentration of NaCl rises from 50 mg/L to around 500 mg/L, attaining its highest level of roughly 5.6 mg/g before declining due to electrode saturation and co-ion impacts. Because of increased co-ion attraction and inefficient ion desorption, charge efficiency usually falls with rising salt content, ranging from 50% to 80%. When ion accessibility and transportation impedance are balanced, optimum CDI efficacy is often seen in a concentration that falls between 5 and 50 mM (~300–3000 mg/L). Although greater absolute adsorption, removal efficiency decreases at greater salinity (>1000 mg/L) due to decreased ion specificity and electrical double-layer overlap (Mossad and Zou, 2013; Jia and Zhang, 2016; Quan et al., 2017; Salari et al., 2022).

In essence, both particle size distribution and salt concentration in flow electrodes represent intrinsic limitations to FCDI performance. Improper control of these parameters can compromise ion transport, selectivity, and charge efficiency, emphasizing the need for optimized electrode formulation and flow management in practical systems.

### 5.3. Flow rate

In conventional CDI, it is feasible to treat low-salinity solutions such as brackish water, making the technology potentially suitable for industrial applications (Wang et al., 2013). However, low feedwater ion concentrations create challenging conditions for capacitive electrodes, as reduced ionic availability limits the rate of charge storage and desalination efficiency (Xu et al., 2016). In FCDI, the continuous inflow of fresh carbon slurry mitigates some of these constraints. Specifically, the Stern potential, defined as the voltage drop across the compact layer at the electrode–electrolyte interface, decreases within the micropores under low-concentration conditions. Similarly, the Donnan potential shown in Fig. 11, representing the potential difference between the microporous carbon phase and the macroporous transport channels, becomes comparatively insignificant relative to other voltage contributions, such as the potential drop across the spacer channel and losses due to series resistance.

Because FCDI continuously supplies fresh slurry electrodes into the cell, the impact of these potential drops in ion adsorption is reduced, resulting in lower energy consumption compared to fixed-electrode MCDI systems. Additionally, the dynamic flow allows for partial energy recovery, up to approximately 30% more energy can be extracted from the charged electrodes before they mix for regeneration, further reducing the overall electrical energy usage of the system (Xu et al., 2016). Nevertheless, the effective flow rate of the slurry remains a limiting factor, as insufficient flow reduces residence time, mass

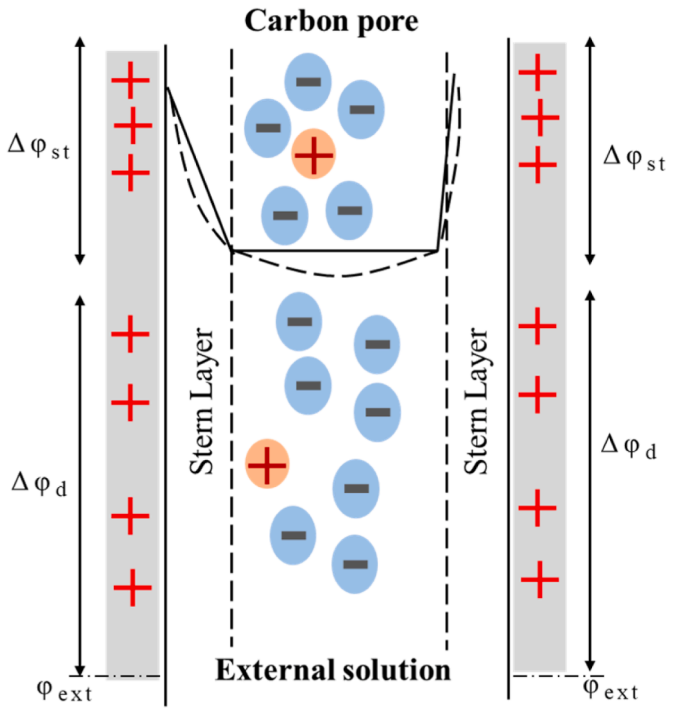



**Fig. 11.** Modified Donnan Model diagram (Ma et al., 2020).

transport, and ultimately desalination performance, highlighting the importance of optimized flow channel design for continuous FCDI operation.

### 5.4. Electrical conductivity

In MC-MCDI systems, electrode stacking significantly amplifies internal resistance, imposing a practical limit on electrical scalability. As the number of electrode pairs increases, the internal voltage drop rises disproportionately. For instance, expanding from one electrode pair (≈0.2 V) to four pairs (≈0.6 V) results in nearly a threefold increase in voltage loss, indicating substantial resistive accumulation within the stacked architecture.

This increased voltage drop arises from combined electronic resistance in current collectors, interfacial contact resistance between stacked components, and ionic resistance across multiple membranes and spacer layers. As stacking progresses, the current distribution becomes increasingly non-uniform, leading to polarization losses and inefficient voltage utilization. Consequently, a larger fraction of the applied potential is dissipated as ohmic loss rather than contributing to ion adsorption.

Slurry conductivity in FCDI systems usually falls between 0.1 and 1 mS/cm, which severely restricts charge transfer and desalination efficiency. It has been demonstrated that improving conductivity may reduce the consumption of energy and increase the rate of salt absorption by up to five times. According to conductivity and systems setup, experimental investigations estimate salt adsorption capacities that vary from 0.9 to 22 mg/g and charging efficiency within 38% and 99%. Additionally, when ions are eliminated during CDI functioning, conductance drops until it reaches equilibrium, at which point no additional adsorption takes place. The findings show that there is an ideal resistivity range where distillation efficacy has been enhanced while ion transportation is increased without severe co-ion impacts (Chen et al., 2018; Salari et al., 2022; Ma et al., 2024; Tirabadi et al., 2025). Comparatively, while conventional CDI is mainly limited by electrode and spacer resistance, MCDI introduces additional membrane-related ionic resistance. FCDI systems face even greater electrical challenges due to slurry conductivity limitations and dynamic interparticle contact resistance. Therefore, internal resistance accumulation remains a key bottleneck restricting large-scale implementation of stacked CDI and FCDI systems. Additionally, the electrode stacking would be hampered by all of the systemic flaws and resistance rise (Kim et al., 2020).

### 5.5. Channel geometry

A major challenge in the scale-up of Multi-Cell Membrane CDI (MC-MCDI) systems lies in the structural complexity introduced by stacking multiple unit cells (Kim et al., 2020b; Kim et al., 2020a). In instance, the pH variation was minimal regardless of the number of carbon pairs suggesting a limited number of side reactions including carbon oxidation and hydrogen peroxide generation (Shapira et al., 2016; Yu et al., 2018). However, MC-MCDI offers superior electrochemical stability; the inclusion of dual ion-exchange membranes suppresses the transport of dissolved oxygen to the electrode surface (Tang et al., 2017; Kim et al., 2018). It should be mentioned that a significant contributing reason to pH fluctuations and low charge efficiency is the generation of hydrogen peroxide through an oxygen reduction process on the carbon electrode (Kim et al., 2016).

In FCDI systems, the challenges are even more pronounced due to the presence of flowable carbon slurry electrodes. Although FCDI enables theoretically continuous adsorption, long-term operation leads to progressive ion enrichment within the circulating slurry. Over-extended operation, the concentration of accumulated ions in the flow electrode can exceed the feed concentration by several orders of magnitude. This creates a substantial concentration gradient at the membrane–slurry interface, which suppresses further ion migration and reduces desalination efficiency. Maintaining stable hydrodynamics and ion transport under such conditions remains a key limitation for large-scale continuous systems (He et al., 2016).

Stack-based FCDI configurations have been proposed as a potential solution for increasing throughput. For example, membrane-stacked arrangements demonstrated improved treatment capacity when two ion-exchange membrane pairs were employed. However, further increases in membrane number resulted in decreased current efficiency, indicating that scaling through stacking introduces transport and electrical losses that must be carefully optimized (Ma et al., 2020). Tubular flow channel designs have also been explored to enhance membrane utilization and reduce fouling susceptibility, particularly for high-turbidity feed water. A four-unit tubular FCDI array demonstrated promising desalination rates (0.15 $mg \cdot s^{-1}$), confirming the feasibility of modular scaling. Nevertheless, the tubular configuration suffers from inherently low flow rates, which limit slurry circulation and mass transport. This hydrodynamic constraint directly impacts ion removal performance and highlights the need for improved internal channel design (He et al., 2021a).

To address flow limitations, Zhang et al. (Zhang et al., 2022) proposed an alternative channel geometry, such as the Archimedean spiral configuration, has been proposed. Computational fluid dynamics (CFD) analyses comparing spiral and conventional serpentine channels revealed that spiral designs provide more uniform velocity fields and extended slurry residence times. Experimentally, the spiral-based FCDI system achieved significantly higher salt removal rate and energy-related performance compared to the serpentine configuration. Despite these improvements, trade-offs between enhanced residence time, pressure drop, structural complexity, and scalability remain unresolved. Overall, while advanced channel geometries and stacking strategies improve hydrodynamic behavior and desalination capacity, challenges related to flow uniformity, concentration polarization, pressure loss, and electrical efficiency continue to constrain large-scale implementation. Future research should prioritize optimized channel architecture that balances mass transfer enhancement with practical manufacturability and operational stability.

### 5.6. Rheological challenges and Non-Newtonian behavior of slurry electrodes

A core challenge in scaling FCDI lies in the complex rheological properties of the flowable carbon slurries. These suspensions display non-Newtonian, shear-thinning behavior with a finite yield stress, making their flow behavior highly dependent on shear rate, carbon loading, particle morphology, and channel geometry. While shear-thinning facilitates pumping and improves interparticle contacts under flow, low-shear regions (e.g., in dead zones or during intermittent operation) promote particle sedimentation, leading to carbon bed formation, increased local resistance, and reduced effective electrode utilization (Hawks, 2025, Shubham Kumar et al., 2026).

At carbon loadings above ~10wt%–15wt%, viscosity rises sharply, elevating pumping energy costs and the likelihood of channel blockage. Conversely, lower loadings compromise electronic conductivity due to insufficient percolation. Non-Newtonian effects also influence mass transfer: shear-thinning can enhance slurry renewal near membranes, but concentration polarization and back-diffusion of ions become more pronounced when rheological instability causes uneven flow (Saif et al., 2024; Said et al., 2022).

Mitigation strategies include optimized flow-field designs (serpentine or spiral channels), surface-modified carbons, and carefully selected dispersants. However, long-term stability remains difficult, as repeated pumping can alter particle size distribution through attrition, further degrading rheological and electrochemical performance. Addressing these rheological limitations through integrated experimental–modeling approaches (e.g., coupling rheology with CFD and EIS) is critical for advancing FCDI toward practical, continuous, large-scale deployment (Hawks, 2025).

## 6. Conclusions

CDI has emerged as attractive electrochemical technologies for sustainable desalination, water purification, selective ion separation, and resource recovery. This review has highlighted the substantial progress achieved in understanding desalination mechanisms, developing advanced system architectures, and engineering high-performance electrode materials. In particular, carbon-based materials remain the foundation of these technologies due to their tunable pore structures, high surface area, favorable conductivity, chemical stability, and cost-effectiveness. Advances in activated carbon, carbon nanotubes, graphene derivatives, hierarchical porous carbons, and carbon-based composites have significantly enhanced ion adsorption behavior, charge efficiency, transport kinetics, and long-term operational stability. Simultaneously, the transition from conventional CDI to MCDI, i-CDI, hybrid CDI, desalination batteries, and FCDI has expanded the operational capabilities of electrochemical desalination systems while addressing several limitations associated with traditional fixed-electrode configurations.

Among these developments, FCDI represents a particularly important advancement because it overcomes electrode saturation through continuously regenerated flow-electrode slurries. This enables continuous operation, improved water recovery, and treatment of higher-salinity feed streams that are often beyond the practical range of conventional CDI systems. However, the progress achieved at the laboratory scale has not yet translated into widespread commercial implementation. While remarkable desalination performances have been reported, many studies continue to focus on maximizing adsorption capacity under controlled conditions rather than addressing long-term reliability, process economics, and operational robustness. Consequently, a significant gap remains between laboratory demonstrations and practical deployment.

Several critical challenges must be addressed before CDI and FCDI can achieve large-scale adoption. In CDI systems, co-ion expulsion, parasitic Faradaic reactions, electrode degradation, membrane fouling, and limited ion selectivity continue to affect overall efficiency and stability. In FCDI systems, slurry conductivity, particle aggregation, rheological behavior, pumping-energy requirements, and membrane durability remain key engineering constraints. Equally important is the lack of standardized testing and reporting methodologies. The wide variation in operating conditions, feed-water compositions, and performance metrics across the literature often makes direct comparison difficult and can obscure the true technological readiness of emerging materials and system designs.

Future progress will depend not only on developing materials with higher adsorption capacities but also on achieving a better balance among performance, durability, scalability, and economic feasibility. Rational design of carbon-based electrodes with hierarchical pore architectures, tailored surface functionalities, and enhanced ion selectivity will remain a major research focus. At the same time, advances in low-resistance and fouling-resistant membranes, optimized flow-electrode formulations, and energy-efficient reactor designs will be essential for improving practical system performance. Greater emphasis should also be placed on pilot-scale demonstrations, long-term stability assessments, techno-economic analyses, and lifecycle evaluations to establish realistic commercialization pathways.

Looking ahead, the future of CDI and FCDI is expected to extend well beyond conventional desalination. Increasing interest in the selective recovery of lithium, ammonium, phosphate, nitrate, and other valuable ions is transforming these technologies from simple desalination systems into multifunctional electrochemical separation platforms. Furthermore, integration with renewable-energy systems, hybrid treatment processes, and data-driven optimization tools such as artificial intelligence and machine learning may improve both sustainability and operational efficiency. Overall, CDI and FCDI are transitioning from emerging desalination technologies toward versatile water-treatment and resource-recovery platforms. Continued advances in materials science, electrochemical engineering, membrane technology, and process integration will be crucial for overcoming current limitations and realizing their full potential in future sustainable water-management systems.

## CRediT authorship contribution statement

**Robel Ahmed:** Data curation, Formal analysis, Investigation, Methodology, Resources, Visualization, Writing – original draft. **S.M Saklain Mostak Saumik:** Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Md Rasel Ahmed:** Formal analysis, Investigation, Methodology, Project administration, Writing – original draft. **Md Yeanur Rahman:** Formal analysis, Investigation, Resources, Visualization, Writing – original draft. **Md Abdullah Al Shahil:** Formal analysis, Investigation, Resources, Visualization, Writing – original draft. **Monjur Mourshed:** Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## References

Ahn, J., et al., 2024. High capacity rocking-chair capacitive deionization using highly crystalline sodium cobalt hexacyanoferrate (NaCoHCF) electrodes. Environ. Eng. Res. 29 (6).

Akbarzadeh, R., et al., 2025. Capacitive deionisation for water desalination review: experimental and simulation. Sci. Technol. Adv. Mater. 26 (1), 2546286.

Al Radi, M., et al., 2021a. Progress in energy recovery and graphene usage in capacitive deionization. Crit. Rev. Environ. Sci. Technol. 52 (17), 3080–3136.

Al Radi, M., et al., 2021b. Progress in energy recovery and graphene usage in capacitive deionization, 52 (17), 3080–3136.

Algurainy, Y., Call, D.F., 2021. Improving long-term anode stability in capacitive deionization using asymmetric electrode mass ratios. ACS ES&T Eng. 2 (1), 129–139.
AlMarzooqi, F.A., et al., 2014. Application of capacitive deionisation in water desalination: a review. Desalination 342, 3–15.
Bao, S., et al., 2023. Application of capacitive deionization in water treatment and energy recovery: a review. Energies 16 (3), 1136.
Barcelos, K.M., et al., 2020. Insights on the role of interparticle porosity and electrode thickness on capacitive deionization performance for desalination. Desalination 492, 114594.
Barcelos, K.M., 2021. Development of Stable and high-performance Polyaniline Activated Carbon Electrodes for Capacitive Deionization Desalination.
Baroud, T.N., Giannelis, E.P., 2018. High salt capacity and high removal rate capacitive deionization enabled by hierarchical porous carbons. Carbon 139, 614–625.
Bharath, G., et al., 2020. Synthesis of hierarchical $Mn_3O_4$ nanowires on reduced graphene oxide nanoarchitecture as effective pseudocapacitive electrodes for capacitive desalination application. Electrochim. Acta 337, 135668.
Bian, Y., et al., 2019. Concurrent nitrogen and phosphorus recovery using flow-electrode capacitive deionization. ACS Sustain. Chem. Eng. 7 (8), 7844–7850.
Biesheuvel, M., 2016. Membrane Capacitive Deionization. Encyclopedia of Membranes. Springer, pp. 1184–1185.
Biesheuvel, P., et al., 2011. Theory of membrane capacitive deionization including the effect of the electrode pore space. J. Colloid Interface Sci. 360 (1), 239–248.
Biesheuvel, P., et al., 2014. Attractive forces in microporous carbon electrodes for capacitive deionization. J. Solid State Electrochem. 18 (5), 1365–1376.
Biesheuvel, P.M., Bazant, M.Z., 2010. Nonlinear dynamics of capacitive charging and desalination by porous electrodes. Phys. Rev. 81 (3), 031502.
Bist, N., et al., 2024. Rare Earth element extraction from geothermal brine using hybrid capacitive-deionisation process. Mater. Today Proc.
Caalim, A.N.A., et al., 2025. Effects of conductive carbon additives with different dimensions in flow electrode capacitive deionization for water desalination. J. Environ. Chem. Eng., 120597
Cha, J.-H., et al., 2018. Sulfonated poly (ether ether ketone) ion-exchange membrane for membrane capacitive deionization applications. Macromol. Res. 26 (13), 1273–1275.
Chang, J., et al., 2018. Application of anion exchange membrane and the effect of its properties on asymmetric membrane capacitive deionization. Sep. Purif. Technol. 207, 387–395.
Chen, F., et al., 2017a. A dual-ion electrochemistry deionization system based on AgCl-$Na_{0.44}MnO_2$ electrodes. Nanoscale 9 (28), 10101–10108.
Chen, F., et al., 2017b. Dual-ions electrochemical deionization: a desalination generator. Energy Environ. Sci. 10 (10), 2081–2089.
Chen, Z., et al., 2018. A study of the effect of carbon characteristics on capacitive deionization (CDI) performance. Desalination 433, 68–74.
Cho, Y., et al., 2019. Flow-electrode capacitive deionization with highly enhanced salt removal performance utilizing high-aspect ratio functionalized carbon nanotubes. Water Res. 151, 252–259.
Choi, J., et al., 2019. Applications of capacitive deionization: desalination, softening, selective removal, and energy efficiency. Desalination 449, 118–130.
Choi, J., et al., 2020. Staged voltage mode in membrane capacitive deionization: comparison with constant voltage and constant current modes. Desalination 479, 114327.
Chowdhury, M.A.R., et al., 2025. Slurry flow electrodes towards scalable environmental and energy storage applications: state of the art and technical challenges. Energy Convers. Manag. X, 101279.
Chu, M., et al., 2022. A comprehensive review of capacitive deionization technology with biochar-based electrodes: biochar-based electrode preparation, deionization mechanism and applications. Chemosphere 307, 136024.
Dahiya, S., Mishra, B.K., 2020. Enhancing understandability and performance of flow electrode capacitive deionisation by optimizing configurational and operational parameters: a review on recent progress. Sep. Purif. Technol. 240, 116660.
Das, M., et al., 2024b. Surfactant-driven dynamic changes in rheology of activated carbon slurry electrodes. ACS Applied Materials & Interfaces 16 (32), 42049–42058.
Daud, M.A., et al., 2025. Influence of $ZrO_2$ content on the mechanical, electrical, and microstructural characteristics of $La_{1-x}Zr_xCo_{1-y}Mn_yO_3$ perovskites for IT-SOFC cathodes. PLoS One 20 (6), e0320562.
Ding, X., et al., 2025. Performance of fluorine removal using flow electrode capacitive deionization (FCDI): validation and optimization. Environmental Technology 46 (22), 4407–4416.
Divyapriya, G., et al., 2019. Development of a novel graphene/$Co_3O_4$ composite for hybrid capacitive deionization system. desalination 451, 102–110.
Długołecki, P., et al., 2013. Energy recovery in membrane capacitive deionization, 47 (9), 4904–4910.
Długołecki, P., van der Wal, A., 2013. Energy recovery in membrane capacitive deionization. Environmental science & technology 47 (9), 4904–4910.
Doornbusch, G., et al., 2016. Fluidized bed electrodes with high carbon loading for water desalination by capacitive deionization. Journal of Materials Chemistry A 4 (10), 3642–3647.
Ehring, J.C., et al., 2023. A new static mixer concept for enhanced desalination performance in flow-electrode capacitive deionization (FCDI) systems. Desalination 566, 116887.
Elimelech, M., Phillip, W.A., 2011. The future of seawater desalination: energy, technology, and the environment. science 333 (6043), 712–717.
Erinmwingbovo, C., et al., 2017. Intercalation into a Prussian blue derivative from solutions containing two species of cations. ChemPhysChem 18 (8), 917–925.
Farmer, J.C., et al., 1996. Capacitive deionization of NaCl and $NaNO_3$ solutions with carbon aerogel electrodes. Journal of the Electrochemical Society 143 (1), 159.
Ferguson, G., Gleeson, T., 2012. Vulnerability of coastal aquifers to groundwater use and climate change. Nature climate change 2 (5), 342–345.
Folaranmi, G., et al., 2020. Towards electrochemical water desalination techniques: a review on capacitive deionization, membrane capacitive deionization and flow capacitive deionization. Membranes 10 (5), 96.
Folaranmi, G., et al., 2022. Investigation of fine activated carbon as a viable flow electrode in capacitive deionization. Desalination 525, 115500.
Furukawa, H., et al., 2013. The chemistry and applications of metal-organic frameworks. Science 341 (6149), 1230444.
Galama, A., 2015. Ion Exchange Membranes in Seawater Applications: Processes and Characteristics. Wageningen University and Research.
Gao, M., et al., 2023. Recent advanced freestanding pseudocapacitive electrodes for efficient capacitive deionization. Separation and Purification Technology 324, 124577.
Gao, M., et al., 2024d. Prussian blue and its analogs: a robust platform for efficient capacitive deionization. Desalination 574, 117278.
Gao, X., et al., 2015. Surface charge enhanced carbon electrodes for stable and efficient capacitive deionization using inverted adsorption–desorption behavior. Energy & Environmental Science 8 (3), 897–909.
Gao, X., et al., 2020. Potential of zero charge-based capacitive deionization. Google Patents.
Gendel, Y., et al., 2014. Batch mode and continuous desalination of water using flowing carbon deionization (FCDI) technology. Electrochemistry Communications 46, 152–156.
Gleeson, T., et al., 2012. Water balance of global aquifers revealed by groundwater footprint. Nature 488 (7410), 197–200.
Gong, C., et al., 2023. Controlled fabrication of nitrogen-doped porous carbon foam with refined hierarchical architectures for desalination via capacitive deionization. Journal of colloid and interface science 643, 516–527.
Guo, L., et al., 2020. High speed capacitive deionization system with flow-through electrodes. Desalination 496, 114750.
Halder, B., et al., 2025. Toward scalable and energy efficient desalination: synergistic advances in FCDI design. Energy Reports 14, 4750–4765.
Han, L., et al., 2014. Exploring the impact of pore size distribution on the performance of carbon electrodes for capacitive deionization. Journal of Colloid and Interface Science 430, 93–99.
Hatzell, K.B., et al., 2014. Capacitive deionization concept based on suspension electrodes without ion exchange membranes. Electrochemistry Communications 43, 18–21.
Hatzell, K.B., et al., 2015. Effect of oxidation of carbon material on suspension electrodes for flow electrode capacitive deionization. Environmental science & technology 49 (5), 3040–3047.
Hawks, S.A., 2025. Rheo–Electric Foundations and Engineering of Carbon Slurry Flow Electrodes. Lawrence Livermore National Laboratory (LLNL), Livermore, CA (United States).
He, C., et al., 2018. Short-circuited closed-cycle operation of flow-electrode CDI for brackish water softening. Environmental Science & Technology 52 (16), 9350–9360.
He, C., et al., 2021a. Scale-up and modelling of flow-electrode CDI using tubular electrodes. Water research 203, 117498.
He, C., et al., 2021b. Scale-up and modelling of flow-electrode CDI using tubular electrodes, 203, 117498.
He, D., et al., 2016. Faradaic reactions in water desalination by batch-mode capacitive deionization, 3 (5), 222–226.
He, Y., et al., 2022. Highly efficient and selective extraction of phosphorous from wastewater as vivianite in a strategically operated four-chamber flow electrode capacitive deionization. Desalination 544, 116089.
He, Y., et al., 2023. Emerging electro-driven technologies for phosphorus enrichment and recovery from wastewater: a review. Water research 246, 120699.
He, Z., et al., 2023. Insufficient desorption of ions in constant-current membrane capacitive deionization (MCDI): problems and solutions. Water research 242, 120273.
Hipp, J.B., 2020. Structure, Rheology, and Electrical Conductivity of high-structured Carbon Black Suspensions. University of Delaware.
Honarparvar, S., et al., 2021. Frontiers of membrane desalination processes for brackish water treatment: a review. Membranes 11 (4), 246.
Huang, Z.-H., et al., 2017. Carbon electrodes for capacitive deionization. Journal of Materials Chemistry A 5 (2), 470–496.
Hurlbutt, K., et al., 2018. Prussian blue analogs as battery materials. Joule 2 (10), 1950–1960.
International Desalination Association, 2017. IDA Desalination Yearbook 2016-2017. Water Desalination Report, Oxford.
Jain, A., et al., 2019. Self assembled, sulfonated pentablock copolymer cation exchange coatings for membrane capacitive deionization. Molecular Systems Design & Engineering 4 (2), 348–356.
Jeon, S.-i., et al., 2013. Desalination via a new membrane capacitive deionization process utilizing flow-electrodes. Energy & Environmental Science 6 (5), 1471–1475.
Jeon, S.-i., et al., 2014. Ion storage and energy recovery of a flow-electrode capacitive deionization process. Journal of Materials Chemistry A 2 (18), 6378–6383.
Jeong, K.S., et al., 2015. Synthesis of an aminated poly (vinylidene fluride-g-4-vinyl benzyl chloride) anion exchange membrane for membrane capacitive deionization (MCDI). Journal of Membrane Science 495, 316–321.
Jia, B., Zhang, W., 2016. Preparation and application of electrodes in capacitive deionization (CDI): a state-of-art review. Nanoscale Research Letters 11 (1), 64.
Jiang, T., et al., 2026. Sulfonated poly(fluorenylene alkylene)-based cation-exchange ionomers enabling high-performance and stable capacitive deionization. Desalination 623, 119817.

Jiang, Y., et al., 2022. Energy consumption in capacitive deionization for desalination: a review. International journal of environmental research and public health 19 (17), 10599.
Käärik, M., et al., 2023. Effect of pore size distribution on energy storage of nanoporous carbon materials in neat and dilute ionic liquid electrolytes. Molecules 28, 7191. https://doi.org/10.3390/molecules28207191.
Kang, J., et al., 2014. Comparison of salt adsorption capacity and energy consumption between constant current and constant voltage operation in capacitive deionization. desalination 352, 52–57.
Kang, K.W., et al., 2015. Synthesis and properties of sodium vinylbenzene sulfonate-grafted poly (vinylidene fluoride) cation exchange membranes for membrane capacitive deionization process. Macromolecular Research 23 (12), 1126–1133.
Kim, C., et al., 2017. Concentration-gradient multichannel flow-stream membrane capacitive deionization cell for high desalination capacity of carbon electrodes. ChemSusChem 10 (24), 4914–4920.
Kim, C., et al., 2018. Semi-continuous capacitive deionization using multi-channel flow stream and ion exchange membranes, 425, 104–110.
Kim, N., et al., 2020a. Performance analysis of the multi-channel membrane capacitive deionization with porous carbon electrode stacks, 479, 114315.
Kim, N., et al., 2020b. Short review of multichannel membrane capacitive deionization: principle, current status, and future prospect. Applied Sciences 10 (2), 683.
Kim, N., et al., 2021. Parametric investigation of the desalination performance in multichannel membrane capacitive deionization (MC-MCDI). desalination 503, 114950.
Kim, N., et al., 2023. Comprehensive electrochemical impedance spectroscopy study of flow-electrode capacitive deionization cells. Environmental science & technology 57 (23), 8808–8817.
Kim, T., et al., 2015. Enhanced charge efficiency and reduced energy use in capacitive deionization by increasing the discharge voltage. Journal of colloid and interface science 446, 317–326.
Kim, T., et al., 2016. Hydrogen Peroxide Generation in flow-mode Capacitive Deionization, 776, pp. 101–104.
Kim, Y.-J., Choi, J.-H., 2010. Enhanced desalination efficiency in capacitive deionization with an ion-selective membrane. Separation and Purification Technology 71 (1), 70–75.
Köller, N., et al., 2024. Towards pilot scale flow-electrode capacitive deionization. Desalination 572, 117096.
Koo, J.S., et al., 2012. Synthesis and properties of nonfluoro aminated poly (vinylbenzyl chloride-co-ethyl methacrylate-co-styrene) anion exchange membranes for MCDI process. polymer (Korea) 36 (5), 564–572.
Li, D., et al., 2024. Acid-free treatment of fiber-structured biocarbon material enhances flow capacitive deionization performance. Separation and Purification Technology 330, 125288.
Li, H., et al., 2008. Electrosorptive desalination by carbon nanotubes and nanofibres electrodes and ion-exchange membranes. Water research 42 (20), 4923–4928.
Li, Q., et al., 2020. Faradaic electrodes open a new era for capacitive deionization. Advanced Science 7 (22), 2002213.
Liang, P., et al., 2017. Optimized desalination performance of high voltage flow-electrode capacitive deionization by adding carbon black in flow-electrode. desalination 420, 63–69.
Lim, H., et al., 2020. Energy storage and generation through desalination using flow-electrodes capacitive deionization. Journal of Industrial and Engineering Chemistry 81, 317–322.
Lim, J., et al., 2022. TiO2 nanotube electrode for organic degradation coupled with flow-electrode capacitive deionization for brackish water desalination. npj Clean Water 5 (1), 7.
Lim, J., et al., 2024. Energetic comparison of flow-electrode capacitive deionization and membrane technology: assessment on applicability in desalination fields. Environmental science & technology 58 (14), 6181–6191.
Lin, L., et al., 2020. Selective ammonium removal from synthetic wastewater by flow-electrode capacitive deionization using a novel K2Ti2O5-activated carbon mixture electrode. Environmental science & technology 54 (19), 12723–12731.
Lin, S., 2019. Energy efficiency of desalination: fundamental insights from intuitive interpretation. Environmental science & technology 54 (1), 76–84.
Liu, M., et al., 2022. Recent advances in capacitive deionization: research progress and application prospects. Sustainability 14 (21), 14429.
Liu, P., et al., 2016. Grafting sulfonic and amine functional groups on 3D graphene for improved capacitive deionization. Journal of Materials Chemistry A 4 (14), 5303–5313.
Liu, R., et al., 2024. Optimization of flow field distribution to improve desalination performance of battery electrode deionization by designing flow channel structure. Separation and Purification Technology 331, 125661.
Liu, T., et al., 2026. Prussian blue-derived cobalt oxide/cerium oxide@carbon microsphere heterostructures for high-property electrochemical deionization. Journal of Colloid and Interface Science 720, 140603.
Liu, X., et al., 2020. Cost comparison of capacitive deionization and reverse osmosis for brackish water desalination. Acs Es&T Engineering 1 (2), 261–273.
Lu, D., et al., 2017. Optimization of the voltage window for long-term capacitive deionization stability. Desalination 424, 53–61.
Ma, D., Wang, Y., 2021. Structure and process optimization for highly-efficient membrane capacitive deionization. Energy Technology 9 (4), 2001077.
Ma, J., et al., 2018. Analysis of capacitive and electrodialytic contributions to water desalination by flow-electrode CDI. Water research 144, 296–303.
Ma, J., et al., 2019. Water recovery rate in short-circuited closed-cycle operation of flow-electrode capacitive deionization (FCDI), 53 (23), 13859–13867.
Ma, J., et al., 2020. Flow-electrode capacitive deionization (FCDI) scale-up using a membrane stack configuration, 168, 115186.
Ma, J., et al., 2023. Review of flow electrode capacitive deionization technology: research progress and future challenges. Desalination 564, 116701.
Ma, J., et al., 2024. Improving the energy utilization efficiency of flow electrode capacitive deionization (FCDI) with multiple series flow electrodes. Separation and Purification Technology 329, 125153.
Mahima, S., et al., 2025. Impact of ion intercalation materials on advancing capacitive deionization: from theory to practical. Nanoscale Advances.
Mantel, T., et al., 2021. Electrosorptive removal of organic water constituents by positively charged electrically conductive UF membranes. Water research 201, 117318.
Matsumoto, F., Fukunishi, M., 2024. Review of current collector-, binder-, conductive additive-free, and freestanding electrodes in lithium and related batteries. Batteries 10 (9), 330.
McNair, R., et al., 2020. Ion-exchange materials for membrane capacitive deionization. ACS ES&T Water 1 (2), 217–239.
Mezher, T., et al., 2011. Techno-economic assessment and environmental impacts of desalination technologies. Desalination 266 (1–3), 263–273.
Miao, L., et al., 2024. Progress toward adsorption mechanism exploration method for capacitive deionization: experimental, mathematical model, computational chemistry and machine learning. Desalination 586, 117850.
Ming, G., et al., 2025. Elucidating the efficacious capacitive deionization defluorination behaviors of heteroatom-doped hierarchical porous carbon nanofibers membrane. Separation and Purification Technology 359, 130803.
Ming, G., Wenqing, C., 2024. Engineering strategies toward electrodes stabilization in capacitive deionization. Coordination Chemistry Reviews 505, 215695.
Mossad, M., Zou, L., 2013. Evaluation of the salt removal efficiency of capacitive deionisation: kinetics, isotherms and thermodynamics. Chemical Engineering Journal 223, 704–713.
Mourshed, M., et al., 2021. Carbon-based slurry electrodes for energy storage and power supply systems. Energy Storage Materials 40, 461–489.
Mourshed, M., et al., 2022. Experimental study of electronic and ionic conductivity of a carbon-based slurry electrode used in advanced electrochemical energy systems. ACS Applied Energy Materials 5 (9), 11413–11430.
Mourshed, M., et al., 2023a. Using electrical conductivity to determine particle sedimentation status of carbon-based slurry electrodes in electrochemical energy storage systems. Materials Science for Energy Technologies 6, 290–300.
Mourshed, M., et al., 2023b. Electronical conductivity improvement of carbon-based slurry electrodes using carbon foams for enhanced performance in advanced electrochemical energy storage systems. ACS omega 8 (11), 10525–10544.
Mourshed, M., et al., 2024. Carbon foam to enhance the performance of a slurry flow energy system used for hydrogen storage and transportation: an experimental investigation. International Journal of Hydrogen Energy 69, 1199–1211.
Mourshed, M., et al., 2025. Carbon foam for next-generation electrochemical energy storage: advances, challenges, and outlook. Energy Conversion and Management X, 101281.
Naveed, H., et al., 2021. Investigation of capacitive deionization; performance assessment based on operational parameters and single-objective optimization. Arabian Journal for Science and Engineering 46 (7), 6727–6739.
Nie, P., et al., 2014. Prussian blue analogues: a new class of anode materials for lithium ion batteries. Journal of Materials Chemistry A 2 (16), 5852–5857.
Oh, C., et al., 2024. Performance optimization of a pilot-scale membrane capacitive deionization (MCDI) system operating with circulation process. Separation and Purification Technology 343, 126937.
Oladunni, J., et al., 2018. A comprehensive review on recently developed carbon based nanocomposites for capacitive deionization: from theory to practice. Separation and Purification Technology 207, 291–320.
Orozco-Barrera, S., et al., 2023. Effects of layer-by-layer coating on activated carbon electrodes for capacitive deionization. Physical Chemistry Chemical Physics 25 (13), 9482–9491.
Pan, Y.-T., et al., 2017. Interfacial growth of MOF-derived layered double hydroxide nanosheets on graphene slab towards fabrication of multifunctional epoxy nanocomposites. Chemical Engineering Journal 330, 1222–1231.
Pang, T., et al., 2024. Advances and challenges in capacitive deionization: materials, architectures, and selective ion removal. desalination 592, 118140.
Parant, H., et al., 2017. Flowing suspensions of carbon black with high electronic conductivity for flow applications: comparison between carbons black and exhibition of specific aggregation of carbon particles. Carbon 119, 10–20.
Park, H.-r., et al., 2016b. Surface-modified spherical activated carbon for high carbon loading and its desalting performance in flow-electrode capacitive deionization, 6 (74), 69720–69727.
Pasta, M., et al., 2012. A desalination battery. Nano letters 12 (2), 839–843.
Patel, S.K., et al., 2020. Energy efficiency of electro-driven brackish water desalination: electrodialysis significantly outperforms membrane capacitive deionization. Environmental science & technology 54 (6), 3663–3677.
Pernía, A.M., et al., 2011. Up–down converter for energy recovery in a CDI desalination system. IEEE Transactions on Power Electronics 27 (7), 3257–3265.
Porada, S., et al., 2013b. Review on the science and technology of water desalination by capacitive deionization. Progress in materials science 58 (8), 1388–1442.
Porada, S., et al., 2014. Carbon flow electrodes for continuous operation of capacitive deionization and capacitive mixing energy generation. Journal of Materials Chemistry A 2 (24), 9313–9321.
Pothanamkandathil, V., et al., 2020. Electrochemical desalination using intercalating electrode materials: a comparison of energy demands. Environmental science & technology 54 (6), 3653–3662.

Presser, V., et al., 2012. The electrochemical flow capacitor: a new concept for rapid energy storage and recovery. Advanced energy materials 2 (7), 895–902.
Qiu, Q., et al., 2017. Preparation of polyethylene membranes filled with crosslinked sulfonated polystyrene for cation exchange and transport in membrane capacitive deionization process. desalination 417, 87–93.
Quan, X., et al., 2017. Capacitive deionization of NaCl solutions with ambient pressure dried carbon aerogel microsphere electrodes. RSC Advances 7 (57), 35875–35882.
Rahman, M.A.A., et al., 2025. Transforming waste into clean energy: the future of hydrogen energy generation in Bangladesh. International Journal of Hydrogen Energy 136, 275–293.
Rimon, S.T.A., et al., 2025. Flow field configurations in PEMFCs: design, modeling, and performance insights. Energy Conversion and Management: X, 101263.
Robin, H.M., et al., 2025b. A comprehensive analysis of hydrogen production through electrolysis of industrial wastewater: prospects and challenges. Energy Reviews 4 (3), 100155.
Rommerskirchen, A., et al., 2020. Flow-electrode capacitive deionization enables continuous and energy-efficient brine concentration. desalination 490, 114453.
Said, I.A., et al., 2022. Energy recovery in electrified capacitive deionization systems for wastewater treatment and desalination: a comprehensive review. Chemical Engineering and Processing-Process Intensification 178, 109030.
Saif, H.M., et al., 2024. The influence of flow electrode channel design on flow capacitive deionization performance: experimental and CFD modelling insights. Desalination 578, 117452.
Saif, H.M., et al., 2025. Activated carbons for flow electrode capacitive deionization (FCDI) – morphological, electrochemical and rheological analysis. Desalination 602, 118638.
Salari, K., et al., 2022. Knowledge and technology used in capacitive deionization of water. Membranes (Basel) 12 (5).
Saleem, M.W., et al., 2018. Electrochemical CDI integration with PRO process for water desalination and energy production: concept, simulation, and performance evaluation. Journal of Electroanalytical Chemistry 822, 134–143.
Santos, C., La Mantia, F., 2023. Insights into desalination battery concepts: current challenges and future perspectives. Chemical Communications 59 (43), 6437–6452.
Shajid, S.R., et al., 2025b. Optimizing flow capacitive deionization: a review of advances in flow channel geometry and active material selection. Journal of Industrial and Engineering Chemistry.
Shannon, M.A., et al., 2008. Science and technology for water purification in the coming decades. Nature 452 (7185), 301–310.
Shapira, B., et al., 2016. Side reactions in capacitive deionization (CDI) processes: the role of oxygen reduction, 220, 285–295.
Shatat, M., et al., 2013. Opportunities for solar water desalination worldwide. Sustainable cities and society 9, 67–80.
Shubham Kumar, M., et al., 2026. Geometrical optimization of flow-electrode capacitive deionization leading to streamlined spacer and electrode channel combination for enhanced ion transport. Desalination 619, 119573.
Song, J., et al., 2025. Simultaneous removal and recovery of ammonium and phosphate ions using flow electrode capacitive deionization through the struvite generation mechanism. Separation and Purification Technology 358, 130395.
Song, Z., et al., 2023. Recent advances in the fixed-electrode capacitive deionization (CDI): innovations in electrode materials and applications. Environmental Functional Materials 2 (3), 290–303.
Sun, Z., et al., 2023. Synthesis of low-crystalline $MnO_2$/MXene composites for capacitive deionization with efficient desalination capacity. Metals 13 (6), 1047.
Suss, M.E., et al., 2015. Water desalination via capacitive deionization: what is it and what can we expect from it? Energy & Environmental Science 8 (8), 2296–2319.
Taha, M.M., et al., 2021. Controlled fabrication of mesoporous electrodes with unprecedented stability for water capacitive deionization under harsh conditions in large size cells. Desalination 511, 115099.
Tang, K., et al., 2020. Optimal conditions for efficient flow-electrode capacitive deionization. Separation and Purification Technology 240, 116626.
Tang, K., Zhou, K., 2020. Water desalination by flow-electrode capacitive deionization in overlimiting current regimes. Environmental science & technology 54 (9), 5853–5863.
Tang, W., et al., 2017. Comparison of faradaic reactions in capacitive deionization (CDI) and membrane capacitive deionization (MCDI) water treatment processes. Water research 120, 229–237.
Tang, W., et al., 2019. Various cell architectures of capacitive deionization: recent advances and future trends. Water research 150, 225–251.
Tauk, M., et al., 2023. Recent advances in capacitive deionization: a comprehensive review on electrode materials. Journal of Environmental Chemical Engineering 11 (6), 111368.
Tauk, M., et al., 2024. Exploring flow-electrode capacitive deionization: an overview and new insights. desalination, 118392.
Tauk, M., et al., 2025. Exploring flow-electrode capacitive deionization: an overview and new insights. Desalination 597, 118392.
Taylor, R.G., et al., 2013. Ground water and climate change. Nature climate change 3 (4), 322–329.
Thu Tran, N.A., et al., 2020. Improved desalination performance of flow-and fixed-capacitive deionization using redox-active quinone. ACS Sustainable Chemistry & Engineering 8 (44), 16701–16710.
Tian, G., et al., 2014. Preparation and characterization of cross-linked quaternised polyvinyl alcohol membrane/activated carbon composite electrode for membrane capacitive deionization. desalination 354, 107–115.
Tirabadi, F.H., et al., 2025. Behavior of silica mesoporous materials for capacitive deionization desalination. Scientific Reports 15 (1), 22839.
Tu, X., et al., 2023. Ternary-metal Prussian blue analogues as high-quality sodium ion capturing electrodes for rocking-chair capacitive deionization. Journal of colloid and interface science 642, 680–690.
ul Haq, O., et al., 2018. Anion-exchange membrane for membrane capacitive deionization prepared via pore-filling polymerization in a porous polyethylene supporting membrane. Reactive and Functional Polymers 132, 36–42.
Usman, M., et al., 2024. Elucidating the mechanism of electro-adsorption on electrically conductive ultrafiltration membranes via modified poisson-boltzmann equation. Membranes 14 (8), 175.
Wang, H., et al., 2013. Three-dimensional macroporous graphene architectures as high performance electrodes for capacitive deionization, 1 (38), 11778–11789.
Wang, J., et al., 2018. Self-template-directed metal–organic frameworks network and the derived honeycomb-like carbon flakes via confinement pyrolysis, 14 (14), 1704461.
Wang, L., et al., 2020. Equivalent film-electrode model for flow-electrode capacitive deionization: experimental validation and performance analysis. Water research 181, 115917.
Wang, L., et al., 2023. Up-shifting the desalination rate limit of capacitive deionization via integrating chloride-capturing Bi nanocluster with flow-through cell architecture. Chemical Engineering Journal 460, 141726.
Wang, Q., et al., 2022. Ammonia removal from municipal wastewater via membrane capacitive deionization (MCDI) in pilot-scale. Separation and Purification Technology 286, 120469.
Wang, R., et al., 2022. Dimensional optimization enables high-performance capacitive deionization. Journal of Materials Chemistry A 10 (12), 6414–6441.
Wang, R., Lin, S., 2020. Thermodynamic reversible cycles of electrochemical desalination with intercalation materials in symmetric and asymmetric configurations. Journal of colloid and interface science 574, 152–161.
Wang, Z., et al., 2019. Nanoarchitectured metal–organic framework/polypyrrole hybrids for brackish water desalination using capacitive deionization. Materials Horizons 6 (7), 1433–1437.
Werner, A.D., et al., 2013. Seawater intrusion processes, investigation and management: recent advances and future challenges. Advances in water resources 51, 3–26.
Wheeler, S., et al., 2019. Low-potential prussian blue analogues for sodium-ion batteries: manganese hexacyanochromate. Chemistry of Materials 31 (7), 2619–2626.
World Water Assessment Programme, 2019. UN world water development report 2019 - leaving no one behind. from. https://www.unesco.org/en/wwap/wwdr/2019.
Wu, Q., et al., 2020. Enhanced capacitive deionization of an integrated membrane electrode by thin layer spray-coating of ion exchange polymers on activated carbon electrode. desalination 491, 114460.
Wu, Q., et al., 2021. Novel inorganic integrated membrane electrodes for membrane capacitive deionization. ACS Applied Materials & Interfaces 13 (39), 46537–46548.
Wu, Q., et al., 2022. Advances and perspectives in integrated membrane capacitive deionization for water desalination. Desalination 542, 116043.
Xiao, Q., et al., 2024. Membrane capacitive deionization (MCDI) for selective ion separation and recovery: fundamentals, challenges, and opportunities. Journal of Membrane Science 699, 122650.
Xie, J., et al., 2020. Carbon nanotubes in-situ cross-linking the activated carbon electrode for high-performance capacitive deionization. Separation and Purification Technology 239, 116593.
Xu, X., et al., 2016. Design and fabrication of mesoporous graphene via carbothermal reaction for highly efficient capacitive deionization. Electrochimica Acta 188, 406–413.
Xu, X., Pan, L., 2023. Inverted capacitive deionization. Capacitive Deionization, Royal Society of Chemistry 32.
Xu, Y., et al., 2020. Selective pseudocapacitive deionization of calcium ions in copper hexacyanoferrate. ACS Applied Materials & Interfaces 12 (37), 41437–41445.
Yang, F., et al., 2021. Flow-electrode capacitive deionization: a review and new perspectives. Water research 200, 117222.
Yang, S., et al., 2016. Stack design and operation for scaling up the capacity of flow-electrode capacitive deionization technology. ACS Sustainable Chemistry & Engineering 4 (8), 4174–4180.
Yang, S., et al., 2017. Plate-shaped graphite for improved performance of flow-electrode capacitive deionization. Journal of The Electrochemical Society 164 (13), E480.
Yang, Z., et al., 2023. One-dimensional electrospinning nanomaterials toward capacitive deionization: fundamentals, development, and perspectives. Desalination 567, 117010.
Yekun, F., et al., 2025. Seawater desalination by multistage flow-electrode capacitive deionization with graded electric field and electrode salinity. desalination 615, 119274.
Yin, G., Chen, F., 2003. Progress in capacitive deionization. Technology of water treatment 29 (2), 63–66.
Yoon, H., et al., 2017. Hybrid capacitive deionization with Ag coated carbon composite electrode. Desalination 422, 42–48.
Younes, H., et al., 2024. A review on capacitive deionization: recent advances in Prussian blue analogues and carbon materials based electrodes. Hybrid Advances 6, 100191.
Yu, J., et al., 2018. Temporal and Spatial Distribution of Ph in flow-mode Capacitive Deionization and Membrane Capacitive Deionization, 439, pp. 188–195.
Zhang, C., et al., 2020. Evaluation of long-term performance of a continuously operated flow-electrode CDI system for salt removal from brackish waters. Water research 173, 115580.
Zhang, C., et al., 2021. Flow electrode capacitive deionization (FCDI): recent developments, environmental applications, and future perspectives. Environmental science & technology 55 (8), 4243–4267.
Zhang, J., et al., 2018. N, P, S co-doped hollow carbon polyhedra derived from MOF-based core–shell nanocomposites for capacitive deionization. Journal of Materials Chemistry A 6 (31), 15245–15252.

Zhang, Y., et al., 2019. Fabrication of porous graphene electrodes via $CO_2$ activation for the enhancement of capacitive deionization. Journal of colloid and interface science 536, 252–260.
Zhang, Y., et al., 2022. Selectivity toward heavier monovalent cations of carbon ultramicropores used for capacitive deionization. Desalination 542, 116053.
Zhao, R., et al., 2010. Charge efficiency: a functional tool to probe the double-layer structure inside of porous electrodes and application in the modeling of capacitive deionization. The Journal of Physical Chemistry Letters 1 (1), 205–210.
Zhao, R., et al., 2012. Energy consumption and constant current operation in membrane capacitive deionization. Energy & Environmental Science 5 (11), 9520–9527.
Zhao, R., et al., 2013. Optimization of salt adsorption rate in membrane capacitive deionization. Water research 47 (5), 1941–1952.
Zhao, Y., et al., 2013. Performance Comparison and Energy Consumption Analysis of Capacitive Deionization and Membrane Capacitive Deionization Processes, 324, pp. 127–133.
Zhao, Y., et al., 2025. A review of modification of carbon-based materials based on defect engineering in capacitive deionization. Water 17 (16), 2478.
Zhou, S., et al., 2023. A review of the development in shale oil and gas wastewater desalination. Science of the Total Environment 873, 162376.