

Enhanced desalination performance of pilot-scale membrane capacitive deionization (MCDI) system with circulation process

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HIGHLIGHTS

- Circulation outperformed conventional methods in pilot-scale MCDI operations.
- Production yield increased with high TDS removal efficiency.
- Dual-module setup improved TDS removal but increased energy use.
- Concentrate replacement enhanced desalination performance significantly.
- TDS and replacement frequencies showed interaction in Two-way RM ANOVA.

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ABSTRACT

Desalination is crucial for providing a sustainable source of fresh water to support agricultural, industrial, and domestic needs, particularly in areas facing water scarcity. This study fills a gap in previous research by evaluating cycle-based concentrate replacement strategies in a pilot-scale membrane capacitive deionization (MCDI) system. We used an MCDI system and compared the desalination efficacy of the circulation process in the MCDI system, where concentrated brine is reintroduced to the system for the desorption phase, to the with a conventional process under identical operational conditions. The total dissolved solids (TDS) removal efficiency and energy consumption were examined across single- and dual-module configurations at initial TDS concentrations of 1000 and 2000 mg/L. Both processes exhibited high TDS removal efficiency, particularly in the dual-module configuration, reaching up to 99 %. The energy consumption of the circulation process was superior, at 0.561 kWh/m³ at 10 cycles compared to 0.615 kWh/m³ for the conventional process. The two-way RM ANOVA analysis revealed significant interactions between initial TDS concentrations and concentrate replacement frequencies, demonstrating that these factors jointly influence desalination efficiency and energy demands. These findings indicate the importance of optimizing the balance between desalination efficiency and energy consumption, especially at higher TDS levels, to enhance the practicality of MCDI for sustainable desalination.

1. Introduction

Access to clean water is vital for maintaining public health, food security, and economic growth. However, global challenges such as water pollution and scarcity leave millions without access to safe drinking water [1–4]. To address these issues, water treatment technologies have been implemented, including conventional methods, such as sand filtration and chlorination, and more advanced approaches, such as nanofiltration and reverse osmosis (RO) [5–7]. As the demand for

water increases, it is crucial to enhance the efficiency, cost-effectiveness, and sustainability of these technologies to effectively meet global needs.

Capacitive deionization (CDI) and membrane capacitive deionization (MCDI) are emerging water desalination technologies that provide energy-efficient alternatives to traditional methods. CDI uses an electric field to remove dissolved ions from water, which are subsequently adsorbed onto porous carbon electrodes [8–11]. MCDI further improves this process by introducing ion-exchange membranes that selectively remove cations or anions, resulting in higher desalination efficiency and

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prolonged electrode life [12–14]. CDI and MCDI are well suited for treating brackish water and other low-salinity sources, making them viable in regions with limited freshwater resources [15–18]. Due to their low energy demands, modular design, and ability to regenerate electrodes, MCDI systems are increasingly applied in diverse settings, including irrigation, industrial wastewater treatment, and potable water production [19–22]. Some studies have focused on optimizing the operational parameters using capacitive deionization systems for large-scale applications [23–25]. However, despite advancements in CDI and MCDI technologies, pilot-scale systems still face challenges in water recovery, and operational efficiency. Overcoming these challenges necessitates adopting advanced operational strategies beyond conventional methods to minimize water loss, sustain desalination efficiency, and optimize energy consumption. Such methods are vital for enhancing the feasibility of MCDI systems in large-scale, real-world applications.

In our previous study, we developed a multi-module MCDI system to assess the feasibility of the circulation process, which involves

reintroducing concentrated brine into the system to minimize water loss and enhance water recovery, with different operational conditions for optimized desalination performance [26]. By monitoring the effluent total dissolved solids (TDS) concentrations, we observed that module configuration and brine recirculation notably impacted both desalination efficiency and the operational stability of the system. However, this initial study primarily focused on establishing practical module configurations and continuous circulation and did not thoroughly investigate the role of cycle-based management strategies, specifically, the frequency of replacing concentrated brine. Therefore, the influence of concentrate replacement frequencies on system performance remains unexplored, requiring further investigation into how these frequencies might affect TDS removal efficiency and energy consumption.

The present study aimed to advance previous work by comparing the conventional MCDI and circulation processes under identical operational conditions. Our primary objective was to quantify the differences in the TDS removal efficiency, water recovery, and energy consumption

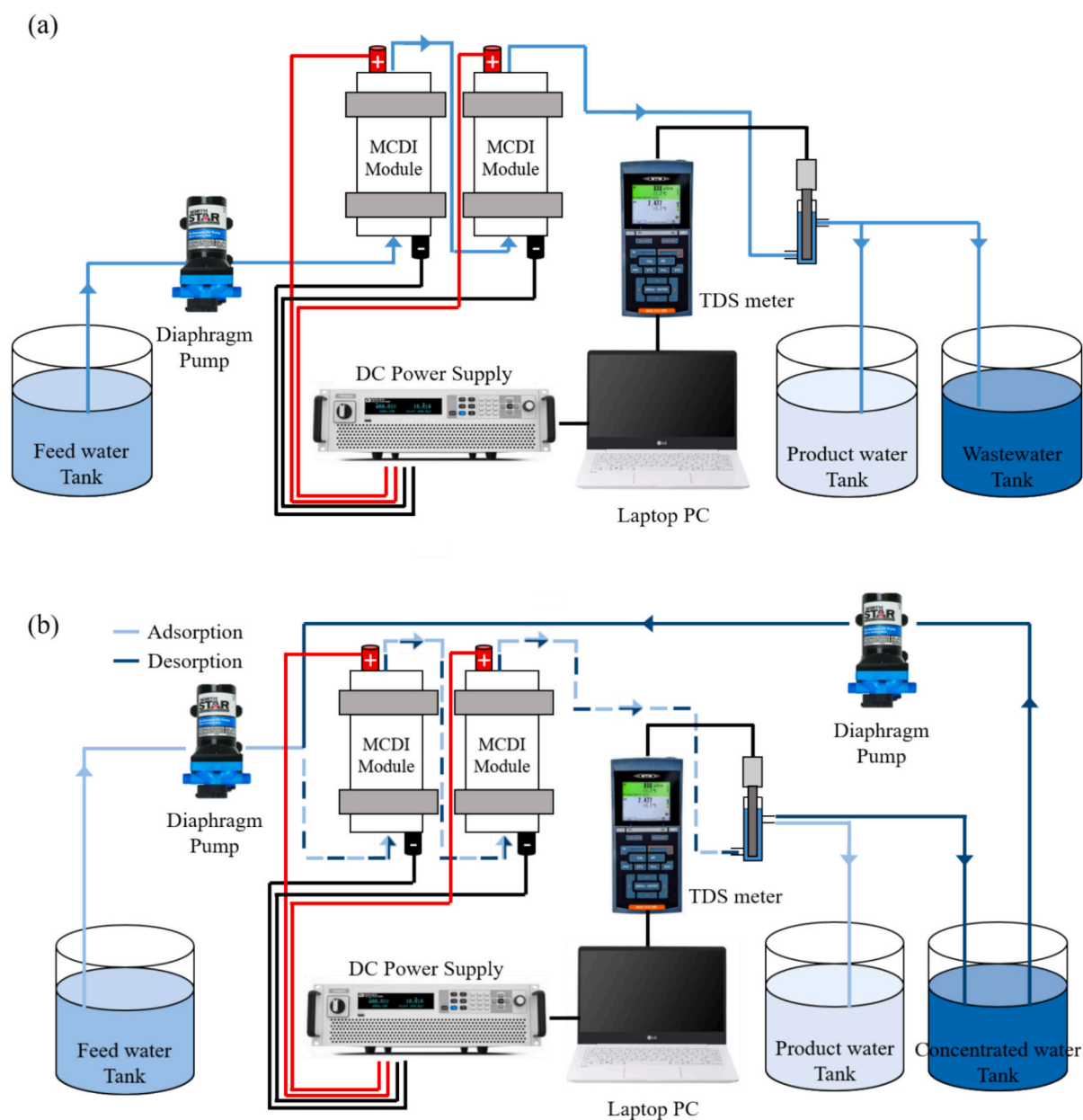


Fig. 1. Configuration of the MCDI system for (a) the conventional process and (b) the circulation process. The system was operated using either a single module or two modules connected in series, depending on the configuration.

between these two processes, highlighting the unique advantages of adopting the circulation process. We incorporated single-module and dual-module setups for each process at two initial TDS concentrations (1000 and 2000 mg/L). Additional tests were conducted for the circulation process by replacing the concentrate tank every 5 or 10 cycles to assess how different replacement frequencies influence the desalination efficiency and energy demands. This study provides practical insights for optimizing MCDI operational strategies for pilot-scale water treatment applications by examining whether cycle-based concentrate replacement, a newly introduced concept of circulation process operation, improves desalination efficiency and energy consumption.

2. Materials and methods

2.1. MCDI system configuration

The MCDI system used in this study comprised diaphragm pumps (3055R, NorthStar, Australia), solenoid valves (HPW154ST, Hyo Shin Electric Co., Ltd., Republic of Korea), flow meters (ZYIA Instrument Company, China), pressure gauges (Sigmatech, Republic of Korea), and a direct current power supply (IT6006D-300-75, ITECH, China) (Fig. 1). The system was configured to arrange modules as either single module (single-module configuration) or two modules connected in series (dual-module configuration), allowing for a comparative analysis of the TDS removal efficiency and energy consumption across different configurations. The effluent TDS concentrations were continuously monitored and recorded every second using conductivity meters (Multi 3630 IDS, WTW, Germany). Fig. 1 presents the MCDI system configuration, depicting the conventional and circulation processes that differ in the flow control of the concentrate tank.

The MCDI modules were sourced from the S Company (Republic of Korea). Each module comprised 250 porous bipolar carbon electrodes positioned between the anion- and cation-exchange membranes. Adjacent membranes were separated by nylon net spacers of 180 μm thickness to facilitate water flow through the ion exchange membranes and electrodes (Fig. S1). All components, including the electrodes, ion-exchange membranes, and spacers, had a diameter of 20 cm, providing a consistent framework for optimized ion removal efficiency within the system.

2.2. Experimental method

To assess the performance of the MCDI system, feed water was prepared by dissolving sodium chloride (99.5 %, Samchun, Republic of Korea) in tap water to achieve target TDS concentrations of 1000 mg/L and 2000 mg/L. These concentrations simulated mild-to-moderate brackish water conditions, ensuring a standardized basis for comparison across all tests.

The MCDI system was operated using two processes: conventional and circulation (Fig. 1). Both were operated at a flow rate of 3 L/min and maintained 2-min cycles for the adsorption and desorption phases. Assuming an operating schedule of 20 h per day, the system demonstrated a treatment capacity of 3600 L/d, aligning well with capacities reported in other pilot-scale studies [27,28]. In each experiment, over 20 cycles were conducted, producing at least 120 l of clean water to ensure system stabilization, provide sufficient data for analysis, and demonstrate the capability of the system to operate at a practical scale. In the conventional process (Fig. 1a), the feed water passes through the MCDI module in a single pass per cycle. During the adsorption phase, ions in the feed water were attracted to electrodes with opposite charges, thereby reducing the TDS concentration of the effluent. In the desorption phase, the charge is reversed, releasing the accumulated ions flushed from the system into the wastewater tank or drainage. This process does not involve a concentrate tank, resulting in a one-time flow path without recirculation.

The circulation process (Fig. 1b) operates by recirculating water

through the system during the desorption phase to enhance production yield (water recovery). During the adsorption phase, the feed water flows through the MCDI module, removing ions and reducing the TDS in the feed water, the same as the conventional process. In contrast, during the desorption phase, instead of using feed water, the system draws water from a concentrated tank, which is initially filled with clean tap water with low TDS concentration, until replaced. By preventing the loss of feed water during desorption, this approach significantly improves production yield while maintaining stable system operation over multiple cycles. The production yield, defined as the percentage of feed water converted into produced water, is a critical measure of the efficiency and practicality of desalination. Normally, to calculate the production yield, the following equation applies:

$$\text{Production yield (\%)} = \frac{V_{\text{produced}}}{V_{\text{feed}}} \times 100\% \quad (1)$$

where V_{feed} and V_{produced} represent the volume of the feed water and MCDI-treated water during adsorption, respectively.

However, for the circulation process, a cumulative production yield is calculated over n_{cycles} , where a fraction of the concentrate is continuously recycled unless changed. The equation is adapted as:

$$\text{Production yield}_{\text{cumulative for the circulation process}} (\%) = \frac{\sum_{i=1}^n V_{\text{produced},i}}{V_{\text{feed},1} + \sum_{i=2}^n V_{\text{feed},i}} \times 100\% \quad (2)$$

where $V_{\text{feed},1}$ represents the initial feed water volume, $V_{\text{feed},i}$ includes both the newly added feed water and recycled concentrate, and $V_{\text{produced},i}$ represents the volume of produced water in the i -th cycle.

As the desorption cycles progressed, the ions released from the electrodes gradually increased the TDS concentration in the concentrate tank, creating a high-TDS solution over time. This progressive concentration of ions is the reason for the tank's designated as a "concentrate tank." Concentrate tank replacement with clean tap water was performed at frequencies of 5 cycles, 10 cycles, or no replacement during each experiment to examine the effect of replacement frequency on the system efficiency for the circulation process operation.

In summary, experiments were structured to assess three main variables: (i) initial TDS concentration, (ii) module configuration, and (iii) concentrate tank replacement frequency within the circulation process. Additionally, experiments without concentrate replacement were included for baseline comparisons. Owing to its standard operational design, the conventional process does not involve the replacement of the concentrate tank. Sixteen experimental setups were evaluated, as listed

Table 1
Summary of experimental conditions.

Operational method	Module configuration	Initial TDS concentration (mg/L)	Concentrate tank replacement frequency
Conventional	Single	1000	Not applicable
		2000	Not applicable
	Dual (Series)	1000	Not applicable
		2000	Not applicable
Circulation	Single	1000	No replacement
		1000	5 cycles
		1000	10 cycles
		2000	No replacement
		2000	5 cycles
		2000	10 cycles
	Dual (Series)	1000	No replacement
		1000	5 cycles
		1000	10 cycles
		2000	No replacement
		2000	5 cycles
		2000	10 cycles

in Table 1.

2.3. TDS removal efficiency and energy consumption calculation

TDS removal efficiency was calculated to evaluate the desalination performance of the MCDI system under different configurations and operating conditions. It was calculated using the following formula:

$$\text{Removal efficiency (\%)} = \frac{C_0 - C_A}{C_0} \times 100\% \quad (3)$$

where C_0 and C_A represent TDS concentrations of the feed water and MCDI-treated water during adsorption, respectively, measured in mg/L.

The direct current power supply was set to 300 V to operate the MCDI module during both the adsorption and desorption phases. This voltage was determined based on the configuration of the module, which consists of 250 electrodes, ensuring sufficient voltage (250×1.2 V) for effective ion adsorption and release while avoiding water electrolysis [29]. The power supply was equipped with an auto-logging system that recorded the voltage, current, and power output every second. This enabled continuous monitoring and storage of energy data throughout each cycle, providing precise real-time power consumption measurements. Energy consumption data were collected for each experimental configuration to assess the relationship between TDS removal efficiency and energy demands across single- and dual-module setups and under various concentrate replacement cycles and TDS levels. Energy consumption reflects the product of the applied constant voltage (300 V) and corresponding current over time, inherently capturing the electrical behavior of the system during MCDI operation.

2.4. Statistical analysis

Two-way repeated measures ANOVA (two-way RM ANOVA) was used to investigate the impact of the initial TDS concentration (1000 and 2000 mg/L) and concentrate replacement frequency (5 cycles, 10 cycles, and no replacement) on the effluent TDS concentrations during the circulation process operation for both single- and dual-module configurations. It was performed using Origin Pro 2022 software (OriginLab Corporation, Northampton, MA, USA). The effluent TDS concentration was set as the dependent variable, with time (s) as the repeated measure. Significant main and interaction effects identified using ANOVA were further analyzed by post hoc pairwise comparisons using the Bonferroni test to clarify specific pairwise differences between the levels of each factor. Key outputs were listed for significant effects, including F-values, p -values, and pairwise comparisons. Statistical significance was set at p

< 0.05.

3. Results and discussion

3.1. TDS removal efficiency and production yield

3.1.1. Conventional process

During the adsorption phase (0–120 s) of the conventional process, ions from the feed water were attracted and adsorbed onto the electrodes in both the single- and dual-module configurations, which decreased the effluent TDS concentration (Figs. 2 and 3). At 40 s, the lowest average effluent TDS concentrations in the single-module configuration was 23.7 mg/L for the 1000 mg/L feed and 50.6 mg/L for the 2000 mg/L feed, achieving the TDS removal efficiency of 97.6 % and 97.5 %, respectively (Fig. 2a). When examining the TDS removal efficiency trend during the adsorption phase, the higher initial TDS concentration of 2000 mg/L resulted in a slow increase in efficiency with a higher standard deviation than the results of 1000 mg/L (Fig. S2a). The difference in the effluent TDS concentrations and TDS removal efficiencies between the 1000 and 2000 mg/L initial TDS feeds further signifies the impact of feed concentration. A higher TDS concentration led to a lower removal efficiency, likely owing to faster electrode saturation under high ionic loads, as previously reported [30]. Notably, despite its high efficiency, a slight increase in effluent TDS and a decrease in TDS removal efficiency around the 60-s mark indicated a limitation in the ion adsorption capacity of the single-module configuration when managing high TDS loads.

In contrast, the dual-module configuration demonstrated more stable and efficient TDS reduction than the single-module configuration, which could be attributed to the increased electrode surface area provided by the additional module. The lowest average values, observed at 110 s, were 7.4 and 15.4 mg/L for the 1000 and 2000 mg/L feed, respectively. The corresponding TDS removal efficiencies were 99.3 % and 99.2 %, respectively (Fig. 2b). The effluent TDS remained low, while the TDS removal efficiencies also revealed stable during the adsorption phase (Fig. S2b), indicating that the dual-module configuration could better handle higher ionic loads, supporting the findings from our previous studies and others on the influence of electrode surface area on ion capture efficiency [25,26,31].

The effluent TDS sharply increased during the desorption phase (120–240 s) when the ions accumulated on the electrodes were released. In the single-module configuration, the effluent TDS concentration

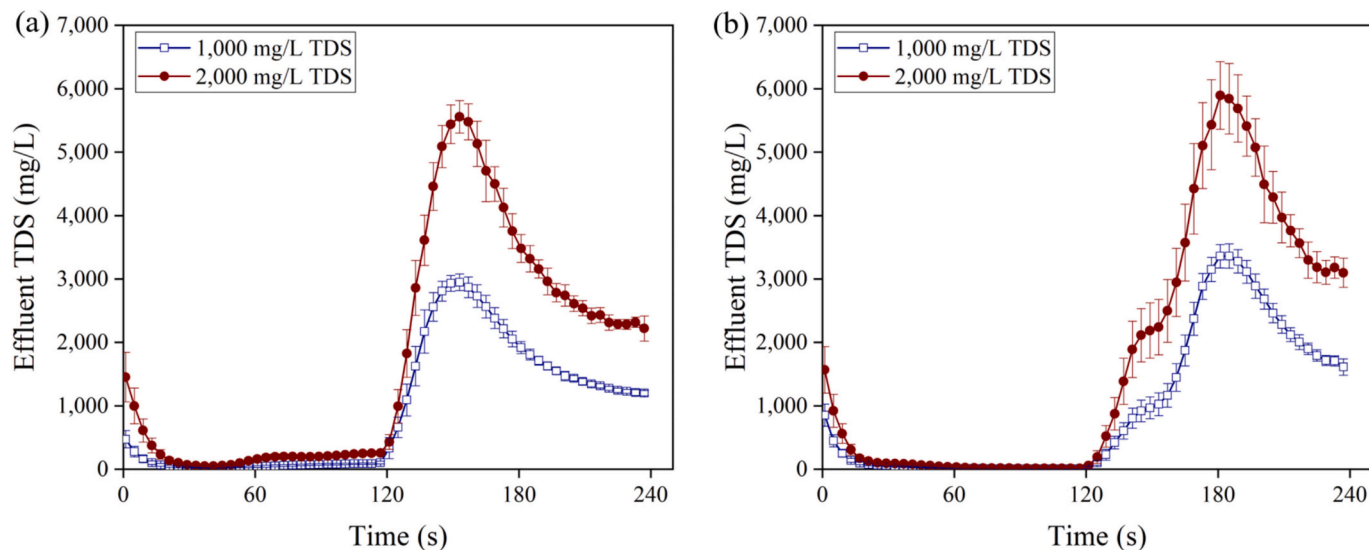


Fig. 2. Changes in the concentration of total dissolved solids (TDS) in the conventional process in (a) single module and (b) dual module. Data represent average TDS concentrations over 20 operational cycles.

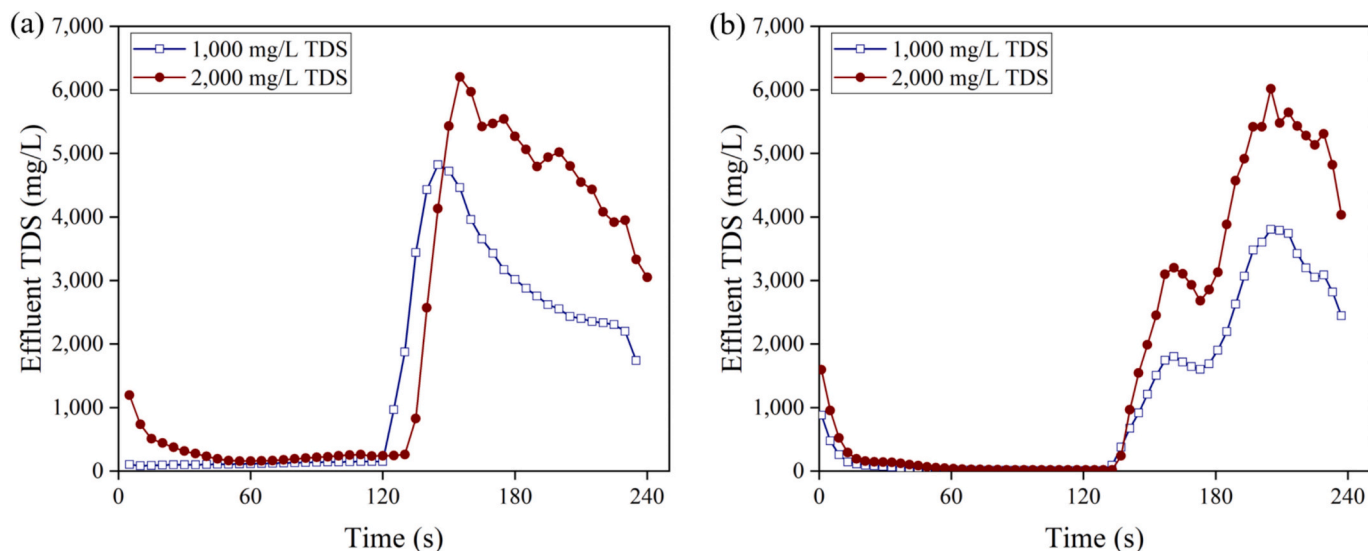


Fig. 3. Changes in the concentration of total dissolved solids (TDS) in the circulation process in (a) single module and (b) dual module. The concentrate tank was not replaced. Data represent average TDS concentrations over 20 operational cycles.

peaked at approximately 150 s, 30 s after the start of desorption. It nearly reached the feedwater concentration by the end of the desorption phase. The dual-module configuration showed a different desorption behavior around 150 s, with the TDS increase temporarily stabilizing before continuing to rise. This can be attributed to the retention of ions within the tube connecting the two modules, which delays the timing of complete ion release. Unlike the single-module configuration, the dual-module configuration did not return to the initial TDS levels of feed water by the end of desorption, indicating incomplete desorption. It has been reported that brief desorption periods lead to incomplete desorption by limiting the capacity of the next cycle, which results in a diminishing sodium adsorption rate [32]. However, in this study, the TDS removal efficiency remained above 90 % over 20 cycles of operation, suggesting the need for a long-term operation to fully understand the capacity of the tested MCDI module before adopting the system at the operational scale.

3.1.2. Circulation process

The circulation process displayed similar TDS removal efficiency trends during the adsorption phase as observed in the conventional process. In the single-module configuration, the average effluent TDS levels dropped to 83.7 mg/L and 158 mg/L when initial TDS concentrations were 1000 mg/L and 2000 mg/L, respectively (Fig. 3a). The dual-module configuration significantly reduced TDS, similar to the results of the conventional process, for which the average effluent TDS levels dropped to 10.1 and 18 mg/L for initial TDS concentrations of 1000 and 2000 mg/L, respectively, achieving the TDS removal efficiency of 99 % (Fig. 3b). The same as the conventional process, larger surface areas of the electrodes enhance ion adsorption. These trends are further supported by the TDS removal efficiencies, which confirm the superior performance of the dual-module configuration during the adsorption phase (Fig. S3).

However, neither configuration returned to the feed water TDS levels during the desorption phase by the end of the 240-s cycle. The increasing effluent TDS at the end of the desorption phase agreed with the results of our previous study on circulation process operation with the same MCDI modules, where the effluent TDS concentration from the desorption phase gradually increased [26]. However, the dual-module results differed from those of the previous study, with the highest peak TDS occurring at approximately 210 s, compared to 10 s in the previous study. Differences in the module configuration can explain this. In the previous study, the two modules were directly connected. However, this

study used tubes to connect the MCDI modules in the dual-module configuration (Fig. 1b), resulting in a delay. In addition, the data of this study are presented as average values from over 20 cycles of operation, owing to the accumulation of ions in the concentrate tank and within the recirculation loop, which can slow down ion release rates.

These results indicate that while the dual-module configuration enhances TDS removal during adsorption, the added complexity of the multi-module and circulation configurations introduces challenges in achieving rapid and complete ion release during desorption. Operational adjustments such as optimizing the circulation rate or adjusting the electrode material properties may be necessary to fully understand the advantages of the circulation process under high-TDS conditions.

3.1.3. Production yield

Fig. 4 compares the production yield across 20 cycles for both the conventional and circulation processes and highlights the advantages of the circulation process in maximizing water recovery. In the conventional process, the production yield remained relatively stable at 50 %

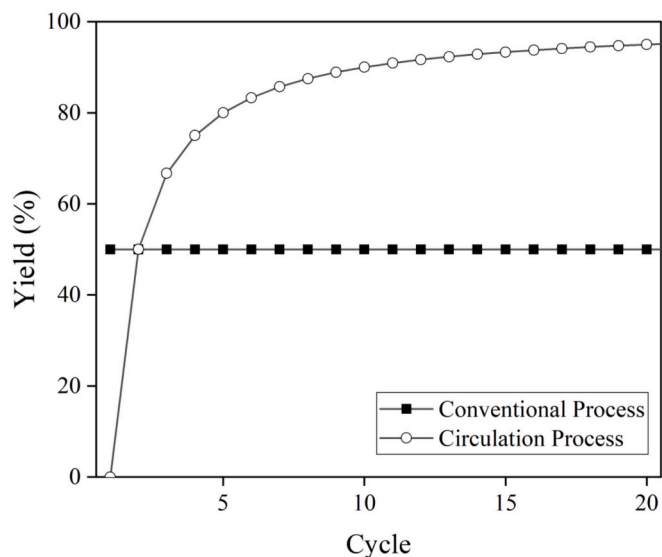


Fig. 4. Produced water yield per cycle during the conventional and circulation processes.

throughout the 10 cycles. The lack of concentrate recycling means that the system relies solely on single-pass desalination, in which the effluent water not retained by the system is discharged. Consequently, the conventional process operates with reduced water recovery, which affects its viability for large-scale desalination, for which resource conservation is essential.

In contrast, the circulation process showed a substantial improvement in production yield as operation continued. After the first cycle, the yield rapidly increased, reaching 80 % by the fifth cycle and stabilizing to over 90 % by the tenth cycle. This significant increase can be attributed to the reuse of water within the concentrate tank, which minimized the wastage of feed water. During each cycle, only concentrated brine was circulated, whereas desalinated water was continually extracted, allowing for a steady increase in the yield across cycles. The high yield observed in the circulation process correlated with its high TDS removal efficiency, indicating that the brine recirculation maximized water recovery while achieving high ion removal. The contrasting yield trends of the two processes highlight the advantages of brine recirculation in MCDI systems. The ability of the circulation process to reuse water is promising for advanced MCDI studies, considering its potential as a more sustainable and resource-efficient alternative to conventional approaches, particularly in high-demand desalination applications.

3.2. Impact of concentrate tank change on TDS removal in the circulation process

3.2.1. Single-module configuration

Fig. 5 presents the impact of concentrate tank replacement

frequencies on the effluent TDS over 5000 s of circulation process operation in the single-module configuration. When the concentrate tank was replaced every 5 cycles, the effluent TDS remained relatively stable during adsorption, reflecting effective ion removal (Fig. 5a). However, as the number of cycles increased, a gradual increase in the effluent TDS values was observed during both the adsorption and desorption phases, indicating a cumulative build-up of ions within the recirculated concentrate.

After each replacement point (cycles 6, 11, 16, and 21), the effluent TDS values showed an apparent decrease, indicating a reset in the ion concentrations within the system. This periodic drop in the effluent TDS highlights the effectiveness of frequent replacement in preventing excessive ion accumulation, thereby stabilizing the TDS removal efficiency across multiple cycles. Such regular replacement frequencies mitigate ion saturation in the concentrate tank, allowing the system to maintain steady desalination performance.

The build-up of ions was more pronounced when the concentrate tank was replaced every 10 cycles (Fig. 5b). Although a similar decrease in TDS was observed immediately after replacement (at cycles 11 and 21), the extended replacement frequency allowed for more significant ion accumulation within the concentrate tank between the replacements. Consequently, the lowest and peak TDS values increased progressively, reflecting the reduced capacity of the system to maintain low effluent TDS levels consistently. This trend indicates that less frequent replacement reduces operational demands and compromises the TDS removal efficiency, particularly as the number of cycles increases, and the concentration gradient across the electrodes diminishes. However, minor deviations in effluent TDS trends were observed at specific cycles, such as cycle 2 with both 1000 and 2000 mg/L influent,

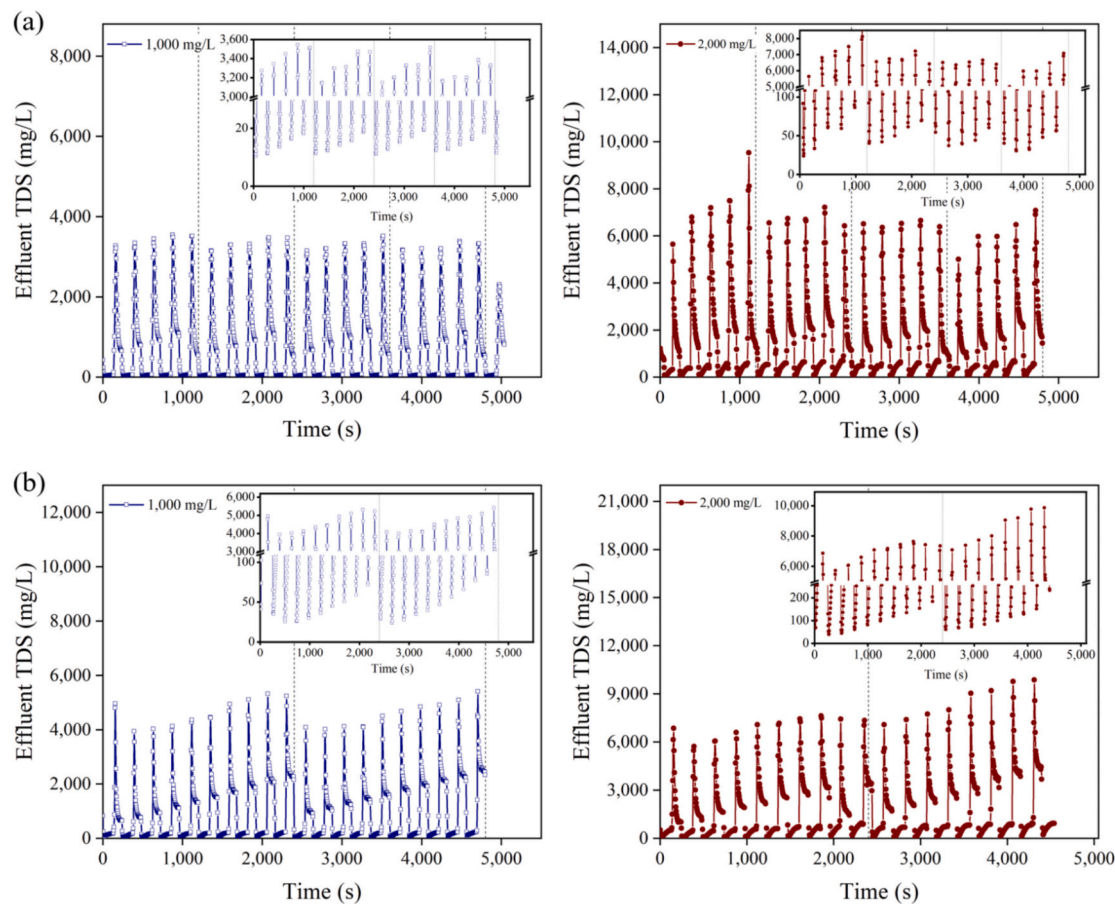


Fig. 5. Changes in TDS concentration by changing the concentrate tank in (a) 5 cycles and (b) 10 cycles in the single module arrangement. Data points represent 5-s intervals of continuous measurements.

likely due to transient behavior during the early cycles, where operational stabilization was incomplete. These deviations are consistent with the operational dynamics of the system and do not significantly impact the overall trends.

In the single-module configuration, two-way RM ANOVA results revealed a significant main effect of the initial TDS concentration ($F(1, 42) = 4.18, p = 0.047$) and a significant interaction effect between the initial TDS concentration and the concentrate replacement frequency ($F(2, 41) = 9.63, p < 0.0001$) (Table 2). However, the main effect of the concentrate replacement frequency alone was not statistically significant ($F(2, 41) = 2.35, p = 0.101$). These results indicate that concentrate replacement frequency affects TDS removal efficiency. This relationship is particularly pronounced at higher initial TDS concentrations, where ion accumulation occurs more rapidly.

Post hoc pairwise comparisons for the 1000 mg/L concentration showed significant differences between the 5-cycle replacement and no-replacement groups (Mean Difference = -711.63 mg/L, $p = 0.007$), whereas the 10-cycle replacement group showed moderate improvements without reaching significance. For the 2000 mg/L concentration, the differences across replacement frequencies were significant but less distinct, with Mean Differences of -339.87 mg/L (5-cycle vs. no replacement, $p = 0.06854$) and -445.19 mg/L (10-cycle vs. no replacement, $p = 0.01673$). These results suggest that, while concentrate replacement improves desalination performance, high initial TDS levels challenge the capacity of a single module to maintain stable effluent TDS effectively.

For the 1000 mg/L initial TDS, the effluent TDS levels consistently decreased during each adsorption phase, with minor increases across cycles. When the concentrate tank was replaced every 5 cycles, a substantial drop in the effluent TDS was observed, emphasizing the importance of regular replacement in sustaining low TDS levels. This pattern was more pronounced for the 2000 mg/L concentration, with the effluent TDS increasing rapidly across the cycles until replacement. This finding highlights the impact of concentrate replacement on maintaining efficient desalination, particularly under high-TDS conditions, although concentrate replacement alone was not significant in this configuration.

3.2.2. Dual-module configuration

The dual-module configuration demonstrated significantly better TDS removal efficiency under both replacement frequencies (Fig. 6). This improvement is due to the increased electrode surface area and ion adsorption capacity inherent in the dual-module configuration, which facilitates more effective desalination and reduces ion accumulation over successive cycles. In both replacement cycles, the effluent TDS values remained consistently low during adsorption, reflecting the effectiveness of dual-module in minimizing ion build-up. Unlike the single-module configuration, which showed a distinct increase in effluent TDS over cycles, the dual-module configuration maintained steady desalination performance without pronounced concentration spikes. The superior TDS removal and stability compared to the single-module configuration, with frequent replacement cycles, further support steady desalination efficiency under high-TDS conditions.

Two-way RM ANOVA results revealed significant main effects for

both the initial TDS concentration ($F(1, 42) = 763.23, p < 0.0001$) and concentrate replacement frequency ($F(2, 41) = 290.78, p < 0.0001$) as well as a significant interaction effect ($F(2, 41) = 16.65, p < 0.0001$; Table 2). These results indicate that the initial TDS level strongly influences the effects of the concentrate replacement frequency on TDS removal and that the dual-module configuration also benefits from frequent concentrate replacement.

Post hoc pairwise comparisons for the 1000 mg/L concentration revealed significant differences between the 5 cycle replacement and both the 10-cycle and no replacement conditions, with Mean Differences of -920.78 mg/L and -978.70 mg/L, respectively (both $p < 0.001$). This finding highlights the efficiency of the dual-module in maintaining a lower effluent TDS with more frequent replacement at lower initial TDS levels, especially compared to the single-module, where TDS increases were more pronounced at higher TDS loads. At a 2000 mg/L concentration, the 5-cycle replacement produced lower effluent TDS levels than no replacement (Mean Difference = -241.04 mg/L, $p < 0.05$). However, the difference between the 5-cycle and 10-cycle replacements was insignificant (Mean Difference = -152.71 mg/L, $p = 0.837$). This suggests that while frequent replacement is beneficial, the impact diminishes slightly at higher TDS levels, a trend observed in both the single- and dual-module configurations.

These results suggest that the dual-module configuration is more effective in sustaining low effluent TDS levels across cycles than the single-module configuration, particularly when a 5-cycle replacement frequency is applied. The reduced effectiveness at a higher initial TDS of 2000 mg/L indicates that, even with a dual-module, higher TDS levels present challenges for stable desalination performance, implying the potential benefits of additional modules or alternative configurations under high-TDS conditions. The increased resilience of the dual-module to ion buildup highlights its advantage over the single-module in managing a higher initial TDS, particularly with regular concentrate tank replacements.

The relationship between energy consumption and desalination performance was further analyzed through specific adsorption capacity (SAC) calculations, presented in Figs. S4 and S5 with detailed results and discussions in SI. The results showed distinct clustering patterns based on initial TDS concentrations with both configurations demonstrating SAC values ranging from 35 to 80 mg/g. In the single-module configuration, cycle progression indicated decreasing efficiency with higher energy consumption, while the dual-module maintained stable SAC values despite increased energy demands. These findings complement the earlier observations about TDS removal efficiency and energy consumption patterns, providing additional insights into the operational characteristics of the system under various conditions.

3.3. Energy consumption and efficiency

Fig. 7 shows the energy consumption of the conventional (Fig. 7a) and circulation (Fig. 7b) processes across the single- and dual-module configurations during 10 cycles, with initial TDS concentrations of 1000 and 2000 mg/L. In both processes, the energy consumption was higher in the dual-module configuration than in the single-module configuration. This is attributed to the increased number of electrodes

Table 2

Two-way repeated measures ANOVA results for the effects of initial TDS concentration and concentrate replacement frequency on TDS removal efficiency.

Configuration	Effect	Sum of squares	df	Mean square	F-value	p-value	Significance
Single module	Initial TDS concentration	5.53×10^6	1	5.53×10^6	4.18	0.047	Significant
	Concentrate replacement	9.31×10^6	2	4.66×10^6	2.35	0.101	–
	Interaction (TDS x Replacement)	1.79×10^7	2	8.95×10^6	9.63	<0.0001	Significant
	Error (within-subjects)	7.80×10^7	42	1.86×10^6	–	–	–
	Total	9.90×10^7	45	–	–	–	–
Dual module	Initial TDS concentration	7.75×10^8	1	7.75×10^8	763.23	<0.0001	Significant
	Concentrate replacement	2.17×10^8	2	1.08×10^8	290.78	<0.0001	Significant
	Interaction (TDS x Replacement)	2.88×10^7	2	1.44×10^7	16.65	<0.0001	Significant
	Error (within-subjects)	9.75×10^8	42	2.32×10^7	–	–	–
	Total	1.26×10^9	45	–	–	–	–

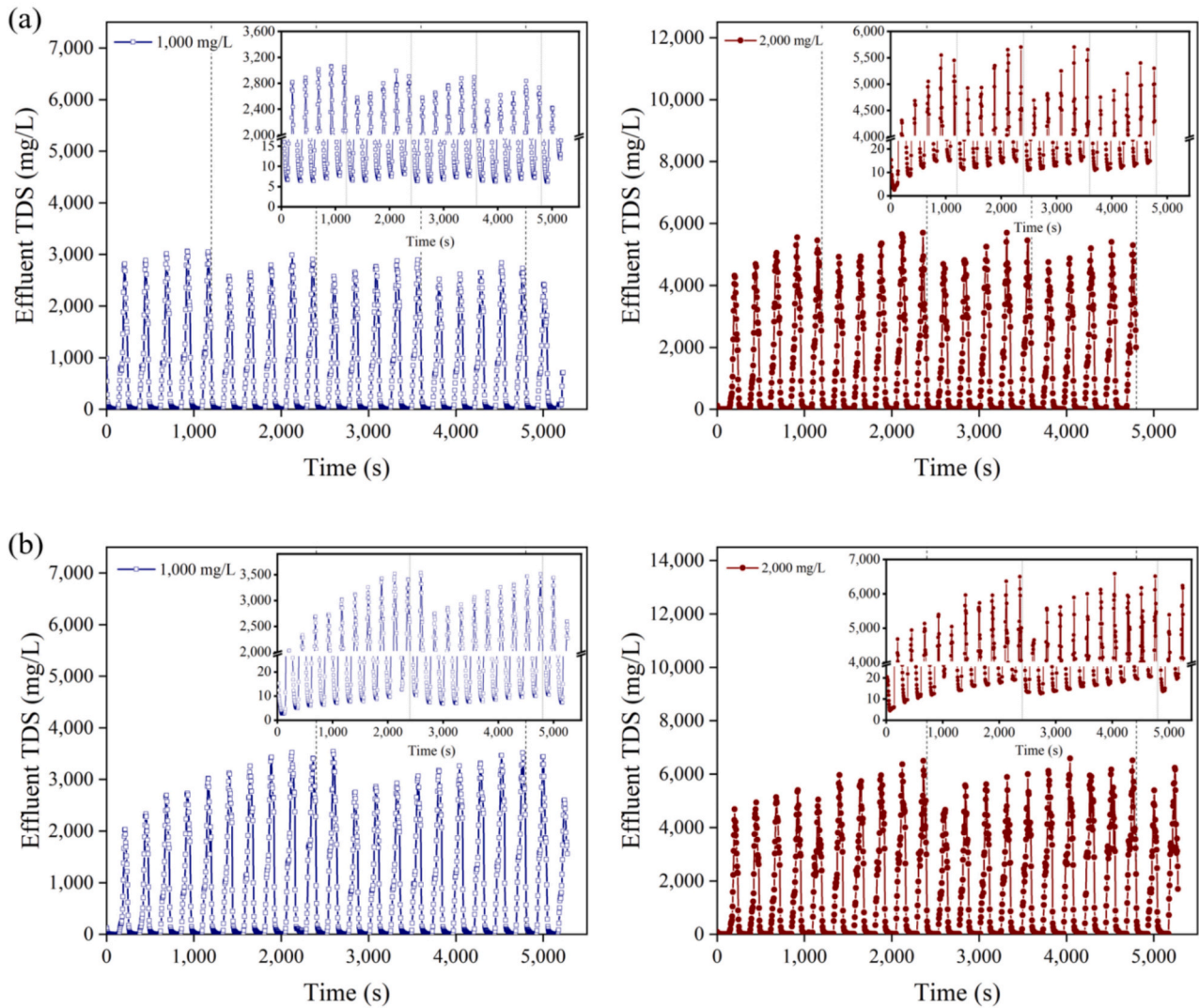


Fig. 6. Changes in TDS concentration by changing the concentrate tank in (a) 5 cycles and (b) 10 cycles in the dual module arrangement. Data points represent 5-s intervals of continuous measurements.

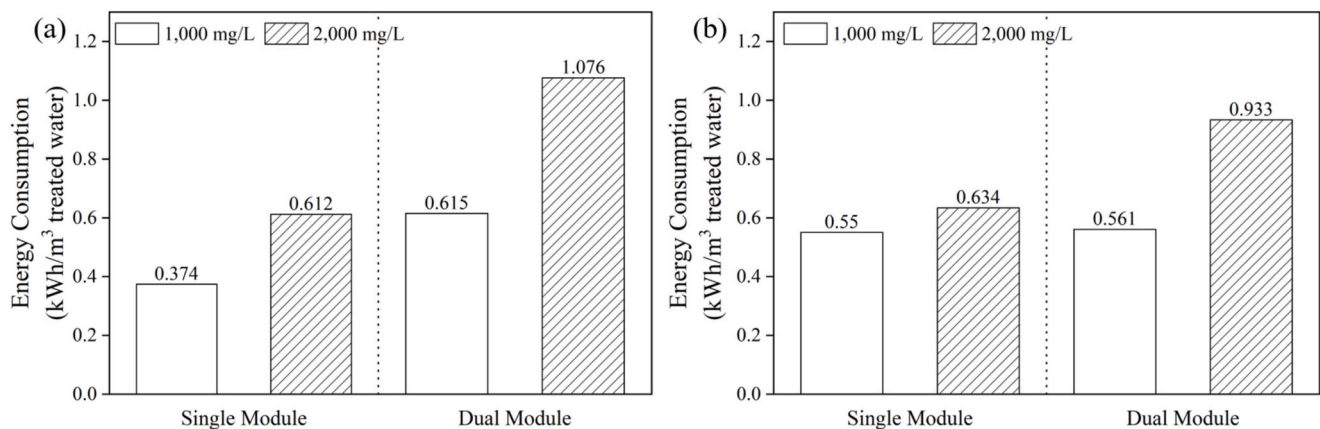


Fig. 7. Energy consumption of (a) conventional and (b) circulation processes at 10 cycles.

and larger surface area for ion removal. For the conventional process, the single-module configuration consumed 0.374 kWh/m³ for the 1000 mg/L initial TDS and 0.612 kWh/m³ for 2000 mg/L, whereas the dual-

module configuration consumed 0.615 and 1.076 kWh/m³ for 1000 and 2000 mg/L, respectively. In the circulation process, the single-module configuration consumed 0.550 kWh/m³ at 1000 mg/L and 0.634

kWh/m³ at 2000 mg/L, whereas the dual-module configuration consumed 0.561 and 0.933 kWh/m³ for 1000 and 2000 mg/L, respectively. The circulation process consumed less energy in the dual-module configuration because the higher capacity for ion removal helped mitigate the impact of concentrate recirculation on energy consumption. The circulation process generally consumes more energy than the conventional process because of the concentrate circulation mechanism, where the concentration of ions in the concentrate tank keeps increasing as the desorption continues. Despite this increase in energy consumption, the high desalination efficiency, reduced ion build-up, and much higher production yield achieved by the circulation process can justify the additional energy requirements, particularly in applications where stable and efficient desalination is prioritized. Furthermore, the data presented for the circulation process reflected operations without concentrate replacement up to the tenth cycle, signifying its potential for extended, lower-maintenance operations in long-term desalination settings.

To better contextualize the energy consumption of the circulation process, reported energy consumption ranges for RO and electrodialysis systems under similar TDS conditions are summarized. For brackish water reverse osmosis (BWRO), energy consumption varies depending on system design, operational conditions, and salinity levels. Studies on BWRO systems have reported specific energy consumption (SEC) ranging from 1.82 to 2.21 kWh/m³ for full-scale plants treating feed water with a TDS of 5256 mg/L [33], and from 0.270 to 0.555 kWh/m³ for simulated systems treating feed TDS from 1501 to 5815 mg/L, albeit with lower rejection rates of 50–70 % [34]. Energy requirements for electrodialysis vary significantly with feed salinity and system configuration. At feed concentrations of 2.0, 3.5, and 5.0 g/L, SEC values of 0.7, 1.1, and 1.8 kWh/m³, respectively, were reported [35]. Another study on electrodialysis brine management with a feed TDS of 23,216 mg/L showed SEC values increasing from 1 to 7.14 kWh/m³ as the removal ratio approached 1 [36]. While the energy consumption of the circulation process was not directly compared to these technologies due to differences in scale, configuration, and objectives, this study focuses on the feasibility of integrating a circulation process into MCDI to enhance water recovery with manageable energy demands. The results demonstrate the potential of the circulation process as an energy-efficient approach, particularly for brackish water desalination at the pilot scale.

However, this design choice has limitations, particularly the increased energy demand associated with continuous circulation and the potential for ion accumulation over prolonged operation without maintenance. In real-world applications, the absence of concentrate replacement can lead to performance degradation over extended periods, suggesting the need for periodic interventions to sustain optimal

desalination efficiency. Future studies should examine strategies to balance the benefits of long-cycle low-maintenance operations with energy efficiency for operational-scale applications of MCDI systems. Investigating the optimal concentrate replacement frequencies or alternative recirculation methods can reduce energy demands while preventing ion saturation. Additional research on larger module configurations (e.g., triple or quadruple modules) and adaptive power management, such as dynamic voltage control across cycles, may enhance the scalability of the circulation process.

To understand how concentrate replacement affects energy demand, the energy consumption across each cycle was measured within the circulation process, with concentrate replacement occurring every 5 or 10 cycles (Fig. 8). Energy consumption trends across cycles indicate the influence of initial TDS levels on operational demand, with the 2000 mg/L concentration consistently requiring more energy than the 1000 mg/L concentration across all configurations. This indicates the higher ion loads leads to a gradual increase in energy demand over time reflecting the accumulation of ions in the concentrate tank and intensifying the energy requirement to achieve steady TDS removal.

Periodic concentrate replacement effectively resets energy demand, creating noticeable dips following each replacement. The 5-cycle replacement frequency consistently maintains a lower energy consumption, as frequent replacement reduces ion buildup. Conversely, with the 10-cycle replacement, the energy peaks became more pronounced before each replacement because the prolonged frequency allowed for more significant ion accumulation. This pattern is especially evident in the 2000 mg/L condition, where a higher initial TDS concentration accelerates the rate of ion buildup, pushing the energy demand to higher levels.

Comparing the single- and dual-module configurations, the dual-module exhibited higher energy consumption throughout, which is a trade-off for their superior TDS removal performance and stability over extended cycles. These results highlight the importance of balancing concentrate replacement frequency with energy efficiency, particularly in high-TDS feedwater applications.

4. Conclusions

This study provided insights into the relationships between initial TDS concentration, module configuration, and concentrate replacement frequency on desalination efficiency and energy consumption in the MCDI system. Our findings demonstrated that the circulation process, particularly in the dual-module configuration, outperformed the conventional process by maintaining lower effluent TDS levels and achieving higher production yields. The two-way RM ANOVA results

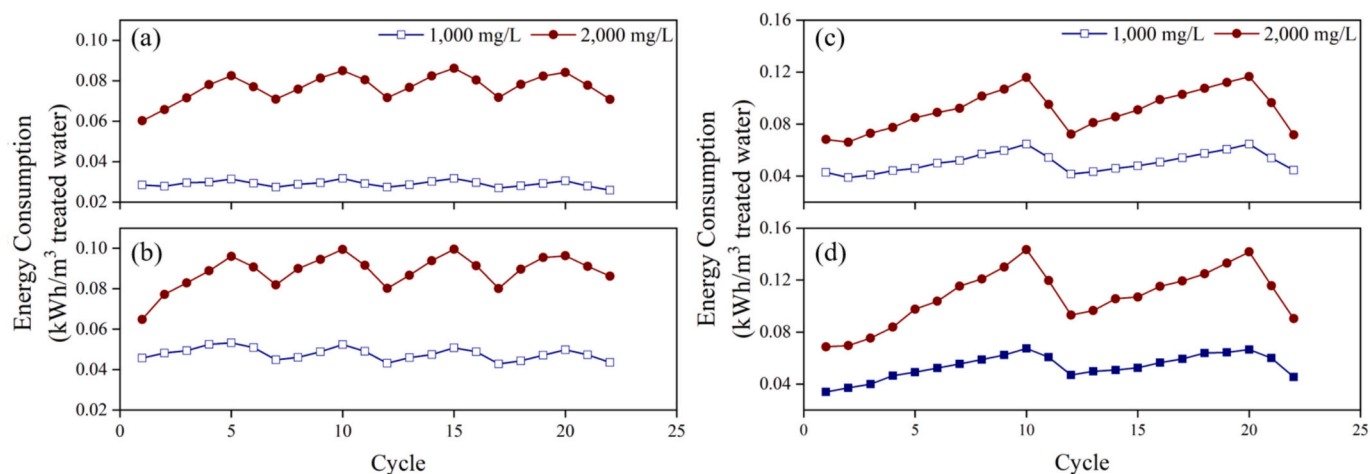


Fig. 8. Energy consumption of the circulation process (a) using the single module at 5 cycles, (b) using the dual module at 5 cycles, (c) using the single module at 10 cycles, and (d) using the dual module at 10 cycles.

further confirmed that the dual-module configuration with frequent concentrate replacement (every 5 cycles) delivered the most effective desalination performance, particularly at higher TDS feed concentrations. Although the circulation process consumed more energy than the conventional approach, the high TDS removal efficiency and superior production yield offset the increased energy demand with solid potential for high-efficiency desalination. Regular concentrate replacement further enhanced performance under high-TDS conditions, though continuous real-world application may face operational challenges.

This study had limitations that require further investigation. The energy data reflect operations without concentrate replacement for up to 10 cycles, which, while suitable for low-maintenance applications, may not capture all real-world conditions. While the conventional process offers simplicity and lower energy consumption, its limited production yield makes it less favorable for scenarios prioritizing water recovery and desalination efficiency. The circulation process was advantageous for applications requiring high water recovery and desalination efficiency, offering a sustainable solution for maximizing treated water quality and production yield. Overextended operations, ion accumulation, and membrane fouling could impact energy demands, highlighting the need for field trials and long-term assessments. Future research should focus on multimodule systems, optimized configurations, and energy-efficient controls to evaluate the feasibility of continuous desalination with concentrate replacement.

CRedit authorship contribution statement

Bokjin Lee: Conceptualization, Formal analysis, Writing – original draft. **Jusuk An:** Conceptualization, Data curation, Writing – review & editing. **Seungjae Yeon:** Investigation, Funding acquisition, Writing – review & editing. **Changseog Oh:** Formal analysis, Visualization, Writing – review & editing. **Hyun Je Oh:** Conceptualization, Funding acquisition, 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.desal.2025.118686>.

Data availability

All data supporting the findings of this study are provided in this manuscript and Supplementary File.

References

- [1] W.A. Jury, H.J. Vaux, The emerging global water crisis: Managing scarcity and conflict between water users, in: *Advances in Agronomy*, Academic Press, 2007, pp. 1–76, [https://doi.org/10.1016/S0065-2113\(07\)95001-4](https://doi.org/10.1016/S0065-2113(07)95001-4).

- [2] V.G. Gude, Desalination and water reuse to address global water scarcity, *Rev. Environ. Sci. Bio Technol.* 16 (2017) 591–609, <https://doi.org/10.1007/s11557-017-9449-7>.
- [3] World Health Organization (WHO), Drinking-water, 2022. <https://www.who.int/news-room/fact-sheets/detail/drinking-water>.
- [4] D. Adityawarman, G. Lugito, S. Kawi, I.G. Werten, K. Khoiruddin, Advancements and future trends in nanostructured membrane technologies for seawater desalination, *Desalination* 597 (2025) 118390, <https://doi.org/10.1016/j.desal.2024.118390>.
- [5] A.W. Mohammad, Y.H. Teow, W.L. Ang, Y.T. Chung, D.L. Oatley-Radcliffe, N. Hilal, Nanofiltration membranes review: recent advances and future prospects, *Desalination* 356 (2015) 226–254, <https://doi.org/10.1016/j.desal.2014.10.043>.
- [6] Z. Yang, Y. Zhou, Z. Feng, X. Rui, T. Zhang, Z. Zhang, A review on reverse osmosis and nanofiltration membranes for water purification, *Polymers* 11 (2019), <https://doi.org/10.3390/polym11081252>.
- [7] A. Shabib, B. Tatan, Y. Elbaz, A.A. Hassan, M.A. Hamouda, M.A. Maraqa, Advancements in reverse osmosis desalination: technology, environment, economy, and bibliometric insights, *Desalination* (2024) 118413, <https://doi.org/10.1016/j.desal.2024.118413>.
- [8] S. Porada, R. Zhao, A. van der Wal, V. Presser, P.M. Biesheuvel, Review on the science and technology of water desalination by capacitive deionization, *Prog. Mater. Sci.* 58 (2013) 1388–1442, <https://doi.org/10.1016/j.pmatsci.2013.03.005>.
- [9] K. Maheshwari, M. Agrawal, A.B. Gupta, Experimental investigation for treating the RO reject stream through capacitive deionization, *Sep. Purif. Technol.* 276 (2021) 119261, <https://doi.org/10.1016/j.seppur.2021.119261>.
- [10] O. Sufiani, H. Tanaka, K. Teshima, R.L. Machunda, Y.A.C. Jande, Capacitive deionization: capacitor and battery materials, applications and future prospects, *Desalination* 587 (2024) 117923, <https://doi.org/10.1016/j.desal.2024.117923>.
- [11] Q. Huang, L. Sheng, T. Wu, L. Huang, J. Yan, M. Li, Z. Chen, H. Zhang, Research progress on the application of carbon-based composites in capacitive deionization technology, *Desalination* 593 (2025) 118197, <https://doi.org/10.1016/j.desal.2024.118197>.
- [12] M.E. Suss, S. Porada, X. Sun, P.M. Biesheuvel, J. Yoon, V. Presser, Water desalination via capacitive deionization: what is it and what can we expect from it? *Energ. Environ. Sci.* 8 (2015) 2296–2319, <https://doi.org/10.1039/C5EE00519A>.
- [13] H. Yoon, K. Jo, K.J. Kim, J. Yoon, Effects of characteristics of cation exchange membrane on desalination performance of membrane capacitive deionization, *Desalination* 458 (2019) 116–121, <https://doi.org/10.1016/j.desal.2019.02.009>.
- [14] T.-H. Chen, Y.-H. Kao, Y.-Y. Shen, C.-S. Fan, C.-H. Hou, Pilot-scale membrane capacitive deionization for water reclamation: commissioning, performance benchmarking, and long-term assessment, *Desalination* (2024) 118428, <https://doi.org/10.1016/j.desal.2024.118428>.
- [15] Y. Zhao, Y. Wang, R. Wang, Y. Wu, S. Xu, J. Wang, Performance comparison and energy consumption analysis of capacitive deionization and membrane capacitive deionization processes, *Desalination* 324 (2013) 127–133, <https://doi.org/10.1016/j.desal.2013.06.009>.
- [16] W. Tang, D. He, C. Zhang, P. Kovalsky, T.D. Waite, Comparison of faradaic reactions in capacitive deionization (CDI) and membrane capacitive deionization (MCDI) water treatment processes, *Water Res.* 120 (2017) 229–237, <https://doi.org/10.1016/j.watres.2017.05.009>.
- [17] A. Hassanvand, G.Q. Chen, P.A. Webley, S.E. Kentish, A comparison of multicomponent electrosorption in capacitive deionization and membrane capacitive deionization, *Water Res.* 131 (2018) 100–109, <https://doi.org/10.1016/j.watres.2017.12.015>.
- [18] Q. Wu, D. Liang, S. Lu, H. Wang, Y. Xiang, D. Aurbach, E. Avraham, I. Cohen, Advances and perspectives in integrated membrane capacitive deionization for water desalination, *Desalination* 542 (2022) 116043, <https://doi.org/10.1016/j.desal.2022.116043>.
- [19] A. Hemmatifar, J.W. Palko, M. Stadermann, J.G. Santiago, Energy breakdown in capacitive deionization, *Water Res.* 104 (2016) 303–311, <https://doi.org/10.1016/j.watres.2016.08.020>.
- [20] C. Bales, B. Lian, J. Fletcher, Y. Wang, T.D. Waite, Site specific assessment of the viability of membrane capacitive deionization (MCDI) in desalination of brackish groundwaters for selected crop watering, *Desalination* 502 (2021) 114913, <https://doi.org/10.1016/j.desal.2020.114913>.
- [21] M. Tauk, G. Folaranmi, M. Cretin, M. Bechelany, P. Siatat, C. Zhang, F. Zavisla, Recent advances in capacitive deionization: a comprehensive review on electrode materials, *J. Environ. Chem. Eng.* 11 (2023) 111368, <https://doi.org/10.1016/j.jece.2023.111368>.
- [22] J. Si, C. Xue, S. Li, L. Yang, W. Li, J. Yang, J. Lan, N. Sun, Selective membrane capacitive deionization for superior lithium recovery, *Desalination* 572 (2024) 117154, <https://doi.org/10.1016/j.desal.2023.117154>.
- [23] Y. Zhao, X. Hu, B. Jiang, L. Li, Optimization of the operational parameters for desalination with response surface methodology during a capacitive deionization process, *Desalination* 336 (2014) 64–71, <https://doi.org/10.1016/j.desal.2013.12.024>.
- [24] M.W. Saleem, W.-S. Kim, Parameter-based performance evaluation and optimization of a capacitive deionization desalination process, *Desalination* 437 (2018) 133–143, <https://doi.org/10.1016/j.desal.2018.02.023>.
- [25] B. Lee, C. Oh, J. An, S. Yeon, H.J. Oh, Optimizing operational conditions of pilot-scale membrane capacitive deionization system, *Sustainability* 15 (2023), <https://doi.org/10.3390/su152416809>.
- [26] C. Oh, B. Lee, J. An, S. Yeon, H. Je Oh, Performance optimization of a pilot-scale membrane capacitive deionization (MCDI) system operating with circulation process, *Sep. Purif. Technol.* 343 (2024) 126937, <https://doi.org/10.1016/j.seppur.2024.126937>.

- [27] C. Tan, C. He, J. Fletcher, T.D. Waite, Energy recovery in pilot scale membrane CDI treatment of brackish waters, *Water Res.* 168 (2020) 115146, <https://doi.org/10.1016/j.watres.2019.115146>.
- [28] N. Köller, L. Mankertz, S. Finger, C.J. Linnartz, M. Wessling, Towards pilot scale flow-electrode capacitive deionization, *Desalination* 572 (2024) 117096, <https://doi.org/10.1016/j.desal.2023.117096>.
- [29] W. Xing, J. Liang, W. Tang, D. He, M. Yan, X. Wang, Y. Luo, N. Tang, M. Huang, Versatile applications of capacitive deionization (CDI)-based technologies, *Desalination* 482 (2020) 114390, <https://doi.org/10.1016/j.desal.2020.114390>.
- [30] A. Ramachandran, D.I. Oyarzun, S.A. Hawks, M. Stadermann, J.G. Santiago, High water recovery and improved thermodynamic efficiency for capacitive deionization using variable flowrate operation, *Water Res.* 155 (2019) 76–85, <https://doi.org/10.1016/j.watres.2019.02.007>.
- [31] H. Yoon, T. Min, S.-H. Kim, G. Lee, D. Oh, D.-C. Choi, S. Kim, Effect of activated carbon electrode material characteristics on hardness control performance of membrane capacitive deionization, *RSC Adv.* 13 (2023) 31480–31486, <https://doi.org/10.1039/D3RA05615E>.
- [32] J.B. Waugh, S.K. Babu, Q. Kang, N.K. Moehring, A. Benavidez, X. Wang, P. R. Kidambi, P.N. Pintauro, J.S. Spendelow, Hierarchically porous electrospun carbon nanofiber for high-rate capacitive deionization electrodes, *Desalination* 584 (2024) 117610, <https://doi.org/10.1016/j.desal.2024.117610>.
- [33] A. Ruiz-García, I. Nuez, Long-term intermittent operation of a full-scale BWRO desalination plant, *Desalination* 489 (2020) 114526, <https://doi.org/10.1016/j.desal.2020.114526>.
- [34] A. Ruiz-García, I. Nuez, M.D. Carrascosa-Chisvert, J.J. Santana, Simulations of BWRO systems under different feedwater characteristics, Analysis of operation windows and optimal operating points, *Desalination* 491 (2020) 114582, <https://doi.org/10.1016/j.desal.2020.114582>.
- [35] Z. Yang, L. Ren, Q.-B. Chen, Y. Xu, T. Han, Y. Gao, J. Wang, Temperature effects on ion migration and energy consumption during brackish water electrodialysis desalination, *Desalination* 586 (2024) 117792, <https://doi.org/10.1016/j.desal.2024.117792>.
- [36] T.L. Oddonetto, E. Deemer, A. Lugo, M. Cappelle, P. Xu, I. Santiago, W.S. Walker, Assessment of salt-free electrodialysis metathesis: a novel process for brine management in brackish water desalination using monovalent selective ion exchange membranes, *Desalination* 592 (2024) 118160, <https://doi.org/10.1016/j.desal.2024.118160>.