



Enhancement of Cleaning-in-Place (CIP) Using Chemical Cleaning to Control Fouling and Scaling on Seawater Reverse Osmosis (SWRO) Membrane Full-Scale Plant Producing Demineralized Water in Central Java

Retno Dwi Nyamiati^{1*}, Renung Reningtyas¹, Ayu Utami², Dodi Eko Nanda^{3,4}, Adi ilcham¹, Retno Ringgani¹, Avido Yuliestyan¹, Putri Restu Dewati¹, Susanti Rina Nugraheni¹, Daniel Timotius¹, Muhammad Redo Ramadhan¹, Aditya Kurniawan¹, Fauzan Irfandy¹, Merreta Noorenza Biutty¹ and Shofirul Sholikhatun Nisa¹

¹ Faculty of Industrial Technology, Universitas Pembangunan Nasional "Veteran" Yogyakarta, 55283, Indonesia

² Faculty of Mineral and Energy Technology, Universitas Pembangunan Nasional "Veteran" Yogyakarta, Jl. SWK No. 104, Ngropoh, Condong Catur, Depok, Sleman, DI Yogyakarta, Postcode. 5598, Indonesia

³ Energi Quarto Indonesia, 12590, Jakarta, Indonesia

⁴ Department of Geographical Environment and Pollution Control, Zhejiang Normal University, China

* Correspondence: retno.dwinyamiati@upnyk.ac.id

Citation:

Nyamiati, D.R.; Reningtyas, R.; Utami, A.I. Nanda, E.D.; Ilcham, A.; Ringgani, R.; Yuliestyan, A.; Dewati, R.P.; Nugraheni, R.S.; Timotius, D.; Ramadhan, R.M.; Kurniawan, A.; Irfandy, F.; Biutty, N.M.; Nisa S.S. Enhancement of cleaning-in-place (CIP) using chemical cleaning to control fouling and scaling on seawater reverse osmosis (SWRO) membrane full-scale plant producing demineralized water in central java. *ASEAN J. Sci. Tech. Report.* **2026**, 29(6), e260790. <https://doi.org/10.55164/ajstr.v29i6.260790>

Article history:

Received: August 11, 2025

Revised: February 18, 2026

Accepted: February 22, 2026, 2026

Available online: May 15, 2026

Publisher's Note:

This article is published and distributed under the terms of the Thaksin University.

Abstract: Despite recent advances in membrane technology for sustainable water treatment, fouling remains a key challenge to long-term performance, as it leads to surface deposits and concentration polarization. To address this issue, this study evaluates the effectiveness of cleaning-in-place (CIP) in controlling fouling and scaling in a seawater reverse osmosis system at Sumber Segara Primadaya Co. Ltd. Evaluation parameters include pressure drop, flux recovery ratio, salt rejection recovery, and membrane characterization before and after cleaning. The CIP process showed positive results, as indicated by the recovery of differential pressure (ΔP) to its initial condition. The membrane flow rate also returned to its original value of 103–104 m³/h under the same operating pressure of 3.6 bar. Membrane productivity, which had declined by 19%, was successfully restored, with recovery improving from 38% to 40%. In addition, salt rejection increased from 98.8% back to approximately 99.03%, representing a 2% improvement toward the initial value of 99.1%. These findings demonstrate that CIP is an effective method for restoring membrane performance and extending operational lifespan.

Keywords: Seawater; desalination; membrane; fouling; Cleaning-in-Place (CIP)

1. Introduction

Membrane technology offers an effective desalination method for converting seawater into fresh water through filtration. The development of membranes for desalination has progressed from nanofiltration (NF) and forward osmosis (FO) to reverse osmosis (RO), which currently stands out as the most promising technology for seawater filtration [1–3]. Membrane fouling remains an unavoidable challenge in desalination operations, despite decades of research aimed at enhancing anti-fouling properties and developing control strategies using supporting materials. Nevertheless, significant fouling still occurs over time [4].

Fouling reduces membrane performance by causing foulant buildup and surface deposits, leading to concentration polarization [4]. This occurs as rejected solutes accumulate along the membrane surface during filtration, gradually increasing solute concentration and worsening membrane efficiency [4]. A decline in membrane performance, including reduced permeate flux, selectivity, and permeability, can significantly shorten the membrane's operational life [9]. This reduction in performance is often caused by the accumulation of unwanted substances, influenced by feed characteristics such as composition, pH, ionic strength, and foulant concentration [5]. The deposition of these materials can occur either on the membrane surface or within its internal structure. Additionally, the types of accumulated impurities can be classified as organic, inorganic, or biological, often resulting from continuous filtration and microbial activity in the feed solution [4].

Fouling generally begins with the accumulation of particles on the membrane surface, which causes pore obstruction and narrowing. Over time, this leads to the formation of a thick layer that reduces membrane efficiency, a phenomenon known as concentration polarization [6]. To enhance membrane performance, several approaches can be applied, including feed pretreatment, modification of membrane properties, optimization of operating conditions, and membrane cleaning. Among these, membrane cleaning is the most widely used and practical method in industrial applications [7]. When performed regularly according to a set schedule, cleaning can improve process efficiency and extend membrane service life. Membrane cleaning techniques are commonly grouped into four main categories: hydraulic, mechanical, chemical, and electrical. The selection of an appropriate method depends on the membrane module design, chemical resistance, and the type of foulants present [8].

Chemical cleaning is considered one of the most effective methods for addressing membrane fouling, using a variety of cleaning agents either individually or in combination. The effectiveness of this method depends on several factors, including the type of chemicals used and the duration of the cleaning process. Common cleaning agents include acids, alkalis, surfactants, enzymes, complexing agents, disinfectants, and blended formulations [9]. Although chemical cleaning, particularly for reverse osmosis (RO) membranes, has been widely studied in the literature, the relationship between laboratory-scale results and full-scale cleaning performance remains poorly defined [10], [11], [12]. This study investigates the effectiveness of CIP in controlling fouling and scaling in a seawater RO system at Sumber Segara Primadaya Co. Ltd. Key evaluation parameters include pressure drop, flux recovery ratio, salt rejection recovery, and membrane performance monitoring over several weeks post-cleaning. This study provides a comprehensive evaluation of CIP performance in a full-scale SWRO plant under real industrial operating conditions, offering valuable insights that bridge the gap between laboratory-scale research and practical field application. The novelty of this study lies in its full-scale industrial evaluation of enhanced chemical cleaning-in-place (CIP) strategy under real operational conditions in a seawater reverse osmosis (SWRO) plant producing demineralized water. The exact problem addressed in this study was the progressive performance decline of SWRO membranes, characterized by increasing pressure drop, reduced recovery, and higher permeate conductivity, which led to unstable demineralized water production. The study aimed to evaluate whether optimization of chemical CIP protocols could effectively restore membrane performance and improve operational stability without membrane replacement. Therefore, this work contributes practical operational insights by correlating CIP treatment with normalized performance indicators (pressure drop, recovery, salt rejection, and permeate conductivity) under real plant conditions, providing guidance for membrane maintenance strategies in industrial desalination systems. This study was conducted in a full-scale industrial SWRO system, and therefore direct membrane autopsy or surface characterization was beyond the scope of the investigation. Techniques such as SEM-EDS, FTIR, or ICP-OES, which could provide definitive identification of foulant composition, were not performed. Consequently, the interpretation of organic fouling and inorganic scaling is based on operational indicators and feed-water chemistry rather than direct analytical confirmation.

2. Materials and Methods

2.1 Materials

This research was conducted at a water treatment facility of a coal-fired steam power plant in Indonesia, operated by Sumber Segara Primadaya Co. Ltd (S2P). The chemical cleaning agents used in this industrial-scale study were of research-grade quality. Permea Clean PC-90, composed of 40% sodium hydroxide and 60% tetrasodium EDTA, was used as the alkaline cleaning agent for membrane CIP. A chemical agent consisting of 80% citric acid served as the acidic cleaning agent. In addition, hydrochloric acid (HCl) and sodium hydroxide (NaOH) were used as solvents to adjust the pH of the cleaning solutions as needed. Demineralized water was used as the medium for chemical treatment analysis. Nalco Co., Ltd., Indonesia, supplied all materials. The SWRO system in this study serves as the primary desalination stage before final polishing treatment. The target permeate conductivity from the RO unit was $< 50 \mu\text{S}/\text{cm}$ before downstream demineralization. Final boiler feed water specifications $< 1\text{--}5 \mu\text{S}/\text{cm}$ were achieved after post-treatment units and ion exchange/mixed-bed polishing.

Table 1. Operating conditions of the reverse osmosis membrane

Case Studies	Membrane Specification
Location	S2P Co. Ltd, Indonesia
Company website	https://www.ssprimadaya.co.id
Manufacture	LG Chem
Feed Pressure	60 bar
Hp Pump Flow	255 L/min
HP pump Pressure	3.6 bar
RO Membrane Element	LG SW400 (37.2 m ²)
RO Pressure Vessel	8" 1000 psi 7 core
Amount of Pressure Vessel	28 bar
Total Membrane Core	196 pcs
Feed Conductivity	40000-50000 $\mu\text{S}/\text{cm}$
Permeate Product	102 m ³ /jam
% Recovery	40%
Salt Rejection	>99%
ΔP	<0.25

2.2 Method

2.2.1 RO Indication for Cleaning

The RO membrane at S2P Indonesia was operated to produce demineralized water as feedwater for a supercritical boiler. The operating conditions of the RO membrane are described in **Table 1**. This RO system underwent periodic CIP cleaning when the differential pressure exceeded 0.25 bar. Additionally, when the salt rejection, recovery rate, or permeate production decreased by 10–15% from standard performance levels, chemical cleaning of the membrane was required.

2.2.2 Synthesis of Chemical Solution for Cleaning

The CIP process for the reverse osmosis membrane began with an alkaline cleaning step using Permeate Clean PC-90, a chemical containing dynamic EDTA content. The PC-90 solution was prepared at a concentration of 4% of the total membrane volume and introduced into the CIP chemical tank. Additionally, a 1% EDTA solution was prepared by diluting it with mineral water to match the total volume of the membrane system. NaOH was then added to the solution to adjust the pH to 12–13 before circulating it through the membrane during the cleaning process. Following completion of the alkaline cleaning stage, an acid cleaning process was performed using chemical N-70264, which contains citric acid as the active ingredient. A 4% N-70264 solution (based on the total membrane volume) was prepared, and HCl was added to adjust the pH to 2–3. This acidic solution was then circulated through the membrane during the cleaning process.

2.2.3 Cleaning Procedure

The cleaning process scheme is illustrated in Figure 1. It depicts the sequence of operations and the major components involved in the CIP process for cleaning and maintaining RO membranes. For instance, the CIP procedure for the reverse osmosis (RO) membrane consists of three main stages: (1) RO membrane valve configuration, (2) alkaline cleaning, and (3) acid cleaning. The first stage involves configuring the RO membrane system's valves to prepare for the cleaning process. The inlet and outlet valves of the RO membrane in service (feed and permeate lines) must be fully closed to isolate the system. The CIP inlet and outlet valves for the RO membrane must be opened to allow the cleaning solution to circulate. Before initiating the CIP process, ensure the CIP pump is in proper working order and that the cartridge filter is installed and ready for use. The second stage is the alkaline cleaning process. A pre-prepared alkaline cleaning solution is pumped through the RO system via the CIP line for 60 minutes of continuous circulation. Once the circulation is complete, the membrane is soaked in the alkaline solution for an additional 30 minutes. During both the circulation and soaking phases, the pH of the cleaning solution must be monitored every 10 minutes. If the pH falls below 12, NaOH should be carefully added to the CIP tank to maintain the target pH range of 12–13. This circulation-and-soaking cycle is repeated three times to ensure effective removal of organic and biological foulants. After the final soaking, the alkaline solution is drained, and the membrane is thoroughly rinsed with clean water. It is important to confirm that the rinse water pH is neutral (7–8), and both pH and turbidity should be measured and recorded during this step.

The final stage is the acid cleaning process. A pre-prepared acid solution is circulated through the RO membrane using the CIP line for 60 minutes. After the circulation, the membrane is soaked in the acid solution for 30 minutes. During this phase, the solution's pH should be checked every 10 minutes. If the pH rises above 2, HCl must be added carefully to bring the pH back within the target range of 2–3. The acid cleaning cycle includes both circulation and soaking and is repeated three times to dissolve inorganic scales and mineral deposits effectively. After the final soaking, the acid solution is drained, and the membrane is thoroughly rinsed using clean water. Similar to the previous rinse, the pH of the rinse water should be within the 7 to 8 range, and both pH and turbidity must be monitored and recorded to verify the effectiveness of the cleaning process. The selected three-month dataset represents stable full-load operation under consistent feedwater characteristics, enabling a reliable assessment of CIP effectiveness.

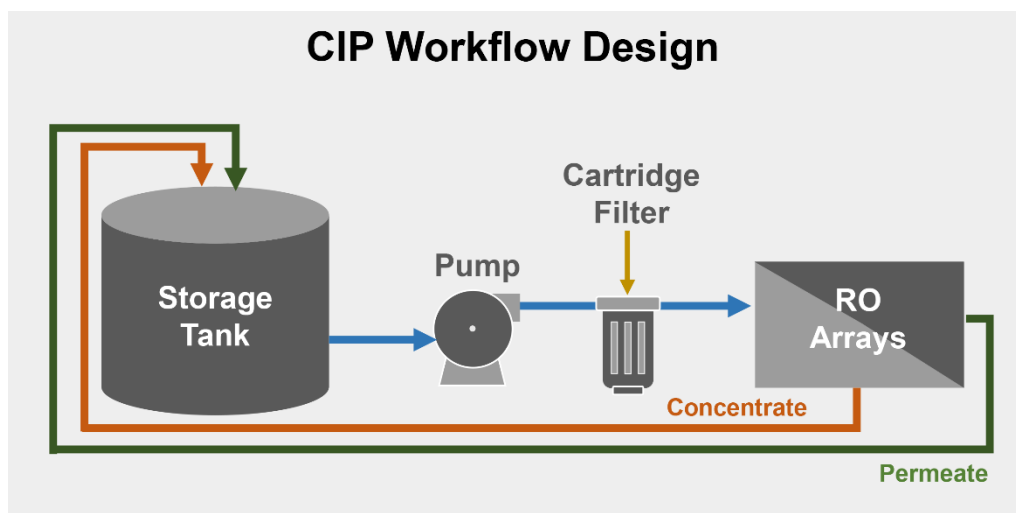


Figure 1. Schematic of cleaning-in-place (CIP) Process

2.2.4 Performance Evaluation Parameters

The performance of the SWRO system was evaluated using several key operational parameters, including recovery, salt rejection, permeate flux, and flux recovery. Recovery (R) represents the fraction of feed water converted into permeate and is calculated as the ratio of permeate flow rate (Q_p) to feed flow rate (Q_f), expressed as a percentage. This parameter indicates the efficiency of water production during

membrane operation. Salt rejection (SR) was used to assess membrane selectivity and desalination performance. It was determined based on the difference between feed concentration or conductivity (C_f) and permeate concentration or conductivity (C_p). A higher salt rejection value reflects better ion removal capability of the membrane. Permeate flux (J) describes the permeate flow rate normalized by the effective membrane area (A), representing the hydraulic productivity of the membrane system. This parameter is commonly used to evaluate the influence of fouling and cleaning processes on membrane performance. To assess the effectiveness of cleaning-in-place (CIP), flux recovery (FR) was calculated as the ratio of the permeate flux after cleaning to the flux before cleaning. In some cases, flux recovery can also be referenced to the initial clean membrane condition to evaluate the extent of performance restoration. Flux recovery values close to 100% indicate successful recovery of membrane permeability after cleaning. The corresponding equations used to calculate these parameters are provided as follows [13], [14], [15]:

$$R (\%) = \frac{Q_p}{Q_f} \times 100 \dots\dots\dots (1)$$

$$SR (\%) = \left(1 - \frac{C_p}{C_f}\right) \times 100 \dots\dots\dots (2)$$

$$FR (\%) = \left(\frac{J_{after}}{J_{before}}\right) \times 100 \dots\dots\dots (3)$$

3. Results and Discussion

3.1 Effect of Cleaning on Membrane Differential Pressure

Figure 2 shows the membrane differential pressure (ΔP) over time during operation from May to June 2022. The graph shows a gradual, consistent increase in ΔP , from 0.18 bar to about 0.22 bar by the end of the monitoring period. This represents a total increase of around 15% from the initial pressure value. The stepwise pattern of the graph suggests periodic accumulation of fouling and scaling within the membrane system, leading to progressive blockage of the feed channels. This rising trend in ΔP is a clear indicator that the membrane experienced increasing resistance to flow, signaling the need for CIP to restore optimal membrane performance [4]. In this regard, monitoring and responding to changes in ΔP is essential to prevent severe membrane damage and to maintain long-term operational efficiency.

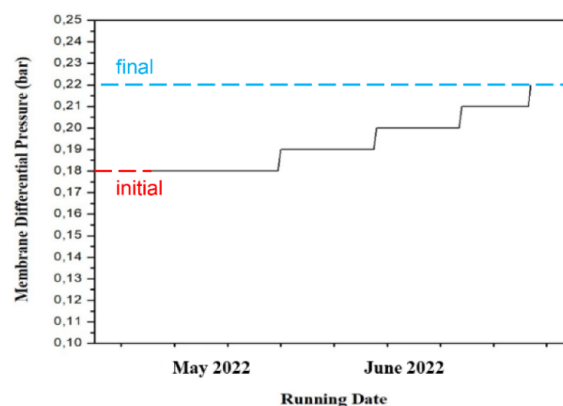


Figure 2. Differential pressure of the seawater reverse osmosis membrane before the CIP process

Before CIP, the membrane had been operating continuously for 49 days, during which the differential pressure increased by approximately 16% from its initial value, indicating a gradual accumulation of fouling and a decline in membrane performance. To restore optimal operation, a CIP procedure was performed, beginning with an alkali cleaning agent and followed by an acid cleaning step. The result of the membrane differential pressure after CIP is presented in **Figure 3**. The results show that the CIP is effective, as evidenced by the post-cleaning ΔP , which stabilized at approximately 0.19 bar. This value remained steady

for at least two weeks after the CIP, demonstrating that the cleaning successfully removed fouling and restored the membrane to acceptable operational conditions.

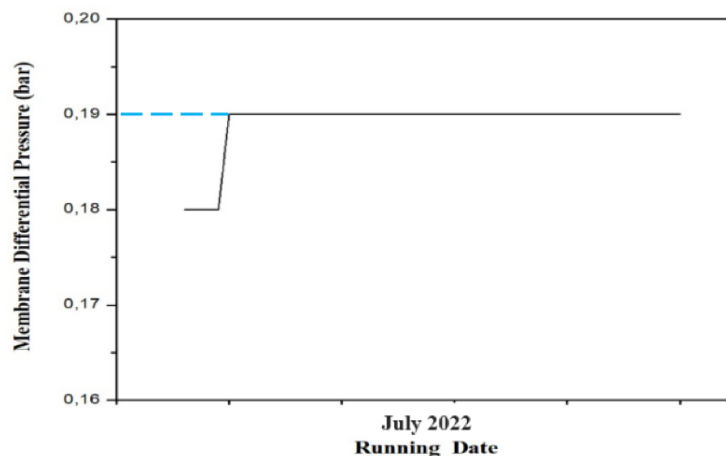


Figure 3. Differential pressure of seawater reverse osmosis membrane after the CIP process

To clearly illustrate the impact of the CIP process, the data before and after cleaning were combined and are shown in Figure 4, highlighting the recovery of membrane differential pressure. In this condition, the recovery in differential pressure was due to the effective two-step CIP process, comprising alkaline and acid cleaning. During the alkaline stage, a basic cleaning solution was used to dissolve and remove organic contaminants such as oils, biofilms, and other organic matter from the membrane surface. This was then followed by the acid cleaning stage, which targeted and eliminated inorganic deposits, including mineral scale and metal oxides [16]. These two cleaning stages worked synergistically to restore the membrane's condition and operational performance. It should be noted that similar findings have been reported in previous studies, supporting the effectiveness of the CIP process used in our system.

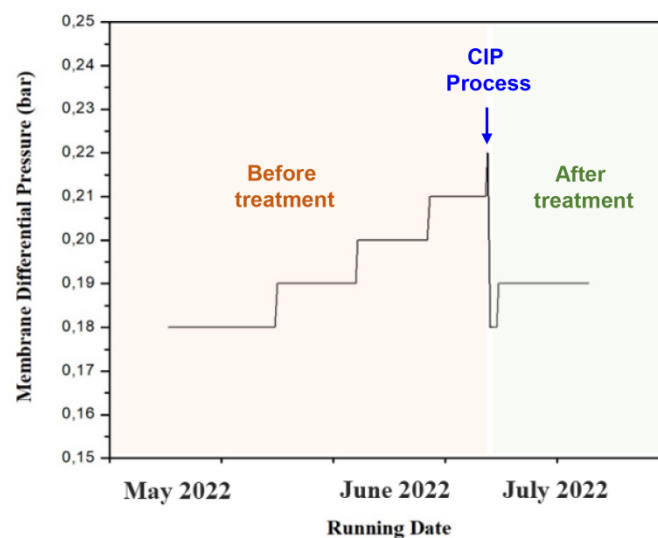


Figure 4. Differential pressure of seawater reverse osmosis membrane before and after the CIP process

3.2 Effect of Cleaning on Membrane Permeate Flow and % Recovery

As shown in Figure 5, the period from May to late June 2022 represents the operating condition before the application of the CIP procedure. During this time, a noticeable decline in membrane performance was recorded. The permeate flow rate gradually decreased from around 103–104 m³/h to ~85 m³/h, accompanied by a reduction in % recovery from 40% to ~35%. These trends reflect the accumulation of fouling materials such as organic compounds, biological growth, and inorganic scales, which can obstruct membrane pores and increase hydraulic resistance across the membrane module [20, 21]. In contrast, the

data in Figure 5 from July 2022 indicate the condition after CIP application, with a clear recovery in system performance. Under identical operating pressure conditions of 3.6 bar, the membrane flow rate returned to its initial state. This recovery corresponds to a 19% improvement in membrane productivity. Additionally, the % recovery, which had previously declined to 35%, increased to 40% after CIP, effectively restoring a 5% loss in membrane recovery. This enhancement can be directly attributed to the effectiveness of the CIP process, as further supported by the results in Figures 2 and 3. The underlying reason for these improvements is the removal of both organic and inorganic foulants accumulated over time. As shown in earlier discussion, the alkaline cleaning step dissolved organic contaminants such as biofilms and oils (*idem atas*), while the acid step removed scaling caused by mineral deposits. By eliminating these layers, the membrane surface and pores were cleared, allowing feed water to pass through more freely, thereby increasing permeate flow and restoring system efficiency.

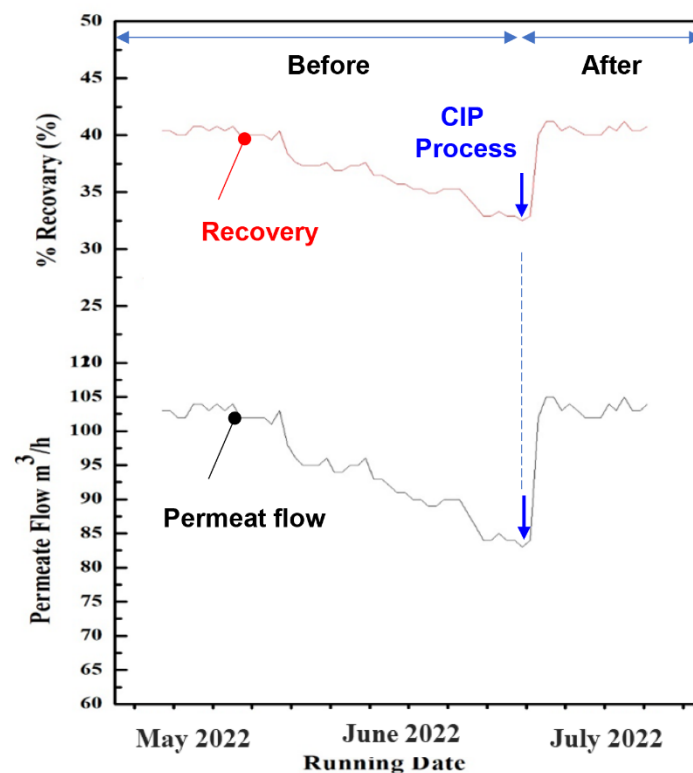


Figure 5. Permeate flow and % Recovery before and after CIP process

3.3 Effect of Cleaning on Permeate Quality and Salt Rejection

Figure 6 illustrates the changes in salt rejection, permeate conductivity, and feed conductivity from May to July 2022, providing insight into membrane performance before and after the CIP process. The data indicate a noticeable decline in membrane performance during May and June, before CIP, followed by a significant recovery in July after CIP was applied. During May and June, salt rejection decreased from 99.1% to 98.8%, while permeate conductivity increased to 690 $\mu\text{S}/\text{cm}$. This represents about a 21% increase from the initial permeate conductivity levels. These changes reflect a decline in membrane selectivity, allowing more dissolved salts to pass through the membrane. At the same time, feed conductivity remained relatively stable, fluctuating between 46,000 and 47,500 $\mu\text{S}/\text{cm}$. Since the feed conductivity did not change significantly, the observed deterioration in permeate quality can be attributed to membrane fouling or scaling rather than to fluctuations in feedwater salinity.

Permeate quality in a seawater reverse osmosis system is directly influenced by the difference between feed conductivity and permeate conductivity. When the membrane is functioning properly, it rejects most dissolved salts, resulting in low permeate conductivity and high salt rejection. However, as fouling from organic substances, microbial growth, or mineral scaling builds up, the membrane's ability to

retain salts is reduced. This leads to higher salt passage and increased permeate conductivity. This condition was clearly observed during May and June, before CIP was conducted. After the CIP process was implemented in early July, membrane performance improved substantially. Permeate conductivity decreased to approximately 540 $\mu\text{S}/\text{cm}$, corresponding to about a 20% improvement in permeate quality. Salt rejection also improved, increasing to 99.03%. This represents about 2% recovery in salt rejection efficiency. Importantly, these improvements occurred while feed conductivity remained relatively unchanged, confirming that the CIP process was effective in restoring the membrane's selectivity and overall performance.

These findings demonstrate that the CIP process successfully removed the foulants and scaling that had impaired the membrane. As a result, the membrane's ability to separate dissolved salts was restored, leading to improved salt rejection and enhanced permeate quality. Finally, the conductivity data clearly illustrate that permeate quality is strongly influenced by the membrane condition and the conductivity difference between feed and permeate water. The improvements in salt rejection and permeate conductivity after the cleaning procedure highlight the critical role of regular chemical cleaning in maintaining long-term operational performance of seawater reverse osmosis systems.

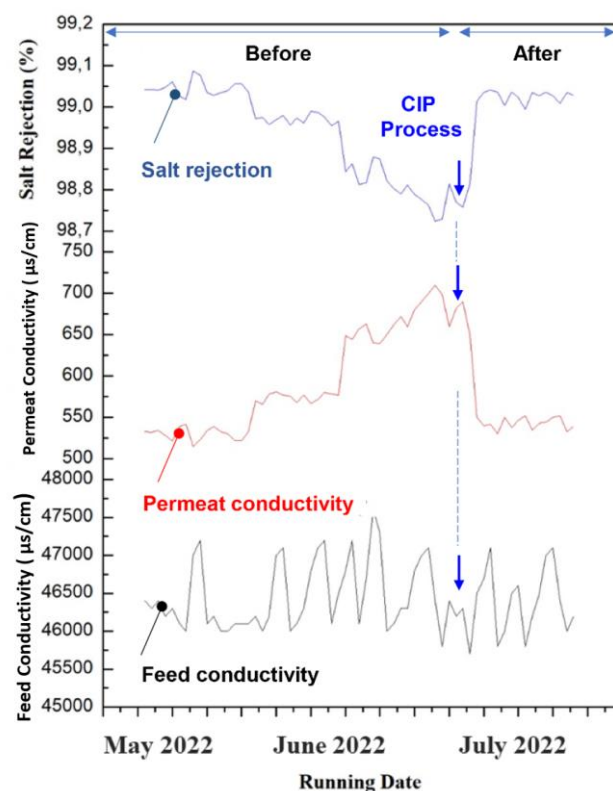


Figure 6. Variation in feed conductivity, permeate conductivity, and salt rejection before and after the CIP process

These full-scale observations align qualitatively with controlled laboratory-scale experiments; however, the quantitative relationship between lab-scale cleaning efficiencies and real industrial system recovery remains poorly defined. Lab studies often focus on idealized conditions, specific foulant types, and simplified flow regimes, while full-scale operations must contend with complex foulant mixtures, variable hydraulic profiles, and prolonged exposure to harsh feed conditions. The findings of this study help bridge this gap by providing practical, field-based evidence that supports the effectiveness of chemical CIP in restoring both hydraulic and separation performance in an industrial SWRO plant [6, 17-18].

4. Conclusions

The CIP procedure applied in this study demonstrated a significant recovery of membrane function under real industrial conditions. Following the CIP process, the pressure drop (ΔP) decreased from 0.22 bar before CIP to approximately 0.19 bar after CIP, corresponding to a reduction of about 0.03 bar ($\approx 14\%$), indicating partial removal of fouling layers and improved hydraulic conditions across the membrane system. The membrane flow rate recovered from its decline, returning to the initial level of 103–104 m³/h at a constant operating pressure of 60 bar, equivalent to a 19% improvement in membrane productivity. Recovery rate also improved, rising from 38% to 40%, resulting in a 5% increase in water recovery efficiency. In terms of separation performance, salt rejection improved from 98.8% to 99.03%, and permeate conductivity decreased from 690 $\mu\text{S}/\text{cm}$ to 540 $\mu\text{S}/\text{cm}$, reflecting enhanced desalination performance and improved membrane selectivity after cleaning. These results confirm the effectiveness of CIP in restoring both hydraulic and separation performance of fouled membranes under full-scale industrial operation. Importantly, the findings also highlight how operational data at full scale can complement laboratory-scale studies, which often fail to capture the full complexity and variability of long-term field operations. Future studies should incorporate membrane-surface characterization to validate the composition and mechanisms of fouling.

5. Acknowledgements

The authors would like to thank the Institute for Research and Community Service (LPPM) Universitas Pembangunan Nasional Veteran Yogyakarta for providing financial support for the implementation of this research through Grant no. 805/UN62.21/PG.00.00/2025, and Sumber Segara Primadaya Co. Ltd.

Author Contributions: Conceptualization, R.D.N.; methodology, D.E.N., A.Y.; validation, R.D.N., D.E.N., and M.N.B.; formal analysis, D.E.N.; investigation, R.D.N. and D.E.N.; data curation, D.E.N., A.U.; writing—original draft preparation, R.D.N. and M.N.B; writing—review and editing, R.D.N., M.N.B., A.I., R.R., R.R., P.R.D., S.R.N., M.R.R. and D.T.; visualization, A.K., F.I., and S.S.N.; supervision, R.D.N. All authors have read and agreed to the published version of the manuscript.

The manuscript has undergone comprehensive language editing, with grammar improvements assisted by AI-based language correction tools to enhance clarity, readability, and overall consistency.

Conflicts of Interest: The authors declare no conflict of interest.

References

- [1] Nurkhamidah, S.; Dwi, R.; Ramadhani, A.; Cintya, B. Effect of Solvents in the Performance of Cellulose Acetate/Poly(1,4-butylenesuccinate) Membrane Prepared by Using Phase Inversion Method. *Indones. Polym. J.* **2019**, *22*(2), 10–15. <https://doi.org/10.37889/mpi.2019.22.2.3>
- [2] El-Din, L. A. N.; El-Gendi, A.; Ismail, N.; Abed, K. A.; Ahmed, A. I. Evaluation of Cellulose Acetate Membrane with Carbon Nanotubes Additives. *J. Ind. Eng. Chem.* **2015**, *26*, 259–264. <https://doi.org/10.1016/j.jiec.2014.11.037>
- [3] Nurkhamidah, S.; Ramadhani, A.; Cintya, B.; Arief, B.; Nyamiati, R. D. Modified of Cellulose Acetate/Polyethylene Glycol Membrane by the Addition of Graphene Oxide. *Indones. Polym. J.* **2019**, *22*(2), 16–20. <https://doi.org/10.37889/mpi.2019.22.2.4>
- [4] Al-Balushi, M. A.; Kyaw, H. H.; Tay, M.; Myint, Z.; Al-Abri, M.; Dobretsov, S. Chemical Cleaning Techniques for Fouled RO Membranes: Enhancing Fouling Removal and Assessing Microbial Composition. *Membranes* **2024**, *14* (10), 204. <https://doi.org/10.3390/membranes14100204>
- [5] Cho, H.; Lee, S.; Choi, Y.; Lee, S. Analysis of Fouling in Hollow Fiber Membrane Distillation Modules for Desalination Brine Reduction. *Membranes* **2025**, *15*(12), 371. <https://doi.org/10.3390/membranes15120371>

- [6] Lim, Y. J.; Goh, K.; Kurihara, M.; Wang, R. Seawater Desalination by Reverse Osmosis: Current Development and Future Challenges in Membrane Fabrication—A Review. *J. Memb. Sci.* **2021**, 629, 119292. <https://doi.org/10.1016/j.memsci.2021.119292>
- [7] Wenten, I. G.; Bazant, M. Z.; Khoiruddin, K. Mitigating Electrodialysis Membrane Fouling in Seawater Desalination. *Sep. Purif. Technol.* **2024**, 345, 127228. <https://doi.org/10.1016/j.seppur.2024.127228>
- [8] Analysis the Effect of Flux and Water Characteristics on Polyethersulfone Ultrafiltration Membrane Performance as Pre-Treatment of SWRO. *J. Ilmu Lingkungan.* **2024**, 22(4), 836–844. <https://doi.org/10.14710/jil.22.4.836-844>
- [9] Xiao, T.; Zhu, Z.; Li, L.; Shi, J.; Li, Z.; Zuo, X. Membrane Fouling and Cleaning Strategies in Microfiltration/Ultrafiltration and Dynamic Membrane. *Sep. Purif. Technol.* **2023**, 318, 123977. <https://doi.org/10.1016/j.seppur.2023.123977>
- [10] Tayeh, Y. A.; Alazaiza, M. Y. D.; Alzghoul, T. M.; Jk, M. A Comprehensive Review of RO Membrane Fouling: Mechanisms, Categories, Cleaning Methods and Pretreatment Technologies. *J. Hazard. Mater. Adv.* **2025**, 18, 100684. <https://doi.org/10.1016/j.hazadv.2025.100684>
- [11] Gul, A.; Aysegul, F. Y. Fouling and Chemical Cleaning of Microfiltration Membranes. *Polymers (Basel)* **2021**.
- [12] Shahid, M. K.; et al. A Review of Membrane-Based Desalination Systems Powered by Renewable Energy Sources. *Water* **2023**, 15 (3), 534. <https://doi.org/10.3390/w15030534>
- [13] Wang, J.; Dong, D.; Lair, L.; Yaroshchuk, A.; Phillip, W. A.; Bruening, M. L. Combined Nanofiltration and Diafiltration for Isolation of Rare-Earth Ions. *J. Memb. Sci.* **2024**, 711, 123173. <https://doi.org/10.1016/j.memsci.2024.123173>
- [14] Zambare, R. S.; Dhopte, K. B.; Patwardhan, A. V.; Nemade, P. R. Polyamine Functionalized Graphene Oxide Polysulfone Mixed Matrix Membranes with Improved Hydrophilicity and Anti-Fouling Properties. *Desalination* **2017**, 403, 24–35. <https://doi.org/10.1016/j.desal.2016.02.003>
- [15] Sanda, N.; et al. Characterization and Application of Cellulose Acetate (CA) Synthesized from Paper Waste. **2025**, 1–7.
- [16] Camacho, L. M.; Dumée, L.; Zhang, J.; Li, J.; Duke, M. Advances in Membrane Distillation for Water Desalination and Purification Applications. *Water* **2013**, 5(1), 94–196. <https://doi.org/10.3390/w5010094>
- [17] Kakkar, R.; Kaur, D. P.; Raj, S. Membrane Distillation for Sustainable Water Desalination: A Review of Principles, Materials, and Applications. *Water Air Soil Pollut.* **2024**, 236(1), 24. <https://doi.org/10.1007/s11270-024-07622-3>
- [18] Ruiz-García, A.; Al-Obaidi, M. A.; Nuez, I. Impact of SWMM Fouling and Position on the Performance of SWRO Systems in Operating Conditions of Minimum SEC. *Membranes* **2023**, 13(7), 676. <https://doi.org/10.3390/membranes13070676>