Advanced assessment of membrane fouling in seawater reverse osmosis plants using permeate quality degradation indicators

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ABSTRACT

Seawater reverse osmosis (SWRO) is the leading technology for large-scale desalination, yet membrane fouling remains a major limitation affecting performance stability, energy consumption, and membrane lifespan. Conventional fouling monitoring in SWRO plants relies primarily on hydraulic indicators such as pressure drop and flux decline, which often detect fouling only after it has reached an advanced stage. This study proposes an advanced fouling assessment approach based on permeate quality degradation indicators, shifting permeate quality from a passive compliance parameter to an active diagnostic signal. Long-term operational data from full-scale SWRO plants were analyzed to investigate the temporal evolution of permeate conductivity, salt passage, and their relationship with hydraulic performance and cleaning-in-place (CIP) events. The results show that permeate quality degradation evolves progressively during fouling development, frequently preceding significant hydraulic deterioration, and responds rapidly and reversibly to CIP operations. Clear evidence of decoupled behavior between permeate quality and pressure drop was observed, highlighting the early-warning potential of permeate quality indicators. The findings demonstrate that permeate quality degradation provides a sensitive, robust, and operationally practical indicator of membrane fouling severity and dynamics. Integrating these indicators into routine SWRO monitoring frameworks can enhance fouling diagnosis, optimize cleaning strategies, and support the development of advanced, data-driven control and predictive maintenance systems for desalination plants.

Keywords: seawater reverse osmosis, membrane fouling, permeate quality, conductivity, salt rejection, cleaning-in-place, fouling diagnostics.

INTRODUCTION

Seawater reverse osmosis (SWRO) has become a cornerstone technology for large-scale desalination and freshwater production worldwide. Its widespread adoption is driven by continuous improvements in membrane materials, energy recovery systems, and process optimization, which have significantly reduced specific energy consumption compared with earlier thermal desalination technologies. In regions facing chronic water scarcity – particularly arid and semi-arid coastal zones – SWRO plays a strategic role in ensuring water security for domestic, industrial, and agricultural uses. As global demand for desalinated water continues to increase, the long-term reliability and efficiency of SWRO plants have become critical concerns for both operators and policymakers (Jha and Ghosh 2025; Ghaffour et al., 2013).

Despite its technological maturity, membrane fouling remains the principal operational constraint affecting SWRO performance and sustainability. Fouling results from the accumulation of particulate matter, organic compounds, inorganic precipitates, and microorganisms on

membrane surfaces, leading to increased hydraulic resistance, higher operating pressures, and elevated energy consumption. Over time, fouling necessitates frequent chemical cleaning-in-place (CIP) operations, which contribute to operational downtime, increased chemical usage, and accelerated membrane aging. Consequently, effective fouling monitoring and management are essential for maintaining stable production, controlling costs, and extending membrane lifespan in SWRO installations (Flemming, 2011; Vrouwenvelder et al., 2011).

In current industrial practice, fouling detection relies predominantly on classical hydraulic indicators such as the pressure drop (ΔP), normalized permeate flux, and permeability decline. While these indicators provide valuable information on overall system performance, they often respond only after fouling has reached a relatively advanced stage. Moreover, routine operational adjustments – such as pressure compensation, flow redistribution, or recovery optimization – can partially mask fouling-related hydraulic deterioration, delaying detection and potentially allowing irreversible membrane damage to occur. As a result, exclusive reliance on hydraulic indicators may limit the effectiveness of proactive fouling control strategies (Pulido Beltran et al., 2024).

In contrast, permeate water quality parameters, including electrical conductivity, salinity, and ion concentrations, are continuously monitored in SWRO plants primarily for regulatory compliance and product water assurance. From a transport phenomena perspective, membrane fouling affects not only hydraulic resistance but also solute transport and concentration polarization within the membrane boundary layer. These effects can lead to gradual increases in salt passage and subtle degradation of permeate quality that may appear before significant changes in P_APP or flux are detected. However, permeate quality has rarely been exploited systematically as a diagnostic signal for fouling assessment, representing a clear scientific and operational gap in existing monitoring frameworks.

The objective of the present study is to address this gap by proposing an advanced assessment of membrane fouling in SWRO plants based on permeate quality degradation indicators derived from long-term full-scale operational data. By analyzing temporal trends in permeate conductivity, salt passage, and their relationship with conventional hydraulic indicators and cleaning events, this work aims to demonstrate the diagnostic value of permeate quality as an early and sensitive fouling indicator. The originality of this study lies in repositioning permeate quality from a passive compliance parameter to an active diagnostic tool, thereby contributing to enhanced fouling monitoring strategies and supporting the development of more proactive and resilient SWRO plant operation.

MATERIALS AND METHODS

Description of SWRO plants and operating conditions

The present study is based on operational data collected from two full-scale seawater reverse osmosis (SWRO) desalination plants, namely the Dunes and Bousfer plants located in Oran region (Kassouar and Abi-Ayad 2024). These plants operating under industrial conditions along the Algerian coastline. The plants are designed for continuous potable water production and operate with comparable process configurations. According to the operational records, daily treated water production ranges from approximately 1450 to 3200 m³·d⁻¹, corresponding to raw seawater intake volumes between 3600 and 8300 m³·d⁻¹ depending on operating conditions and demand. The average conversion (recovery) rate remains relatively stable over the monitoring period, with values predominantly between 38.5% and 40.5%, indicating operation within typical design limits for SWRO systems and ensuring a balance between productivity and fouling control (Philibert et al., 2024)

The RO units are configured as single-pass systems using spiral-wound polyamide thin-film composite membranes arranged in multi-element pressure vessels, which is consistent with standard industrial SWRO designs.

The feedwater supplied to the RO systems consists of open-intake seawater characterized by high salinity and moderate seasonal variability. Electrical conductivity of the raw seawater remains consistently high, with recorded values around 56,200–56,300 µS·cm⁻¹, corresponding to an average salinity of approximately 36.0–36.5‰. Feedwater temperature exhibits seasonal variation, with measured values typically ranging from 16.7 to 19.5 °C during the monitoring period. These physicochemical characteristics

impose a high osmotic pressure on the membranes and significantly influence permeate flux and salt rejection performance. In addition to dissolved salts, the feedwater contains suspended solids and organic matter, as evidenced by the continuous need for chemical conditioning and pretreatment, which are known contributors to membrane fouling in SWRO systems (Abushaban et al., 2021).

Pretreatment processes upstream of the RO units are implemented to mitigate fouling risks and stabilize feedwater quality. The pretreatment scheme applied in the studied plants includes chemical conditioning with coagulants, followed by media filtration and cartridge filtration prior to high-pressure pumping. Operational data indicate regular dosing of treatment chemicals, including coagulants and disinfectants, with hypochlorite consumption varying from approximately 6 to 37 L·d⁻¹, reflecting fluctuations in raw water quality and biological activity. The effectiveness of pretreatment is reflected in the permeate conductivity values, which generally range between 2000 and 3100 µS·cm⁻¹ during stable operation. Nevertheless, despite these pretreatment measures, gradual changes in permeate quality are observed over time, highlighting the persistence of fouling phenomena and justifying the use of permeate quality degradation as an advanced diagnostic indicator (Gomelya et al., 2023).

Data collection and quality parameters

Operational data used in this study were extracted directly from the supervisory control and data acquisition systems of the investigated SWRO plants and archived in structured Excel datasets covering extended operating periods before and after performance changes. The monitored operational parameters include applied pressure (P_APP), feed flow rate, permeate flow rate, and system recovery. Recorded P_APP values show progressive temporal variation, reflecting membrane resistance evolution under fouling conditions, while permeate flow rates remain within operational setpoints due to routine pressure compensation. Recovery rates are maintained within a narrow range, predominantly between 38.5% and 40.5%, in order to limit excessive concentration polarization and scaling risks, in accordance with common SWRO operational guidelines (Philibert et al., 2024).

The availability of continuous operational data allows the identification of fouling development phases and their relationship with permeate quality degradation.

Permeate water quality parameters were collected simultaneously with operational data and constitute the core dataset for the proposed fouling assessment approach. Electrical conductivity of the permeate was systematically measured and shows values typically ranging from 2000 to 3100 µS·cm⁻¹, depending on operating conditions and membrane condition. These values correspond to slight but measurable variations in salt rejection performance over time. In parallel, permeate salinity data were recorded, enabling the calculation of salt passage and normalized rejection indicators. Where available, ion-specific concentrations – particularly chloride and sodium ions – were used to support the interpretation of conductivity trends, as these ions dominate seawater composition and are highly sensitive to changes in membrane selectivity, Lachheb (2026). The combined analysis of global and ion-specific quality parameters provides a more robust diagnostic signal than conductivity alone.

The datasets cover a continuous monitoring period extending over several months of explanation, encompassing stable operation phases, progressive fouling development, and post-cleaning recovery periods. Sampling frequency for operational parameters is daily, ensuring high temporal resolution for detecting gradual performance changes, while permeate quality measurements are conducted at regular intervals consistent with plant quality control protocols. This temporal resolution is sufficient to capture both short-term fluctuations and long-term degradation trends. By aligning permeate quality data with operational timelines and cleaning-in-place events, the study enables a detailed assessment of the sensitivity of permeate quality degradation indicators relative to conventional hydraulic monitoring approaches, as recommended in recent SWRO fouling studies (Teng and Ng, 2024).

Data processing and normalization

Prior to analysis, all operational and water quality datasets were subjected to systematic processing and normalization in order to isolate fouling-related effects from variations induced by operating conditions. Temperature normalization was applied to permeate flow and pressure-related parameters to account for the influence of seawater viscosity on membrane permeability. Given

the observed seasonal temperature variations in the feedwater, ranging approximately from 16.7 to 19.5 °C, measured permeate flow rates were normalized to a reference temperature using standard correction factors recommended for SWRO systems. This procedure ensures that changes in hydraulic performance are attributed primarily to membrane fouling rather than to temperature-driven fluctuations in water properties (Elimelech and Phillip, 2011; Shouman et al., 2024).

Normalization with respect to system recovery was also performed to remove the effect of intentional operational adjustments on performance indicators. As recovery was maintained within a relatively narrow range of 38.5–40.5% during the monitoring period, small variations in recovery could nevertheless influence concentration polarization and salt passage. Recovery-normalized parameters were therefore calculated to ensure comparability across different operating periods. This approach allows subtle changes in permeate quality, particularly conductivity and salt rejection, to be interpreted as intrinsic membrane performance variations rather than as artifacts of changing operating set points (Odabaşı et al., 2022; Teng and Ng, 2024).

To further minimize operational bias, periods associated with non-representative operating conditions were excluded from the analysis. These include plant start-up and shutdown phases, abnormal hydraulic disturbances, sensor calibration periods, and intervals immediately following chemical cleaning-in-place operations. The exclusion of these transient periods improves the robustness of trend analysis by focusing on quasi-steady-state operation, during which fouling development and permeate quality degradation occur progressively. Similar data filtering strategies have been recommended in previous full-scale SWRO performance assessment studies to avoid misinterpretation of short-term operational noise (Porcelli and Judd, 2010).

Baseline conditions were defined for each plant and membrane train based on stable post-cleaning operation characterized by minimum pressure drop, maximum normalized permeability, and lowest recorded permeate conductivity. These baseline periods serve as reference states against which subsequent performance degradation was quantified. All permeate quality degradation indicators developed in this study were expressed relative to these baseline values, enabling consistent comparison of fouling evolution across

different operational phases and plants. The use of relative, baseline-referenced indicators enhances sensitivity to early-stage fouling and reduces dependence on absolute threshold values, which may vary between plants and membrane batches. Importantly, the analysis was conducted using long-term operational data obtained from large-scale commercial SWRO desalination plants, ensuring practical relevance and real-world representativeness of the proposed indicators.

RESULTS

Temporal evolution of permeate quality during operation

The long-term evolution of permeate quality was assessed using electrical conductivity as the primary indicator of membrane selectivity degradation. Table 1 summarizes the statistical characteristics of permeate conductivity measured during stable operation, fouling development, and intensified fouling phases. During initial stable operation, permeate conductivity remained relatively constant, with mean values close to 2050 $\mu S \cdot cm^{-1}$ and low standard deviation, indicating effective salt rejection and limited membrane degradation. As operation progressed over six months of continuous operation, a gradual but persistent increase in permeate conductivity was observed, reaching average values above 2.600 $\mu S \cdot cm^{-1}$, despite recovery and operating pressure being maintained within narrow operational ranges. This progressive increase suggests a degradation of membrane selectivity not directly reflected by hydraulic indicators, consistent with fouling-induced changes in solute transport mechanisms, as reported in previous SWRO studies (Chebil et al., 2024).

A clearer distinction between stable and degradation phases emerges when permeate conductivity is analyzed temporally rather than as isolated values. Table 2 presents the average rate of conductivity increase during successive operating periods. During stable operation, conductivity variation remained negligible, with an average increase of less than 5 $\mu S \cdot cm^{-1} \cdot day^{-1}$. In contrast, during fouling development phases, conductivity increased at rates exceeding 18 $\mu S \cdot cm^{-1} \cdot day^{-1}$, indicating progressive deterioration of membrane selectivity. The acceleration of conductivity increase during fouling intensification phases highlights the non-linear nature of fouling progression, where initial

Table 1. Statistical summary of permeate conductivity during different operational phases

Operational phase	Maximum (µS·cm⁻¹)	Minimum (µS·cm⁻¹)	Mean (µS·cm⁻¹)	Standard deviation (µS·cm⁻¹)
Stable operation	2.180	1.980	2.050	65
Fouling development	2.780	2.120	2.460	185
Fouling intensification	3.120	2.450	2.680	210

accumulation leads to increasingly severe impacts on solute transport. This approach aligns with the findings of (Vrouwenvelder et al. 2011), who emphasized that early detection and the implementation of effective cleaning strategies are critical for preventing biofouling and maintaining stable membrane performance).

To further evaluate the diagnostic value of permeate quality, a comparative analysis was performed between periods before and after fouling intensification. Table 3 shows that although recovery remained nearly constant (average variation <1%), permeate conductivity increased by approximately 31% between the two periods. This decoupling between hydraulic stability and permeate quality degradation confirms that conventional operating parameters alone may underestimate the severity of fouling ($\Delta P = 1.7$ bar.). Such behavior is characteristic of fouling layers that primarily affect diffusion and concentration polarization rather than bulk hydraulic resistance, as previously described for organic and biofouling-dominated systems.

Overall, the results demonstrate that permeate conductivity provides a sensitive and early indication of membrane fouling progression. The identification of stable, transitional, and degraded operation phases based solely on permeate quality trends highlights the potential of permeate quality degradation indicators to complement or even precede traditional hydraulic monitoring in full-scale SWRO plants.

Relationship between permeate quality and fouling development

To evaluate the relationship between permeate quality degradation and membrane fouling development, permeate conductivity trends were analyzed jointly with conventional hydraulic indicators, namely applied pressure (P_APP), pressure drop, and normalized permeability. Table 4 presents the correlation coefficients calculated between permeate conductivity and key operational parameters over the full monitoring period. A moderate positive correlation was observed between permeate conductivity and pressure drop, indicating that as fouling progresses and hydraulic resistance increases, membrane selectivity also tends to deteriorate. However, the correlation remains significantly lower than unity, suggesting that changes in permeate quality are not strictly governed by hydraulic fouling alone. In contrast, permeate conductivity exhibits a stronger negative correlation with normalized permeability, reflecting the combined effect of fouling on both

Table 2. Temporal evolution rate of permeate conductivity

Operational phase	Duration (days)	Mean conductivity increase (µS·cm⁻¹·day⁻¹)
Stable operation	35	3.2
Fouling development	48	18.6
Fouling intensification	27	24.1

Table 3. Comparison of operating conditions before and after fouling intensification

Parameter	After fouling intensification	Before fouling intensification
Recovery (%)	39.8	40.2
P_APP (bar)	58.6	56.9
Permeate conductivity (µS·cm⁻¹)	2,980	2,270
Relative conductivity increase (%)	31.3	–

Table 4. Correlation between permeate conductivity and hydraulic performance indicators

Parameter	Correlation coefficient (r) with permeate conductivity
Applied pressure (P_APP)	+0.58
Normalized permeability	−0.72
Recovery	+0.11

water and solute transport mechanisms, as previously highlighted in full-scale SWRO studies (Adel et al., 2022).

A more detailed examination of the temporal data reveals the existence of decoupled behavior between hydraulic indicators and permeate quality. Table 5 compares average P_APP and permeate conductivity values during periods where P_APP remained relatively stable. Despite P_APP variations remaining within ±3% of baseline values, permeate conductivity increased by more than 20%, indicating a clear degradation of membrane selectivity without a proportional increase in hydraulic resistance. This decoupling demonstrates that fouling layers may initially affect diffusive solute transport and concentration polarization before significantly impacting bulk hydraulic resistance, a phenomenon commonly associated with organic fouling and early-stage biofouling. Al Sawaftah et al (2021) supports the notion that conventional operating parameters alone may not fully capture the severity of foulant accumulation or its impact on permeate quality.

The early sensitivity of permeate quality degradation is further illustrated in Table 6, which compares the onset time of detectable changes in permeate conductivity and P_APP relative to baseline operation. An increase in permeate conductivity exceeding 10% was observed approximately 18–25 days before a comparable 10% increase in P_APP. This temporal lead confirms that permeate quality degradation can serve as an early-warning signal for fouling development, providing valuable diagnostic information before conventional hydraulic thresholds are reached. Such early detection capability is particularly relevant for optimizing cleaning-in-place scheduling and preventing irreversible membrane damage (Al-Balushi et al., 2024).

Overall, these results demonstrate that while permeate quality degradation is related to fouling-induced hydraulic changes, it evolves partly independently and often precedes them. The observed correlations, decoupled behavior, and earlier detection confirm the added diagnostic value of permeate quality indicators for advanced fouling assessment in SWRO plants. Integrating permeate quality trends with conventional hydraulic monitoring therefore offers a more sensitive and comprehensive framework for fouling detection and management.

Response of indicators to cleaning events

The response of permeate quality degradation indicators to CIP events was evaluated by comparing permeate conductivity and hydraulic performance immediately before and after each cleaning operation. Table 7 summarizes the average recovery of permeate quality following CIP. A substantial decrease in permeate conductivity was observed after cleaning, with mean values dropping from approximately 2.950 µS·cm⁻¹ before CIP to 2.180 µS·cm⁻¹ after CIP, corresponding

Table 5. Evidence of decoupled hydraulic and permeate quality behavior

Period	P_APP variation (%)	Mean P_APP (bar)	Mean permeate conductivity (µS·cm⁻¹)	Conductivity increase (%)
Reference (baseline)	–	56.8	2.050	–
Stable P_APP phase	+2.6	58.3	2.480	21.0

Table 6. Comparison of detection time for fouling indicators

Indicator	Threshold criterion	Time to detection (days)
Permeate conductivity	+10% increase	22
P_APP	+10% increase	41
Normalized permeability	−10% decrease	38

to an average quality recovery of 26%. This recovery confirms that a significant fraction of the observed permeate quality degradation is attributable to reversible fouling rather than irreversible membrane damage. Similar recovery behavior following chemical cleaning has been reported for fouling layers dominated by organic and biofouling components (Stover, 2016).

A comparative analysis of hydraulic and quality recovery highlights differences in reversibility between indicators. While P_APP decreased by less than 9% after CIP, normalized permeability recovered by nearly 18%, and permeate conductivity showed the largest relative improvement (about 26%). Table 8 presents the reversibility index calculated as the ratio between post-CIP recovery and total pre-CIP degradation. Permeate conductivity exhibits the highest reversibility index, indicating strong sensitivity to fouling removal. In contrast, P_APP recovery is more limited, suggesting that part of the hydraulic resistance increase may be associated with compaction or irreversible fouling, consistent with observations reported in long-term SWRO operation studies (Lee et al., 2012, Ruiz-García et al., 2017). Indicator sensitivity to cleaning events was further assessed by analyzing the response time of each parameter following CIP. Table 9 shows that permeate conductivity reached post-cleaning stabilization within 2–3

days, whereas P_APP and permeability required 5–7 days to stabilize. This faster response reflects the immediate removal of fouling layers affecting solute transport and concentration polarization, while hydraulic equilibration may be delayed due to gradual membrane relaxation and system rebalancing. The rapid response of permeate quality indicators reinforces their suitability for evaluating CIP effectiveness and detecting residual fouling shortly after cleaning (Singh and Anand., 2025). Overall, the results demonstrate that permeate quality degradation indicators respond rapidly and strongly to CIP events, providing clear evidence of fouling reversibility and cleaning efficiency. Compared with conventional hydraulic indicators, permeate conductivity shows higher sensitivity and faster stabilization, making it a valuable tool for post-cleaning assessment and for distinguishing reversible fouling from irreversible membrane performance loss.

DISCUSSION

Diagnostic value of permeate quality indicators

The results obtained in this study clearly demonstrate that permeate quality indicators, particularly permeate conductivity and derived salt

Table 7. Permeate quality response before and after CIP

Parameter	Before CIP	After CIP	Recovery (%)
Permeate conductivity ($\mu S \cdot cm^{-1}$)	2,950	2,180	26.1
P_APP (bar)	60.2	54.9	8.8
Normalized permeability (%)	82.4	97.1	17.8

Table 8. Reversibility assessment of fouling indicators

Indicator	Pre-CIP degradation (%)	Post-CIP recovery (%)	Reversibility index
Permeate conductivity	31.3	26.1	0.83
Normalized permeability	21.5	17.8	0.83
P_APP	12.6	8.8	0.70

Table 9. Sensitivity and response time of indicators after CIP

Indicator	Stabilization time after CIP (days)	Relative sensitivity
Permeate conductivity	2–3	High
Normalized permeability	4–5	Moderate
P_APP	5–7	Low

passage metrics, provide diagnostic information that complements and, in several cases, surpasses conventional hydraulic indicators such as applied pressure (P_APP) and normalized permeability. Unlike P_APP, which primarily reflects global hydraulic resistance, permeate quality indicators are directly linked to membrane selectivity and solute transport mechanisms. Fouling layers that enhance concentration polarization or modify diffusion pathways can significantly affect salt passage without immediately inducing a proportional increase in hydraulic resistance. This explains the moderate correlation observed between P_APP and permeate conductivity and supports the interpretation that permeate quality degradation captures fouling effects that remain partially invisible to pressure-based monitoring (Hoek and Elimelech, 2003; Ruiz-García et al., 2017). Consequently, permeate quality indicators provide a more nuanced representation of membrane condition, particularly during early and intermediate fouling stages.

A key outcome of this work is the confirmation of the early-warning potential of permeate quality degradation indicators. The temporal analysis revealed that detectable increases in permeate conductivity consistently preceded significant changes in P_APP and normalized permeability by several weeks. This temporal lead is of high practical importance, as it offers plant operators a window for proactive intervention before fouling reaches an advanced and potentially irreversible stage. Early detection enables optimization of CIP scheduling, preventing excessive fouling accumulation and reducing chemical consumption and membrane stress.

Similar conclusions have been suggested in previous studies, although rarely supported by long-term full-scale operational data, reinforcing the originality and applied relevance of the present findings (Porcelli and Judd, 2010; Vrouwenvelder et al., 2011).

Another important aspect highlighted by the results is the robustness of permeate quality indicators under variable operating conditions. Despite fluctuations in feedwater temperature, minor recovery adjustments, and pressure compensation strategies, permeate conductivity trends remained coherent and interpretable when properly normalized. This robustness contrasts with hydraulic indicators, which can be strongly influenced by operational control actions designed to maintain production targets. Because permeate quality parameters are less susceptible to short-term operational manipulation, they offer a more stable basis for long-term fouling assessment. The use of baseline-referenced, relative degradation indicators further enhances this robustness by minimizing plant-specific and membrane-specific variability, making the approach potentially transferable across different SWRO installations.

Overall, the diagnostic value of permeate quality indicators lies in their ability to detect subtle, early-stage fouling effects, to remain responsive under realistic operating conditions, and to provide complementary insight beyond conventional hydraulic monitoring. Integrating permeate quality degradation indicators into routine SWRO performance assessment frameworks can therefore improve fouling diagnosis, support predictive maintenance strategies, and contribute to more resilient and cost-effective desalination plant operation.

Fouling severity and typology inference

The temporal patterns observed in permeate quality degradation provide valuable insight into fouling severity and its mode of development. Progressive increases in permeate conductivity, characterized by low but persistent rates of change over extended periods, are indicative of gradual fouling accumulation on the membrane surface. Such patterns are typically associated with organic fouling and early-stage biofouling, where the formation of thin, heterogeneous fouling layers incrementally enhances concentration polarization and solute diffusion without immediately inducing sharp hydraulic penalties. In contrast, abrupt increases in permeate conductivity over short time intervals, often accompanied by accelerated permeability loss or sudden P_APP escalation, suggest more severe fouling events, such as inorganic scaling or rapid biomass proliferation triggered by unfavorable feedwater conditions. The ability of permeate quality indicators to discriminate between progressive and abrupt degradation patterns constitutes a significant advantage for severity assessment, as it enables differentiation between chronic fouling processes and acute fouling incidents requiring immediate corrective action (Kherraf et al., 2023).

Beyond severity assessment, permeate quality indicators also offer indirect clues regarding fouling typology. Fouling scenarios dominated by biofouling or organic matter accumulation tend to produce gradual increases in salt passage that are

partially reversible following chemical cleaning, as observed in the high recovery rates of permeate conductivity after CIP. This behavior is consistent with fouling layers that primarily affect diffusive transport and concentration polarization rather than permanently altering membrane structure. Conversely, fouling events associated with inorganic scaling are often characterized by sharper and less reversible changes in permeate quality, particularly when scaling crystals obstruct membrane pores or induce localized membrane damage. In such cases, permeate conductivity recovery after CIP is limited, and hydraulic indicators may show disproportionate deterioration. These contrasting response patterns align with mechanisms reported in previous studies on SWRO fouling typology and cleaning efficiency (Jamaly et al., 2014; Jafari et al., 2020).

Despite these diagnostic advantages, it is important to acknowledge the limitations inherent to indirect fouling diagnosis based solely on operational and permeate quality data. Permeate quality degradation indicators do not provide direct information on foulant composition, structure, or spatial distribution on the membrane surface. Similar degradation patterns may arise from different fouling mechanisms, particularly in complex real-world systems where mixed fouling is common. Moreover, operational factors such as antiscalant dosing efficiency, minor recovery fluctuations, or membrane aging can influence permeate quality independently of fouling. As a result, permeate quality indicators should be interpreted as probabilistic diagnostic tools rather than definitive identifiers of fouling type. Their reliability is maximized when combined with complementary information, such as cleaning response analysis, feedwater characterization, or occasional membrane autopsy data, as recommended in comprehensive fouling assessment frameworks.

Overall, permeate quality degradation indicators enable a meaningful inference of fouling severity and dominant fouling tendencies by distinguishing progressive from abrupt degradation patterns and by analyzing reversibility behavior. While indirect by nature, this approach provides actionable diagnostic insight under full-scale operating conditions and represents a practical compromise between detailed but invasive analytical techniques and purely hydraulic monitoring.

Practical implications for SWRO plant operation

The integration of permeate quality degradation indicators into routine SWRO plant monitoring offers significant opportunities to optimize existing performance assessment strategies. Conventional monitoring frameworks rely heavily on hydraulic indicators such as applied pressure (P_{APP}), pressure drop (ΔP), and normalized permeability, which, as demonstrated in this study, may fail to detect early-stage fouling or may respond only after fouling has reached an advanced level. By incorporating permeate conductivity and derived salt passage indicators into daily performance dashboards, operators can gain earlier and more sensitive insight into membrane condition. This multi-indicator approach enhances diagnostic resolution by capturing both hydraulic resistance and selectivity degradation, enabling more informed operational decisions under variable feedwater and operating conditions.

A direct operational benefit of improved fouling detection is the potential reduction of unnecessary CIP operations. CIP is often triggered based on conservative hydraulic thresholds that do not distinguish between reversible fouling, temporary operational disturbances, and irreversible membrane degradation. The results of this study show that permeate quality indicators respond rapidly and proportionally to fouling removal, providing a reliable means of assessing both fouling severity and cleaning effectiveness. By using permeate quality trends to confirm genuine fouling progression, operators can avoid premature CIP events, thereby reducing chemical consumption, downtime, and membrane exposure to aggressive cleaning agents. Conversely, early detection of selectivity degradation allows timely intervention before severe fouling necessitates more intensive cleaning, aligning with best practices for sustainable SWRO operation. Lee et al. (2012) demonstrated that continuous monitoring of water quality, such as tracking permeate TDS enables early detection and prevention of membrane fouling by revealing declines in membrane selectivity.

From a systems integration perspective, permeate quality indicators are particularly well suited for incorporation into existing control and supervisory systems. Electrical conductivity and salinity measurements are already available in most SWRO plants through online

sensors, requiring no additional hardware investment. The implementation of normalized or baseline-referenced degradation indices can therefore be achieved through software-level enhancements within SCADA or plant performance management systems. Such integration enables automated trend analysis, early-warning alarms, and decision-support tools that complement operator expertise. In the longer term, permeate quality indicators can serve as valuable input variables for advanced control strategies, including predictive maintenance models and data-driven optimization algorithms, supporting the transition toward smarter and more resilient desalination plant operation. Ghaffour et al. (2013) point to the fundamental challenges in improving the sustainability of reverse osmosis desalination plant operations, including the need to reduce energy consumption and minimize environmental impact through integrated solutions. In contrast, recent studies indicate that water quality indicators at the outlet, such as TDS, can be used as inputs in smart control strategies and predictive maintenance, allowing for monitoring membrane degradation and predicting contamination before the need for intensive cleaning, there by shifting from traditional operating strategies to more efficient and flexible operation systems based on data and predictive analysis. For example, Bagheri et al. (2019) demonstrated how artificial intelligence and machine learning techniques can be used to control contamination and improve filtration system performance. Tanudjaja et al. (2025) also used artificial intelligence to successfully predict precisely the biofilm development on SWRO membranes at early stages, while Kim et al. (2026) showed applications of machine learning in process design and predicting the performance of small-scale seawater desalination units, directly supporting predictive control, operational efficiency optimization, and reduction of operational risks.

Overall, the practical implications of this work extend beyond improved fouling diagnosis to encompass more efficient monitoring, reduced operational costs, and enhanced process reliability. By leveraging permeate quality degradation indicators within existing operational frameworks, SWRO plants can move toward proactive fouling management strategies that balance productivity, membrane longevity, and sustainability.

CONCLUSIONS

This study demonstrates that permeate quality degradation provides a robust and sensitive basis for advanced assessment of membrane fouling in full-scale seawater reverse osmosis (SWRO) plants. Analysis of long-term operational datasets from large scale SWRO plants revealed that permeate conductivity and derived salt passage indicators evolve progressively during fouling development and respond rapidly to cleaning-in-place events. In contrast to conventional hydraulic indicators, permeate quality parameters were shown to detect fouling at earlier stages and to capture degradation patterns that remain partially decoupled from applied pressure, pressure drop, and permeability variations. These findings confirm that permeate quality contains valuable diagnostic information beyond its traditional role as a compliance parameter.

The results further validate permeate quality degradation as a reliable fouling indicator by demonstrating its consistency across different operating phases, its strong reversibility following CIP, and its robustness under variable operating conditions. The observed temporal lead of permeate conductivity degradation relative to hydraulic deterioration provides clear evidence of its early-warning potential. This sensitivity is particularly relevant for distinguishing between progressive and abrupt fouling scenarios and for assessing fouling severity without reliance on invasive or laboratory-based techniques. As such, permeate quality degradation indicators offer a practical and operationally meaningful complement to existing fouling monitoring approaches.

From an operational perspective, the integration of permeate quality degradation indicators into routine SWRO monitoring frameworks contributes to more effective fouling management strategies. By enabling earlier detection and more accurate assessment of fouling progression, these indicators support optimized CIP scheduling, reduced chemical consumption, and improved membrane lifespan. Their compatibility with existing online sensors and control systems further enhances their applicability, allowing implementation with minimal additional infrastructure and facilitating broader adoption in industrial SWRO plants.

Looking forward, the findings of this study open promising perspectives for real-time and data-driven fouling diagnosis. Permeate quality

degradation indicators can serve as key input variables for advanced monitoring platforms, including predictive maintenance tools and artificial intelligence–based models capable of learning complex fouling patterns from historical data. Coupled with hydraulic and feedwater quality information collected using advanced multifunctional sensors, such approaches have the potential to transform SWRO operation from reactive fouling control to proactive, predictive management, thereby improving the sustainability and resilience of desalination systems.

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REFERENCES

1. Abushaban, A., Salinas-Rodriguez, S. G., Pastorelli, D., Schippers, J. C., Mondal, S., Goueli, S., Kennedy, M. D. (2021). Assessing pretreatment effectiveness for particulate, organic and biological fouling in a full scale SWRO desalination plant. *Membranes, 11*(3), 167. https://doi.org/10.3390/membranes11030167

2. Adel, M., Nada, T., Amin, S., Anwar, T., Mohamed, A. A. (2022). Characterization of fouling for a full-scale seawater reverse osmosis plant on the Mediterranean Sea: Membrane autopsy and chemical cleaning efficiency. *Groundwater for Sustainable Development, 16*, 100704. https://doi.org/10.1016/j.gsd.2021.100704

3. Al-Balushi, M. A., Kyaw, H. H., Myint, M. T. Z., Al-Abri, M., Dobretsov, S. (2024). Chemical cleaning techniques for fouled RO membranes: Enhancing fouling removal and assessing microbial composition. *Membranes, 14*(10), 204. https://doi.org/10.3390/membranes14100204

4. AlSawaftah, N., Abuwatfa, W., Darwish, N., Husseini, G. (2021). A comprehensive review on membrane fouling: Mathematical modelling, prediction, diagnosis, and mitigation. *Water, 13*(9), 1327. https://doi.org/10.3390/w13091327

5. Bagheri, M., Akbari, A., Mirbagheri, S. A. (2019). Advanced control of membrane fouling in filtration systems using artificial intelligence and machine learning techniques: A critical review. *Process Safety and Environmental Protection, 123*, 229–252. https://doi.org/10.1016/j.psep.2019.01.013

6. Chebil, S., Ruiz-García, A., Farhat, S., Bali, M. (2024). Long-term performance evaluation and fouling characterization of a full-scale brackish water reverse osmosis desalination plant. *Water, 16*(13), 1892. https://doi.org/10.3390/w16131892

7. Elimelech, M., Phillip, W. A. (2011). The future of seawater desalination: Energy, technology, and the environment. *Science, 333*(6043), 712–717. https://doi.org/10.1126/science.1200488

8. Flemming, H.-C. (2011). Microbial biofouling: Unsolved problems, insufficient approaches, and possible solutions. *Biofilm, 3*(1), 1–10.

9. Ghaffour, N., Missimer, T. M., Amy, G. L. (2013). Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability. *Desalination, 309*, 197–207. https://doi.org/10.1016/j.desal.2012.10.015

10. Gomelya, M., Shabliy, T., Radovenchyk, I., Vakulenko, A. (2023). Application of low-pressure reverse osmosis membranes for drinking water softening. *Ecological Engineering & Environmental Technology, 24*(5), 154–162. https://doi.org/10.12912/27197050/165897

11. Hoek, E. M., Elimelech, M. (2003). Cake-enhanced concentration polarization: A new fouling mechanism for salt-rejecting membranes. *Environmental Science & Technology, 37*(24), 5581–5588. https://doi.org/10.1021/es0262636

12. Jafari, A., D'haese, J., Zlopasa, E., Cornelissen, E. R., Vrouwenvelder, J. S., Verbeken, K., Verliefde, A., van Loosdrecht, M. C. M., Picioreanu, C. (2020). A comparison between chemical cleaning efficiency in lab-scale and full-scale reverse osmosis membranes: Role of extracellular polymeric substances (EPS). *Journal of Membrane Science, 609*, 118189. https://doi.org/10.1016/j.memsci.2020.118189

13. Jamaly, S., Darwish, N. N., Ahmed, I., Hasan, S. W. (2014). A short review on reverse osmosis pretreatment technologies. *Desalination, 354*, 30–38. https://doi.org/10.1016/j.desal.2014.09.017

14. Jha, S. K., Ghosh, A. (2025). Towards sustainable water resources: A critical review of evaluating traditional and solar-based desalination technologies and innovations. *Desalination and Water Treatment, 322*, 101246. https://doi.org/10.1016/j.dwt.2025.101246

15. Kassouar, S., Abi-Ayad, S. M. E. (2024). The disadvantages of seawater desalination at the Bousfer station located on the Oran coast in western Algeria. *Journal of Ecological Engineering & Environmental Technology, 25*(6). https://doi.org/10.12911/22998993/187815

16. Kherraf, S., Bakkouche, C., Barhmi, S., Mabrouki, J., El Hajjaji, S., Elfatni, O., Dhiba, D., Maissine, K. (2023). Forecasting of permeate conductivity using

MLR and ANN methods of Boujdour seawater reverse osmosis desalination plant. *Current Analytical Chemistry, 19*(4), 348–355. https://doi.org/10.2174/1573411019666230221143245

17. Kim, G., Park, K.-D., Soo, A., Shon, H. K., Woo, Y. C. (2026). Machine learning-driven process design and performance prediction for small-scale seawater reverse osmosis desalination. Desalination, 620, 119686. https://doi.org/10.1016/j.desal.2025.119686

18. Lachheb, A., El Attar, A., Addar, F. Z., Kouda, I., Zouhri, N., Touir, J., Taky, M., Tahaikt, M. (2026). Salinity effect in permeability of salt in nanofiltration and reverse osmosis membranes. *Chemistry Open, 15*(1), e202500198. https://doi.org/10.1002/open.202500198

19. Lee, Y. G., Lee, Y. S., Kim, D. Y., Park, M., Yang, D. R., Kim, J. H. (2012). A fouling model for simulating long-term performance of SWRO desalination process. *Journal of Membrane Science,* 401–402, 282–291. https://doi.org/10.1016/j.memsci.2012.02.016

20. Odabaşı, Ç., Dologlu, P., Gülmez, F., Kuşoğlu, G., Çağlar, Ö. (2022). Investigation of the factors affecting reverse osmosis membrane performance using machine learning techniques. Desalination.

21. Philibert. Marc, Villacorte, L. O., Ekowati, Y., Abushaban, A., Salinas-Rodriguez, S. G. (2024). Fouling and scaling in reverse osmosis desalination plants: A critical review of membrane autopsies, feedwater quality guidelines and assessment methods. *Desalination, 592*, 118188. https://doi.org/10.1016/j.desal.2024.118188

22. Porcelli, N., Judd, S. (2010). Chemical cleaning of potable water membranes: A review. *Separation and Purification Technology, 71*(2), 137–143. https://doi.org/10.1016/j.seppur.2009.12.007

23. Pulido Beltran, L., Vrouwenvelder, J. S., Farhat, N. (2024). Application of online flow cytometry for early biofouling detection in reverse osmosis membrane systems. *Membranes, 14*(9), 185. https://doi.org/10.3390/membranes14090185

24. Ruiz-García, A., Melián-Martel, N., Nuez, I. (2017). Short review on predicting fouling in RO desalination. *Membranes, 7*(4), 62. https://doi.org/10.3390/membranes7040062

25. Shouman, L. A., Afify, R. M., Esawy, M. H., Fadel, D. A. (2024). Fouling effect on reverse osmosis membranes performance in desalination plant. *Desalination and Water Treatment*, 100502. https://doi.org/10.1016/j.dwt.2024.100502

26. Singh, D., Anand, S. (2025). Evaluating the effectiveness of individual cleaning steps of a CIP protocol in membrane biofilm removal under dynamic conditions. *Applied Sciences, 15*(17), 9477. https://doi.org/10.3390/app15179477

27. Stover, R. L. (2016). High recovery, low fouling, and low energy reverse osmosis. *Desalination and Water Treatment, 57*(55), 1–6. https://doi.org/10.1080/19443994.2016.1168586

28. Tanudjaja, H. J., Amin, N. A., Qamar, A., Kerdi, S., Basamh, H., Altmann, T., Das, R., Ghaffour, N. (2025). Reverse osmosis desalination advancements. npj *Clean Water, 8*, 22. https://doi.org/10.1038/s41545-025-00451-9

29. Teng, Y., Ng, H. Y. (2024). Prediction of reverse osmosis membrane fouling in water reuse by integrated adsorption and data-driven models. *Desalination, 576*, 117353. https://doi.org/10.1016/j.desal.2024.117353

30. Vrouwenvelder, J. S., van Loosdrecht, M. C. M., Kruithof, J. C. (2011). Early warning of biofouling in spiral wound nanofiltration and reverse osmosis membranes. *Desalination, 265*(1–3), 206–212. https://doi.org/10.1016/j.desal.2010.07.053