Scaling and Corrosion Dynamics for Full-Scale SWRO Desalination Plants in Egypt: Challenges and Mitigation Strategies

Ali Nada [1,2,3,*], Mahmoud Sharaan [1,4], Mohamed Elshemy [2,5], Manabu Fujii [3], and Mona G. Ibrahim [1,6]

[1]Environmental Engineering Department, Egypt-Japan University of Science and Technology, Alexandria, 21934, Egypt
[2]Department of Irrigation and Hydraulics Engineering, Faculty of Engineering, Tanta University, Tanta, 31512, Egypt
[3]Department of Civil and Environmental Engineering, School of Environment and Society, Tokyo Institute of Technology, Tokyo, 152-8550, Japan
[4]Civil Engineering Department, Faculty of Engineering, Suez Canal University, Ismailia, 41522, Egypt
[5]Faculty of Engineering, Al-Baha University, Al-Baha, 4781, Saudi Arabia
[6]Environmental Health Department, High Institute of Public Health, Alexandria University, Alexandria, 21544, Egypt
Email: ali.nada@ejust.edu.eg (A.N.); mahmoud.sharaan@ejust.edu.eg (M.S.); m.elshemy@f-eng.tanta.edu.eg (M.E.); fujii.m.ah@m.titech.ac.jp (M.F.); mona.gamal@ejust.edu.eg (M.G.I.)
*Corresponding author

Manuscript received March 10, 2025; revised April 7, 2025; accepted April 28, 2025; published August 5, 2025

***Abstract*—Desalination is a non-traditional and sustainable source of safe drinking water. Scaling and corrosiveness are critical issues to ensure the sustainability of desalination plants, as they directly affect economic feasibility, operational efficiency, environmental compliance, and the quality of the produced water. The main objective of this study is to evaluate the scaling and corrosion potential for three different water types (feed water, brine, and permeate) related to Seawater Reverse Osmosis (SWRO) desalination plants in Egypt. Statistical approaches and saturation indicators, including the Langelier Saturation Index (LSI), Stiff & Davis Stability Index (S&DSI), and Ryznar Stability Index (RSI), were applied to data collected monthly during 2023. The results revealed that feedwater exhibited S&DSI values ranging from 0.18 to 0.75, indicating scale formation but non-corrosive states. In contrast, RSI values varied between 7.2 and 8.15, confirming the potential corrosion tendency in all plants except one that used shore wells intake. Accordingly, brine S&DSI values ranged from 0.03 to 1.6, signifying conditions from balanced to scale-forming, while their RSI values varied between 5.5 and 8.1, predicting scaling tendencies at lower values and low to high corrosion risks at higher values. On the contrary, permeate water LSI values ranged from –0.28 to –3.21, indicating undersaturation and a tendency toward corrosivity, and the higher RSI (8.55 to 12.85) further confirmed the aggressive nature of the permeate water. The results showed that a slight change in pH levels has the most significant impact on the water's tendency toward scaling, while normal temperature variations did not have the same influence. However, low calcium concentrations are key to increasing the water's corrosive tendency. The findings highlight the need for careful water chemistry management to balance scaling and corrosion risks in desalination systems. Early and continuous detection is recommended to help operators optimize chemical dosing, adjust pretreatment processes, and enhance desalination system longevity by mitigating scaling and corrosion risks.**

***Keywords*—desalination plants, seawater reverse osmosis, saturation index, scaling and corrosiveness potential, sustainable water management**

I. Introduction

Under global water scarcity and rising demand, societies are increasingly adopting desalination as a crucial strategy to complement dwindling freshwater resources and secure a reliable, drought-resistant water supply. Improving desalination technologies, particularly the reverse osmosis (RO) membrane technique, has effectively provided clean and safe drinking water [1]. However, seawater RO desalination faces several operational and technical challenges that can limit its efficiency and sustainability [2]. Among the most critical issues are high energy demands, membrane fouling and scaling, the potential corrosiveness of the process environment, and concerns related to the consistency and quality of the produced water [3]. Fouling is the unwanted buildup of deposits on the membrane surface, typically forming an additional barrier layer that reduces salt passage and water flow; however, in cases where it causes physical damage, such as membrane puncturing, it may lead to increased salt leakage. It is categorized into four types: inorganic (scaling), organic, biofouling, and colloidal. Although scale accounts for less than 10% of fouling events, it remains a critical contributor to membrane degradation [4]. Scaling refers to the deposition of salts that have exceeded their solubility limits. These salts can accumulate not only on the membrane surfaces but also on the inner surfaces of brine pipes, leading to blockages and negatively impacting the performance of the desalination plant. The six types of salts that can cause membrane scaling include calcium carbonate ($CaCO_3$), calcium sulfate ($CaSO_4$), barium sulfate ($BaSO_4$), strontium sulfate ($SrSO_4$), calcium fluoride (CaF_2), and silica (SiO_2) [5]. On the other hand, Pipeline corrosion refers to the degradation of pipe materials and associated infrastructure caused by their exposure to the surrounding environment. It can lead to structural failures, necessitating costly repairs and continuous monitoring efforts. The financial burden of corrosion-related damage and maintenance expenditures amounts to billions of dollars annually globally [6]. Desalination plants often face significant operational challenges due to scaling and corrosion, which can significantly reduce system performance, increase maintenance costs, and shorten membrane lifespan [7].

II. Literature Review

Water's scaling and corrosion potential in various applications can be measured based on stability indices. The commonly used indices for RO systems are Saturation Index (SI) and Supersaturation ratio (Sr), Langelier Saturation

Index (LSI), and Stiff-Davis Stability Index (S&DSI). SI and Sr are applicable for all scaling species, while LSI and S&DSI are used explicitly for calcium carbonate scaling [8]. Many studies have computed scaling and corrosion indices in different water purification systems and resources. Al-Shammiri and Al-Dawas [9] evaluated the scaling potential in SWRO plants in Kuwait using the S&DSI, highlighting its importance as a predictive technique for assessing scale formation risks in concentrated brine streams. Roque [10] used the LSI and Ryznar Stability Index (RSI) to observe scale formation in a Brackish Water Reverse Osmosis (BWRO) method for a Water Treatment Plant (WTP) in Florida, USA. Hernández-Suárez and León [11] reported that desalinated water from RO plants in Spain had an LSI of less than 4, indicating its tendency to dissolve calcium carbonate and pose a risk of corrosion due to its low bicarbonate content and higher chloride and sulfate concentrations. Mahdavi *et al.* [12] estimated the corrosion and scaling indices values such as LSI, RSI, Puckorius Scaling Index (PSI), and aggressive index (AI) from 40 sites for the water distribution network of Saveh city, Iran. The results indicated that water tends to precipitate calcium carbonate and form scale because of high levels of total hardness, carbonate hardness, and total alkalinity.

Several seawater desalination plants utilizing Reverse Osmosis (RO) technology have been established in Egypt along the Red and Mediterranean Seas. These plants serve as a source of water for coastal areas far from the Nile River and its branches [13], helping to reduce the costs and challenges associated with water distribution through pipelines and pumping stations [14]. Egypt has a long-term strategic plan to increase the number of desalination plants and their capacity to meet the growing water demands for various applications and new sustainable cities [15]. This study makes a new contribution by being the first to conduct a large-scale survey across Egypt, encompassing water quality data from eight full-scale SWRO desalination plants along the Red Sea and Mediterranean coasts. Unlike previous studies, which typically focus on specific plant components or limited water types, this work offers a comprehensive assessment by evaluating three key water streams (feed water, brine, and permeate). Moreover, the study applies three widely recognized stability indices (LSI, RSI, and S&DSI) in parallel over a full annual cycle, providing a robust and multi-dimensional perspective on scaling and corrosion behavior. Using real water quality data enhances the practical relevance of the findings and supports the development of tailored mitigation strategies based on actual plant conditions. This study aims to evaluate the status of eight full-scale SWRO Egyptian desalination plants over a one-year period, focusing on the potential for scaling or corrosion in different types of water (feedwater, brine, and permeate) using various water stability indicators specific to each type. The impact of various water quality parameters on water stability indicators in desalination plants has been discussed. The study also investigates the challenges these plants face and the potential preventive measures to ensure the sustainability of desalination processes.

III. Materials and Methods

Eight SWRO full-scale desalination plants were selected along the Egyptian coasts, including four plants on the Red Sea: El Yusr (DP1), El Tor (DP2), El Galalah (DP3), and Nuweibaa (DP4), and four plants on the Mediterranean Sea: Al Rumaila (DP4), El Alamein (DP5), New Mansoura (DP6), and Cleopatra (DP7), as shown in Fig. 1. Locations and operational descriptions for the studied plants are presented in Table 1.

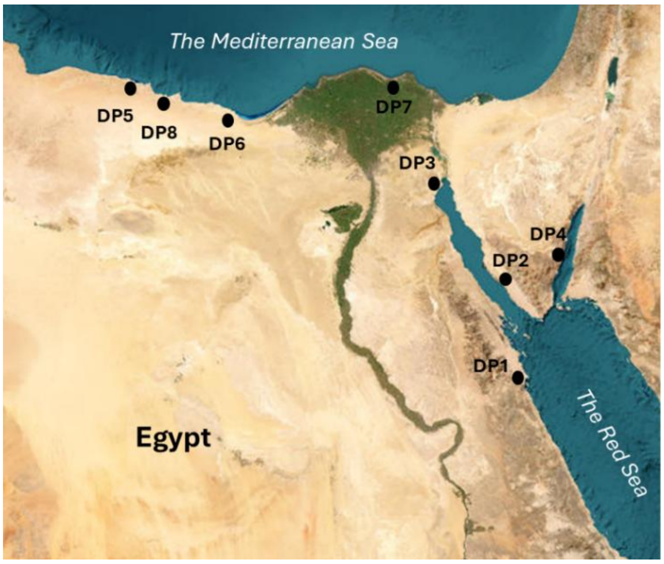

Fig. 1. Locations of the selected desalination plants.

Table 1. Descriptions of the studied SWRO Egyptian desalination plants

Desalination plant	ID	Location		Operational Specifications			
		Longitude (x)	Latitude (y)	Feed Source	Start Operation (Year)	Total Capacity (m³/day)	Recovery ratio (%)
El Yusr	DP1	N 33° 50′ 31′′	E 27° 13′51′′	Red Sea	2016	80000	30–33
El Tor	DP2	N 33° 35′ 42′′	E 28° 15′13′′		2018	30000	43–45
El Galalah	DP3	N 32° 28′ 04′′	E 29° 27′40′′		2019	150000	43–45
Nuweibaa	DP4	N 34° 40′ 42′′	E 28° 58′42′′		2021	15000	42–45
Al Rumaila	DP5	N 27° 20′ 46′′	E 31° 20′20′′	Mediterranean Sea	2016	60000	31–35
El Alamein	DP6	N 28° 49′ 58′′	E 30° 55′19′′		2019	150000	36–40
New Mansoura	DP7	N 31° 21′ 06′′	E 31° 31′33′′		2022	80000	38–40
Cleopatra	DP8	N 27° 11′ 38′′	E 31° 22′31′′		2016	4500	26–30

Ninety-six samples were collected from each plant monthly throughout 2023 for different types of water associated with the plant (feedwater, brine (reject), and permeate water) to ensure a comprehensive assessment under various seasonal and operational conditions. Feedwater, brine, and permeate water samples were analyzed monthly in each plant's laboratory during 2023. Fig. 2 shows a schematic diagram of the SWRO desalination system to illustrate the primary operational components in the studied plants and the sampling locations for feed water, brine, and permeate throughout the study. Water quality parameters include water temperature (T), total dissolved solids (TDS), pH, alkalinity (Alk.), and calcium (Ca), as shown in Table 2 as well as major cations (Magnesium (Mg), Sodium (Na), and Potassium (K)), major anions (Chloride (Cl), Bicarbonate (HCO_3), Sulfate (SO_4), and Nitrate (NO_3)) and Boron (B) especially for seawater and brine samples. All datasets related to water quality parameters used in the study were published in [16].

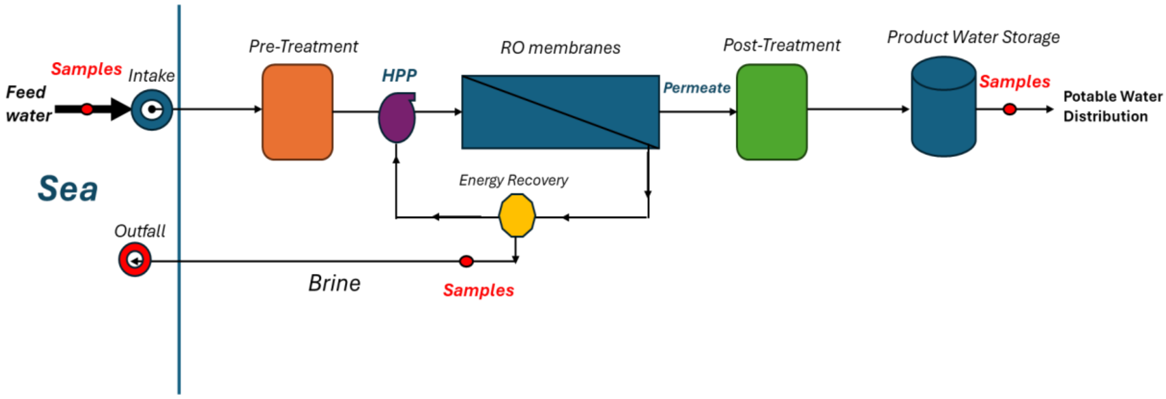

Fig. 2. Schematic diagram of the SWRO desalination system illustrating the main process stages and sampling points (feed, brine, and permeate) in the studied plants.

Table 2. Ranges of the water quality parameters in the studied SWRO Egyptian desalination plants during 2023

DP	Water Type	Temperature (T)	Total dissolved solids (TDS)	pH	Alkalinity (Alk.)	Calcium (Ca)
		°C	mg/L		mg/L	mg/L
DP1	Feed	19.6–28.4	41499–43331	7.97–8.3	99–161	483–505
	Brine		58468–61049	7.14–8.12	200–250	614–641
	Permeate		156–385	7.2–7.8	29.2–39.8	10.7–26.5
DP2	Feed	20–27.2	43524–45001	8.1–8.4	131–148	507–525
	Brine		76098–78680	7.89–8.31	241–334	873–903
	Permeate		109–354	6.1–7.65	50.6–87.6	2.8–9.1
DP3	Feed	20.4–30.1	41264–46231	7.94–8.35	92–188	470–526
	Brine		72144–80829	7.45–8.4	186–319	828–928
	Permeate		213–315	7.02–7.8	60.2–87.7	23.4–34.6
DP4	Feed	18.5–29.1	42666–46842	8.18–8.44	135–148	489–537
	Brine		73469–80629	8.19–8.54	268–362	843–926
	Permeate		133–451	7.01–7.29	60.3–110.6	0.4–8.06
DP5	Feed	17.1–25.5	33500–34341	8.2–8.65	101–168	409–420
	Brine		47235–48363	7.84–8.44	269–320	542–555
	Permeate		158–198	7.8–8.6	38.1–48.5	7.2–9.05
DP6	Feed	18–26.2	37014–38541	7.78–8.22	100–134	453–471
	Brine		57521–59894	7.41–8.02	185–280	604–629
	Permeate		135–365	6.7–8.12	61.2–80.7	12.6–33.8
DP7	Feed	18.2–25.1	38771–40452	7.99–8.3	130–148	453–491
	Brine		70235–73279	8.01–8.14	182–285	844–880
	Permeate		254–281	6.8–7.6	62.1–67.1	27.6–39.5
DP8	Feed	22.2–26.7	40236–41945	7.04–7.45	123–132	733–764
	Brine		54023–57266	6.74–7.36	173–195	746–791
	Permeate		164–285	7.4–7.7	38.4–47.6	7.8–16.6

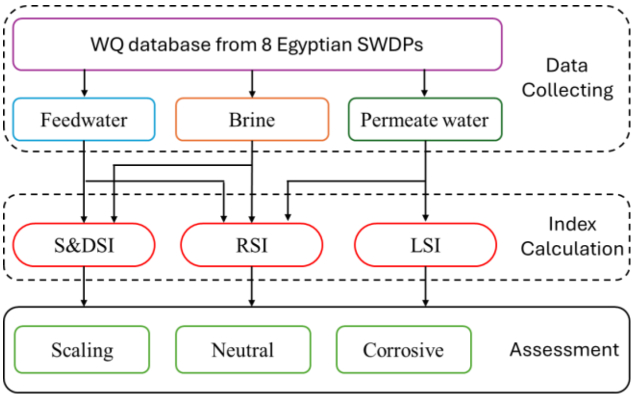

Fig. 3. Flowchart of the study methodology.

This study primarily investigates calcium carbonate scaling, a prevalent type of fouling encountered in Reverse Osmosis (RO) systems and pipelines. The precipitation of calcium carbonate in the desalination system is closely associated with the concentrations of calcium and bicarbonate/carbonate, as well as several other factors, including but not limited to temperature and pH [17]. The scaling potential of calcium carbonate for a specific water composition can be quantified using various indicators, such as the Langelier Saturation Index (LSI), Stiff & Davis Stability Index (S&DSI), and Ryznar Stability Index (RSI). LSI and S&DSI are widely used to assess the potential for calcium carbonate scaling in water. LSI is commonly applied to waters with TDS up to 10,000 mg/L using parameters like Ca, pH, Alk., TDS, and T, whereas S&DSI, which is used for seawater or high-salinity water (TDS > 10,000 mg/L), requires additional significant ion concentrations [18]. RSI, introduced by John Ryznar in 1944, is an empirical predictive tool for assessing scaling potential in water systems. It refines LSI and S&DSI by incorporating observational data on water behavior across various saturation levels, providing a more precise evaluation of a water system's tendency toward scaling or corrosion. The equations are used to calculate saturation indices, and their classifications are presented in Table 3. Fig. 3 summarizes data collection, index calculation, and assessment methodology. The Pearson correlation matrix was used to analyze the relationships between variables and determine the correlation coefficient among them.

This study assumes that the water quality data collected during 2023 accurately represent typical operating conditions in the studied plants, with no major disturbances during sampling. The saturation indices (LSI, RSI, and S&DSI) are valid tools for assessing scaling and corrosion potential under desalination conditions. It is also assumed that the sampled water streams were well-mixed and representative, with stable temperature and pressure during collection. Chemical dosing practices (antiscalants) were consistent across all plants, and no significant cleaning or operational changes occurred during the sampling period. Laboratory measurements are assumed to be accurate and are conducted using standardized procedures.

Table 3. Equations utilized in the calculation of saturation indices

Index	Equations	Range	class	Reference
LSI	$LSI = pH_m - pH_s$ $pH_s = (9.3+A+B)-(C+D)$ $A = (\text{Log (TDS)}-1)/10$ $B = -13.2(\text{Log } (T^{\circ}C+273)) + 34.55$ $C = \text{Log (Ca as } CaCO_3) - 0.4$ $D = \text{Log (Alkalinity as } CaCO_3)$	< 0 = 0 > 0	Corrosive tendency Neutral tendency Scaling tendency	[19]
S&DSI	$S\&DSI = pH_m - pH_s$ $pH_s = pCa + pAlk. + K$ $pCa = -\log_{10} (\text{Ca as } CaCO_3)$ $pAlk. = -\log_{10} (\text{Alkalinity as } CaCO_3)$ K = function of concentrated ionic strength and water temperature	< 0 = 0 > 0	Corrosive tendency Neutral tendency Scaling tendency	[20]
RSI	$RSI = 2\, pH_s - pH_m$	< 6 7–8 > 8	Scaling Low corrosion High corrosion	[21]

$\mathbf{pH_m}$ is the measured pH of the water sample and $\mathbf{pH_s}$ is pH at the saturation state of $\mathbf{CaCO_3}$

IV. Results and Discussions

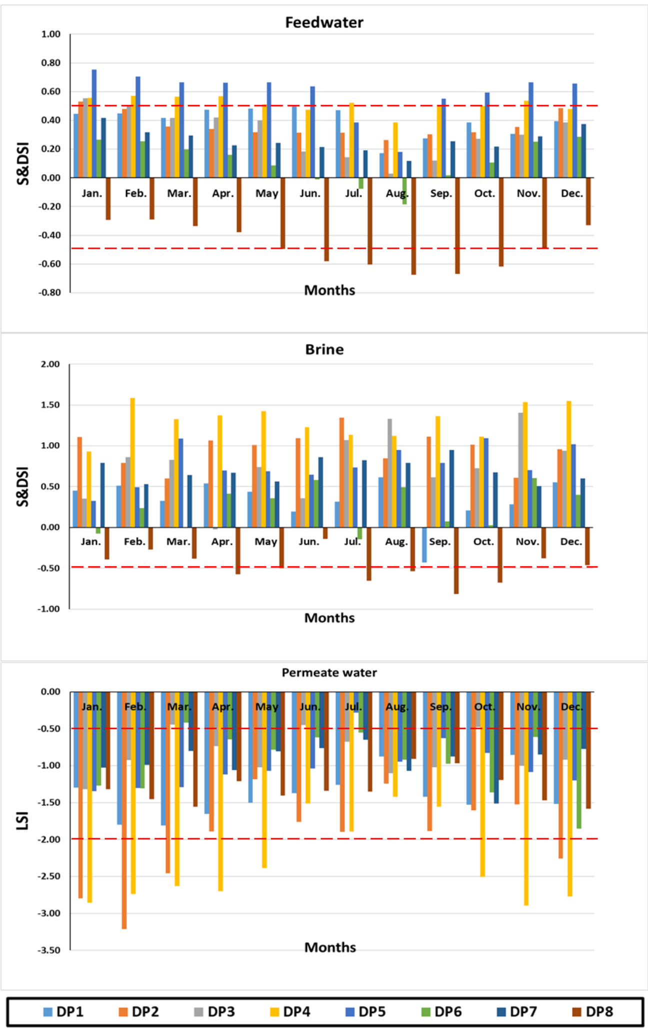

Fig. 4. S&DSI values for (A) feedwater, (B) brine, and LSI values for (C) permeate water in monthly samples of eight desalination plants during 2023.

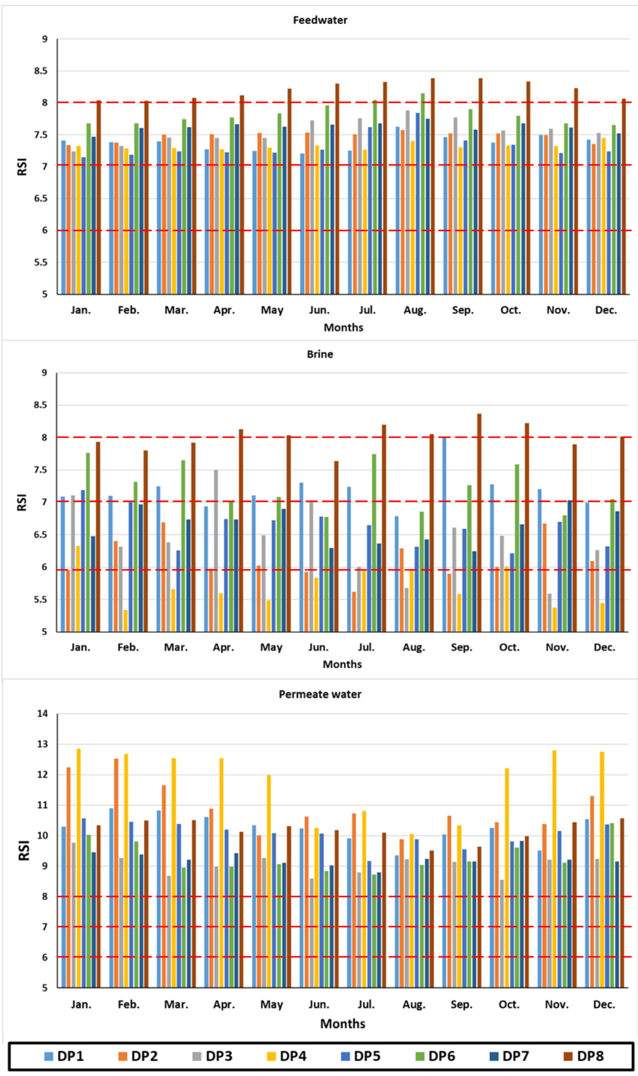

Fig. 5. RSI values for (A) feedwater, (B) brine, and (C) permeate water in monthly samples of eight desalination plants during 2023.

The monthly values of (feedwater and brine) S&DSI and (permeate water) LSI are presented in Fig. 4, while Fig. 5 shows monthly RSI values. Fig. 6 depicts the three heatmaps of Pearson's correlation coefficient between water quality parameters and used scaling/corrosion indices in all feedwater, brine, and permeate samples.

A. Feedwater Samples Assessment

Monthly S&DSI values for seawater exhibited considerable variability throughout the year 2023 (Fig. 4A). Most plants predominantly showed slightly scale-forming (0 < S&DSI < 0.5), with DP4 and DP5 consistently recording the highest values, occasionally reaching the scale-forming but non-corrosive range (S&DSI > 0.5). In contrast, DP6 and DP8 tend to have lower S&DSI values, often indicating slight corrosion but non-scale-forming conditions (S&DSI < 0). Notably, DP8 consistently demonstrated serious corrosion tendencies, with S&DSI values dropping well below –0.5 from June to October, highlighting potential risks for material degradation. These variations suggest that different feedwater quality and seasonal conditions influence plant scaling and corrosion tendencies. Feedwater RSI values indicated that most plants operate within the low corrosion range (7–8), suggesting relatively stable water conditions (Fig. 5A). DP8 consistently exhibited the highest RSI values, often exceeding 8, indicating a higher corrosion potential than other plants. In contrast, DP1, DP3, DP4, and DP5 frequently showed RSI values close to 7, indicating a greater tendency for scaling. DP6 and DP7 generally remained within the range of 8, suggesting minimal corrosion risks. Notably, no plant recorded RSI values persistently below 6, meaning extreme scaling conditions are not observed. These variations highlight the different water stabilization dynamics across the plants, balancing the risks of scaling and corrosion. During the summer months, both indices tend to indicate an increased risk of corrosion, only in DP8, where RSI values exceed 8. Additionally, August presented a unique case where DP6 briefly dipped into negative values, while other plants remained relatively stable. These results agree with the findings of [20]. The effect of temperature in seawater samples did not significantly influence the values of the two indices, which is further confirmed by the correlation matrix (Fig. 6A). There was a slight positive relationship between temperature (T) and RSI (0.23), and the correlation between temperature (T) and S&DSI was –0.30, suggesting a slight negative relationship. This is because no abnormal temperature variations would affect calcium carbonate solubility. While pH and S&DSI had a very strong positive correlation (0.98), indicating that as pH increases, S&DSI increases significantly, pH and RSI had a strong negative correlation (–0.92), meaning that a higher pH leads to lower RSI, which aligns with the fact that higher pH conditions favor scaling rather than corrosion. At higher pH levels, more carbonate ions (CO_3) are present, which react with calcium ions (Ca^{2+}) to form solid $CaCO_3$ precipitate, leading to scaling. Also, it is explained that using beach wells for water extraction in desalination plants like DP8 can lead to lower pH values, which can contribute to water becoming more corrosive. The seawater has been in contact with the sediments and the underlying aquifers, which can introduce dissolved minerals and gases like carbon dioxide, lowering the pH. The lower pH levels make the water more acidic, increasing its corrosiveness, especially towards metal pipes and infrastructure.

B. Brine Samples Assessment

There was a significant variation in scaling tendencies for brine samples among the plants (Fig. 4B). DP4 consistently exhibited the highest S&DSI values, exceeding 1.5 in February and December, indicating a strong tendency for scale formation. While DP2 and DP3 frequently showed S&DSI values between 1.0 and 1.6, suggesting a moderate to high risk of scale formation, DP1, DP5, and DP7 maintained moderate S&DSI levels, mainly fluctuating between 0.5 and 1.2, meaning they are generally scale-forming but non-corrosive. DP6 displayed lower values, mostly between 0.1 and 0.6, meaning it is slightly scale-forming but close to balance, with some corrosion risk in January and July. However, DP8 showed negative values (lower than –0.5) in April, July, August, September, and October, signifying serious corrosion issues. Also, RSI values for brine samples (Fig. 5B) show variations in scaling and corrosion tendencies throughout the year. DP8 consistently recorded the highest RSI values, frequently exceeding 8, indicating a high risk of corrosion. DP6 also exhibited occasional RSI values above 8, suggesting that some months had high corrosion tendencies. DP1, DP3, DP5, and DP7 were within the 7–8 range, indicating low corrosion but no significant scaling issues. In contrast, DP2 and DP4 had RSI values fluctuating between 6 and 7, suggesting a balance between slight scaling and minimal corrosion risks. DP4 occasionally dropped below 6, suggesting a higher tendency for scaling in all months except January. The pH level is crucial in determining both scaling and corrosion tendencies in brine. According to Fig. 6B, a higher pH strongly correlates with increased S&DSI (0.96), indicating a greater tendency for scale formation. A higher pH significantly lowers RSI (–0.90), reducing corrosion risks. This inverse relationship suggests that water becomes more scale-forming as pH rises but less corrosive. Also, higher alkalinity increases S&DSI (0.89), making water more scale-forming and less corrosive, while its negative correlation with RSI (–0.91) shows that rising alkalinity reduces corrosion but promotes scaling. Therefore, controlling pH and alkalinity levels in brine is essential to maintaining a balance between preventing excessive scale deposition and avoiding overly corrosive conditions in desalination plants. These results agree with the findings of [9].

C. Permeate Water Samples Computation

LSI values for permeate water from the eight plants consistently fell within the corrosion range, with most values between –2 and –0.5, indicating serious corrosion (Fig. 4C). DP2 and DP4 exhibited the most negative LSI value which exceeded–2 in most months, suggesting the highest corrosion risk, while DP1, DP3, DP5, and DP7 generally showed less severe corrosion but remained within the serious corrosion class. The variation in LSI values across the months suggested differences in operational conditions and periodic maintenance. However, none of the plants showed positive LSI values, confirming that scaling was not an issue in the permeate water. RSI values further confirmed the findings of the LSI analysis (Fig. 5C), where RSI values consistently exceeded 8, indicating a high corrosion tendency in the permeate water. DP4 exhibited the highest RSI values, peaking at 12.8 in January and November, reinforcing its classification as the most corrosion-prone plant. On the other hand, DP3 recorded the lowest RSI value at 8.55 in October, though it remained in the high corrosion range. Similarly, DP1, DP3, DP5, and DP7 showed relatively lower RSI values but continued to exceed 8. The tendency of the water to be corrosive is due to low calcium concentrations. This can be explained through the correlation matrix (Fig. 6C), where lower calcium levels decrease the LSI (0.69), increasing corrosivity, while they strongly raise the RSI (–0.82), confirming that low-calcium permeate water is more aggressive and prone to corrosion. Also, the correlation matrix confirmed that low alkalinity and low pH contribute to the high corrosivity of produced water from desalination. Our findings are consistent with those reported by [22]. These variations in water stability indices values for the three water types highlight the need for different scaling and corrosion control strategies in the desalination plants to protect the RO membrane, optimize brine management, ensure high produced water quality, and prevent operational issues.

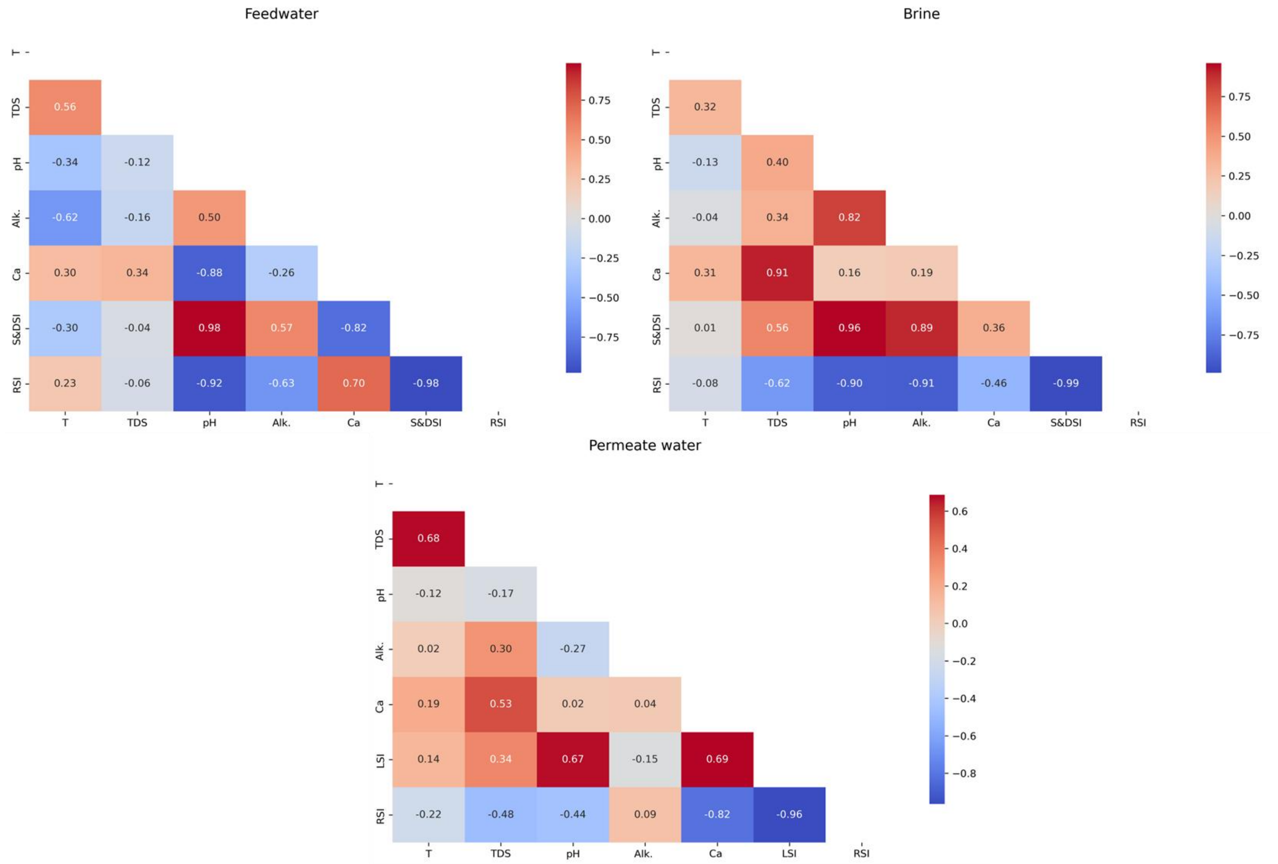

Fig. 6. Heatmaps of correlation coefficient matrix between water quality parameters and saturation indices for (A) feedwater, (B) Brine, and (C) permeate water samples.

D. Mitigation Strategies for Scaling and Corrosion in SWRO Desalination Plants

Mitigation approaches for scaling and corrosion are essential for improving operational efficiency, extending the lifespan of membranes and equipment, and ensuring the water quality of the final product. For the input of the desalination process, feedwater entering the desalination plant contains dissolved salts, mainly $CaCO_3$, which may precipitate if the water is supersaturated. Salt deposition on membranes reduces their efficiency, clogs, and ultimately damages the membranes. Also, if the seawater has a negative S&DSI in some cases, it may be corrosive, potentially causing damage to the pipes and equipment used in the plant, which increases maintenance costs. Maintaining S&DSI at a balanced level (close to zero) ensures that feedwater is neither corrosive nor prone to scaling, which prolongs the membrane's lifespan and reduces operational costs. This can be achieved by implementing certain practices, such as selecting appropriate antiscalants based on the specific types of scale identified in the water quality analysis. Use acid dosing (e.g., sulfuric acid) to control pH levels before the RO process. Adjust alkalinity using neutralizing agents like sodium hydroxide. Proper alkalinity levels can reduce the risk of scaling by keeping calcium and magnesium ions dissolved in the feedwater.

For the output of the desalination process, brine has mainly positive S&DSI; it may cause the precipitation of $CaCO_3$ and other solid deposits within discharge pipelines, leading to clogging and frequent cleaning. The direct discharge of brine into the sea requires careful consideration, as it may lead to salt precipitation on coral reefs or within the marine environment near the discharge site, potentially harming marine ecosystems. The formation of brine scaling can be minimized by adjusting the recovery rate. This can be done by operating at a lower recovery rate during periods of high scaling risk or optimizing the recovery rate based on the specific scaling potential. Selecting biodegradable chemicals through desalination processes that are environmentally friendly and have a minimal impact on marine environments when disposed of is essential. Also, efficient brine management practices like dilution, deep well injection, or zero-liquid discharge (ZLD) technologies can be implemented to reduce the impact of brine on the environment and ensure safe disposal.

Another stream, which is permeate water, typically very low in salts (negative LSI), tends to be corrosive, leading to the corrosion of distribution networks and metal storage tanks. So, remineralization as a post-treatment process can be added to adjust desalinated water, making it more stable (LSI close to zero) and suitable for drinking. Proper calcium and alkalinity balance prevents corrosion and improves the water's taste. In addition, the expansion of corrosion-resistant materials, such as stainless steel and high-density polyethylene in critical components and pipeline networks, is necessary. Generally, continuously monitoring key water quality parameters (e.g., pH, TDS, temperature, and alkalinity) to detect early signs of scaling or corrosion is vital using online sensors and equipment with threshold limits for critical parameters and implementing automatic alarms for any out-of-range values. In addition, predictive Machine Learning (ML) models to anticipate scaling and corrosion issues before they occur based on historical data and real-time monitoring to predict when maintenance or cleaning is needed.

V. Conclusion

Addressing scaling and corrosion in desalination plants is crucial for enhancing efficiency, minimizing maintenance costs, and ensuring long-term operational sustainability. In this study, three water stability indices (Langelier Saturation Index (LSI), Stiff & Davis Stability Index (S&DSI), and Ryznar Stability Index (RSI)) were used to evaluate the scaling and corrosion potential in eight full-scale SWRO desalination plants along Egypt's Red Sea and Mediterranean coasts. The results revealed that 27% of feedwater samples had S&DSI values greater than 0.5, indicating potential for scaling, while 48% of RSI values remained below 7.5, suggesting a low-to-moderate risk of corrosion. Brine samples exhibited similar trends, with 27% showing strong scaling potential (S&DSI > 1) and 71% having RSI values < 7, confirming consistent scaling tendencies. Notably, one plant, which uses beach wells, showed a higher risk of corrosion, with negative S&DSI and RSI values exceeding 8. Due to its low mineral content, permeate water in all plants was consistently corrosive, with LSI < –2 and RSI > 8. These findings demonstrate that minor fluctuations in pH and chloride concentration are crucial in determining scaling and corrosion risks. Mitigation strategies should be tailored to address the specific challenges faced by SWRO desalination plants in Egypt. By combining multiple approaches, including chemical treatment, operational adjustments, and regular maintenance, the plant can reduce scaling and corrosion while enhancing its overall efficiency and lifespan. It is recommended that predictive ML models be integrated with control systems to enable real-time monitoring and early detection, allowing for automatic adjustments of operational parameters in desalination plants.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Ali Nada: Writing – original draft, Methodology, Data curation, Conceptualization. Mahmoud Sharaan: Conceptualization and Writing – review & editing. Mohamed Elshemy: Methodology, Writing – review & editing. Manabu Fujii: Writing – review & editing, Supervision. Mona G. Ibrahim: Writing – review & editing, Supervision; all authors had approved the final version.

Acknowledgment

The first author acknowledges the PhD fellowship support from the Egyptian Ministry of Higher Education (MoHE). Special appreciation is extended to E-JUSTand JICA for supplying the necessary software, resources, and tools for this research. Also, we would like to thank Fujii-Sensei and the Tokyo Institute of Technology for their generous hospitality during the research period.

References

[1] J. Eke *et al.*, "The global status of desalination: An assessment of current desalination technologies, plants and capacity," *Desalination*, vol. 495, 114633, 2020.

[2] M. Philibert *et al.*, "Fouling and scaling in reverse osmosis desalination plants: a critical review of membrane autopsies, feedwater quality guidelines and assessment methods," *Desalination*, 118188, 2024.

[3] J. Rolf *et al.*, "Inorganic scaling in membrane desalination: models, mechanisms, and characterization methods," *Environmental Science & Technology*, vol. 56, no. 12, pp. 7484–7511, 2022.

[4] N. García *et al.*, "Years of data from 500 seawater membrane autopsies," in *Proc. the IDA 2022 World Congress*, 2022.

[5] A. Matin *et al.*, "Scaling of reverse osmosis membranes used in water desalination: Phenomena, impact, and control; future directions," *Desalination*, vol. 455, pp. 135–157, 2019.

[6] V. Bondada, D. K. Pratihar, and C. S. Kumar, "Detection and quantitative assessment of corrosion on pipelines through image analysis," *Procedia Computer Science*, vol. 133, pp. 804–811, 2018.

[7] M. R. Gomaa *et al.*, "Optimal design and economic analysis of a hybrid renewable energy system for powering and desalinating seawater," *Energy Reports*, vol. 9, pp. 2473–2493, 2023.

[8] L. O. Villacorte *et al.*, "Feedwater Quality Guidelines and Assessment Methods for Membrane-based Desalination," *Experimental Methods for Membrane Applications in Desalination and Water Treatment*, IWA Publishing, pp. 1–26, 2024.

[9] M. Al-Shammiri and M. Al-Dawas, "Maximum recovery from seawater reverse osmosis plants in Kuwait," *Desalination*, vol. 110, no. 1–2, pp. 37–48, 1997.

[10] J. C. Roque, "Evaluation of an on-line device to monitor scale formation in a brackish water reverse osmosis membrane process," Electronic Theses and Dissertations, 2012.

[11] M. Hernández-Suárez and F. León, "Characteristics of desalinated water in reverse osmosis plants in Spain," *Desalination and Water Treatment*, vol. 230, pp. 1–8, 2021.

[12] M. Mahdavi *et al.*, "Spatial modeling and economical evaluation of water corrosion and scaling in water distribution network," *ACS Sustainable Resource Management*, vol. 1, no. 10, pp. 2184–2193, 2024.

[13] A. Nada *et al.*, "Water quality modeling and management for Rosetta Branch, the Nile River, Egypt," *Environmental Monitoring and Assessment*, vol. 193, no. 9, p. 603, 2021.

[14] A. El-Sadek, "Water desalination: An imperative measure for water security in Egypt," *Desalination*, vol. 250, no. 3, pp. 876–884, 2010.

[15] Y. Elsaie *et al.*, "Water desalination in Egypt; literature review and assessment," *Ain Shams Engineering Journal*, vol. 14, no. 7, p. 101998, 2023.

[16] A. Nada *et al.*, "Integrated water quality and performance assessment of seawater desalination plants along two coasts in Egypt," *Desalination*, vol. 586, 117844, 2024.

[17] A. Antony *et al.*, "Scale formation and control in high pressure membrane water treatment systems: A review," *Journal of Membrane Science*, vol. 383, no. 1–2, pp. 1–16, 2011.

[18] R. Singh, *Membrane Technology and Engineering for Water Purification: Application, Systems Design and Operation*, Butterworth-Heinemann, 2014.

[19] S. G. Salinas-Rodríguez *et al.*, *Seawater Reverse Osmosis Desalination: Assessment and Pre-treatment of Fouling and Scaling*, IWA Publishing, 2021.

[20] J. Peña *et al.*, "The vaterite saturation index can be used as a proxy of the S&DSI in sea water desalination by reverse osmosis process," *Desalination*, vol. 254, no. 1–3, pp. 75–79, 2010.

[21] M. E. Omeka, J. C. Egbueri, and C. O. Unigwe, "Investigating the hydrogeochemistry, corrosivity and scaling tendencies of groundwater in an agrarian area (Nigeria) using graphical, indexical and statistical modelling," *Arabian Journal of Geosciences*, vol. 15, no. 13, p. 1233, 2022.

[22] F. D. S. Antas *et al.*, "Hydrochemical characterization of water resources from reverse osmosis desalination plants," *Journal of Agricultural Science*, 2018.