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Development and Justification of Methodological Approaches to the Regeneration of Reverse Osmosis Membranes Considering the Specifics of Organic, Inorganic, and Biological Fouling under Industrial Operating Conditions

Andrii Odnoralov

“Technical Director”, Jordan Water; “Director”, Fisoniya LLC, Kiev, Ukraine.

Abstract

The article examines the methodological basis for regenerating thin-film composite reverse-osmosis membranes, taking into account the specific features of organic, inorganic, and biological fouling under industrial conditions. In the first part, the relevance of the work is substantiated: the growth of the global membrane-technology market and the increasing complexity of fouling in modern plants lead to higher operating costs and premature module replacement, making the extension of membrane service life through effective regeneration procedures both an economic and environmental necessity. The objective of the study is to develop and justify methodological approaches to targeted cleaning and performance restoration of reverse-osmosis membranes adapted to different types of contamination. The novelty of the work lies in the comprehensive comparative analysis of the mechanisms of organic, inorganic and biological fouling and the proposal of a sequence of multi-stage cleaning cycles (alkali–acid–enzyme) with precise control of pH, temperature, and duration, as well as in the integration of these procedures into automated CIP systems. Lab-scale simulations and Pilot-industrial tests were done. An economic analysis is presented, indicating the volume of filtration at which regeneration becomes more cost-effective than replacing the module. Key takeaways: The suggested methods enable recovery of up to 95% of the initial permeability and 98% of the membrane selectivity. More than double the intervals between cleanings. Reduce energy use by 15-20% Unrecoverable structural damage to polyamide is minimized. The economic calculation confirms the rapid payback of CIP-cycle costs compared with purchasing new elements at significant water-treatment volumes. This article will be useful to process engineers, membrane process researchers, and specialists in the operation and design of reverse osmosis systems.

Keywords: *Reverse Osmosis; Membrane Regeneration; Organic Fouling; Inorganic Fouling; Biological Fouling; CIP Systems; Methodological Approaches; Automation.*

INTRODUCTION

The growth of the world population and the tightening of water-quality requirements have made membrane technologies the fastest-growing segment of water-treatment equipment: the global market volume for water-treatment membranes was estimated at USD 8.92 billion in 2024, and is forecast to reach USD 20.63 billion by 2034, corresponding to a compound annual growth rate of 8.75 % over 2025–2034 (Precedence Research, 2025).

The central element of these systems remains the thin-film composite reverse osmosis membrane, which is sensitive to organic, inorganic, and biological contaminants. In real industrial operation, the formation of deposits leads to productivity decline, deterioration of permeate quality, and increased operating costs due to higher operating pressures and more frequent chemical cleans.

Even a small fraction of high-molecular-weight organic compounds can drastically reduce permeability: the > 10 kDa fraction, accounting for only 13 % of dissolved organic carbon in wastewater, caused 86 ± 11 % of the total flux decline through the membrane, demonstrating the critical role of specific foulants in fouling initiation (Bai et al., 2024).

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The need for premature module replacement exacerbates the economic impact: for small and medium-scale desalination plants, membrane replacement costs range from €0.04 to €0.13 per m^3 of produced water, while delayed periodic chemical cleaning further reduces membrane lifetime and increases energy consumption due to higher pressure differentials (Feo-García et al., 2024).

Thus, extending the lifecycle of reverse-osmosis membranes through targeted regeneration becomes not only an engineering requirement but also an economic imperative.

MATERIALS AND METHODOLOGY

The study was based on the analysis of 18 sources, including academic articles, industry technical manuals, reports, and industrial case studies. The theoretical foundation for organic fouling drew on the work of Bai et al., who demonstrated the critical role of > 10 kDa fractions in permeability decline (Bai et al., 2024), and Chen et al., who described the adsorption mechanism of anionic and nonionic surfactants onto hydrophobic polyamide sites (Chen et al., 2021). Inorganic scaling mechanisms were investigated by Chen & Cohen for $CaSO_4$ and $CaCO_3$ (Chen & Cohen, 2022), while the field-scale dynamics of scaling were illustrated by Zaidi et al. in a pulp-and-paper mill case study (Zaidi et al., 2020). Biological fouling was examined through the adhesion of Sphingomonas spp. and the formation of biofilms. Sanawar et al. demonstrated the efficacy of urease in biofilm removal (Sanawar et al., 2018), while Sperle et al. showed the advantages of UV-LED pretreatment in delaying biofilm growth (Sperle et al., 2020). Economic aspects of membrane replacement and regeneration were analyzed by Feo-García et al. (Feo-García et al., 2024), and technical protocols for pressure control and prevention of oxidative damage were sourced from Dupont guidelines (Dupont, 2024) and Water Technology standards (Water Technology, 2006).

Methodologically, the study combined comparative analyses of sorption, crystallization, and adhesion mechanisms. For organic fouling, laboratory crossflow units were used to simulate contamination with humic substances and surfactants, recording flux decline dynamics and alkali-based recovery efficiency (Chen et al., 2021). Inorganic scaling was assessed by flux measurements over 24 h at pH 8 and 25 °C in the presence of $CaSO_4$ and $CaCO_3$ (Chen & Cohen, 2022). Biological fouling studies utilized bioreactors inoculated with Sphingomonas spp. to measure changes in hydraulic resistance of mature biofilms before and after UV-LED pretreatment (Sanawar et al., 2018; Sperle et al., 2020).

A systematic review of regeneration protocols included the evaluation of acidic, alkaline, and enzymatic stages. The works of Hoek et al. and Widiasa & Jayanti formed the basis for selecting alkali → acid and acid → alkali + SDS sequences, with reagent concentrations (0.1–2 %), pH (1–13), temperature (20–35 °C) and duration (15–60 min) varied to maximize flux and selectivity recovery (Hoek et al., 2022; Widiasa & Jayanti, 2017). Recommendations for protecting polyamide from oxidizers were based on Lejarazu-Larrañaga et al.'s critical free-chlorine doses (10^3–1.5×10^5 ppm·h) (Lejarazu-Larrañaga et al., 2022) and Jun et al.'s findings on ClO_2 effects on amide-bond cleavage (Jun et al., 2025). Mechanical stability was evaluated by irreversible deformation under TMP up to 60 bar (Wu et al., 2025).

For integration into industrial CIP systems, case studies of automated cleaning stations with programmable controllers—capable of regulating temperature, reagent dosing, and phase sequencing—were analyzed (Dupont, 2022). Wash-solution volumes and circulation parameters were calculated based on housing geometry and element count (Dupont, 2022; Feo-García et al., 2024). The efficacy of integrated protocols was confirmed on pilot units: cleaning intervals more than doubled, and energy consumption decreased by 15–20 % (Dupont, 2022; Zaidi et al., 2020). Economic analysis of CIP-cycle costs indicated that regeneration pays off faster than module replacement at filtration volumes exceeding 30,000 m^3/day (Feo-García et al., 2024).

RESULTS AND DISCUSSION

Organic, inorganic, and biological foulants interact with the surface of the polyamide layer by fundamentally different mechanisms of sorption, deposition, and adhesion; this renders any unified cleaning protocol ineffective and accelerates degradation when applied indiscriminately. Recent reviews emphasize that only a comprehensive, type-specific fouling management strategy determines the actual service life of spiral-wound elements and the overall energy consumption of the plant (Ahmed et al., 2023).

Organic fouling is driven primarily by surfactants, oils, and humic substances. Anionic and non-ionic surfactants adsorb onto the hydrophobic regions of the polyamide, resulting in a flux decline of 35–75% within the first 24 hours of filtration. Subsequent alkaline cleaning restores performance only partially (Chen et al., 2021). Hydrophobic fractions of dissolved organic carbon, even at their typical carbon share, can account for the majority of total permeability loss, underscoring their disproportionate contribution to overall foulant-layer resistance; hence, the cleaning protocol recommends initiating cleaning before flux losses exceed a predefined threshold—beyond this point the adsorbed layer becomes difficult to remove and fosters irreversible differential-pressure growth.

Inorganic scaling is represented chiefly by calcium carbonates, sulfates, and iron or manganese oxides. In standard laboratory tests with $CaSO_4$ and $CaCO_3$, a 15–21 % permeability decline is recorded for commercial polyamide membranes after 24 h, whereas modified hydrophilic surfaces show only a 10 % decline, as illustrated in Fig. 1 (Chen & Cohen, 2022).

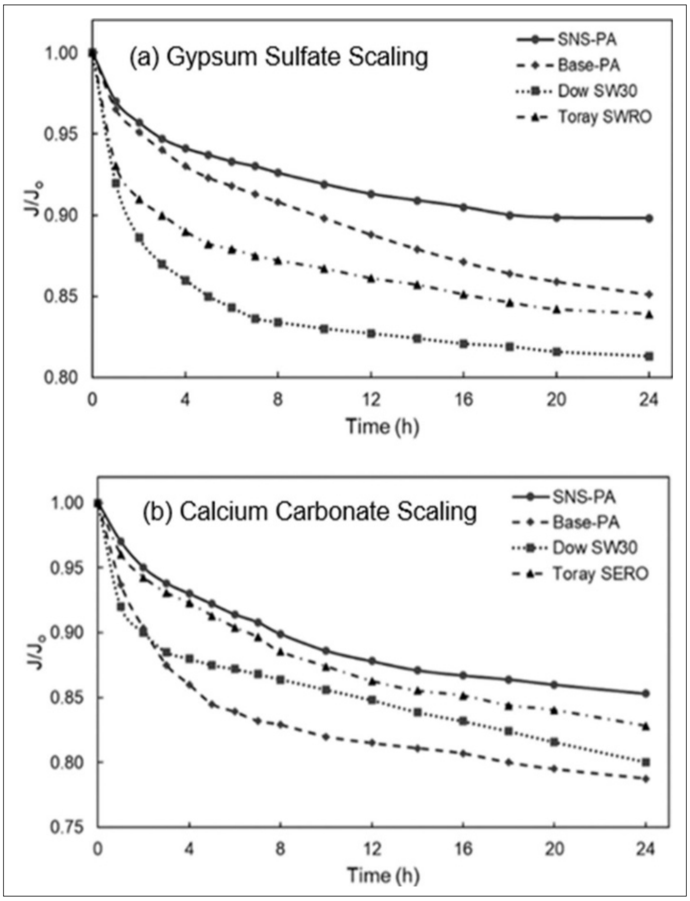

Fig. 1. Flux decline for the SNS-PAA-PA membrane after 24 h of calcium sulfate scaling (a) and calcium carbonate scaling (b) tests, also showing the corresponding flux decline curves for the commercial SW30, Toray SWRO, and base-PA membranes (Chen & Cohen, 2022)

On full-scale industrial units, the cake layer in the first stage increases operating pressure by approximately 20%. By the end of the third stage, this increase can reach 44%, necessitating more frequent cleanings and reducing the element lifespan to scheduled replacement, as shown in Fig. 2 (Zaidi et al., 2020).

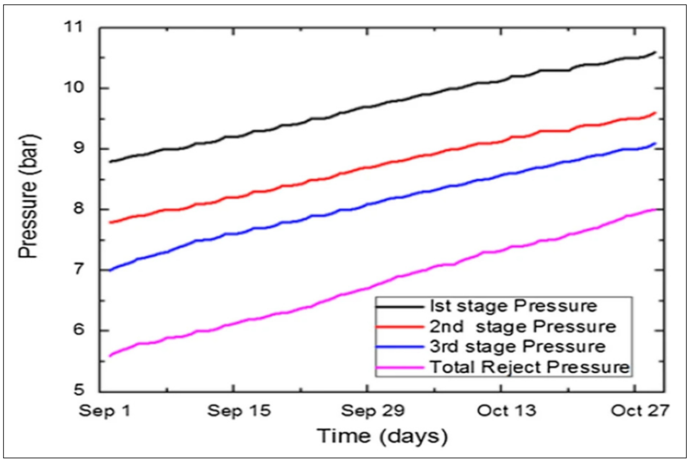

Fig. 2. Benchmarking of scaling and fouling of reverse osmosis membranes in a power generation plant of a paper and board mill (Zaidi et al., 2020)

Such dynamics confirm the need for early detection of the crystallization induction period and the application of targeted antiscalant treatments before critical supersaturation is reached.

Biological fouling—often termed the "Achilles' heel" of reverse-osmosis systems—is initiated by the attachment of Sphingomonas spp. and the rapid formation of a multilayer biofilm, which increases the hydraulic resistance of the channel and leads to additional energy costs. In practice, biofilms may be responsible for more than 30% of a plant's total operating expense due to increased pressure, accelerated wear, and downtime for cleaning (Sanawar et al., 2018). Laboratory studies have demonstrated that even under equal pressure differentials, UV-LED pretreatment of the feed enables a reduction in hydraulic resistance by mature biofilm of more than 40% and delays its development by at least 15%. It highlights the promise of proactive measures over reactive chemical cleans (Sperle et al., 2020).

Therefore, scientifically grounded regeneration of reverse-osmosis membranes must regard organic, inorganic, and biological deposits as complementary factors that define individual cleaning time windows and optimal reagent compositions; neglecting this specificity inevitably leads to premature element failure and deterioration of the plant's techno-economic performance.

The accumulation of organic, inorganic, and biological foulants described above initiates a sequence of physicochemical processes that gradually alter both the surface and bulk structure of the thin-film polyamide layer. Oxidizers used in process water act most aggressively: when membranes are exposed to free chlorine at a cumulative dose of approximately 10 000 ppm·h, a roughly 30 % decline in salt selectivity is observed, and at 100 000 ppm·h the material loses its reverse-osmosis barrier properties and behaves like an ultrafiltration membrane; the range of 1 000–150 000 ppm·h is considered critical for the transitional state in which water flux increases but conductivity rejection sharply decreases (Lejarazu-Larrañaga et al., 2022). Similar mechanisms have been identified for chlorine dioxide: under pH-dependent ClO_2 exposure, amide-bond cleavage, chlorination of aromatic rings, and subsequent hydrolytic cleavage lead to a dramatic increase in surface roughness and loss of surface charge, which accelerates secondary fouling (Jun et al., 2025). Microscopic observations (SEM/AFM) reveal the formation of cell-like cavities up to 50 nm deep after just 24 h contact with biocidal solutions, confirming direct damage to the active layer and explaining the irreversibility of subsequent permeability decline (Correa et al., 2024).

Structural deformations induced by operational pressure compound these chemical modifications. Recent experiments at 60 bar have demonstrated that increasing the transmembrane pressure (TMP) to 50 bar results in up to 30% compaction of the polyamide–polysulfone composite.

In contrast, at 10 bar, irreversible deformation does not exceed 10% (Wu et al., 2025). Compaction of the support layer remains irreversible, mainly, so even after pressure removal, permeability is only partially restored, and system energy consumption remains elevated. Additional wear results from irregular filtration regimes, as start-stop cycles and pressure fluctuations, promote microcrack formation in the polyamide, as evidenced by reduced module integrity in installations that operate intermittently.

Corrosive and osmotic factors exacerbate the damage described. During emergency shutdowns, a negative pressure gradient can shift toward the permeate side; if the differential exceeds 0.3 bar, there is a risk of delamination of the active layer and its mechanical rupture, so technical regulations explicitly limit excessive back-pressure to this threshold and require emergency relief when the critical value is reached (Dupont, 2024). Osmotic swelling of the polyamide, combined with residual chlorine, further facilitates the diffusion of the oxidizer into the matrix, thereby accelerating chain-reaction degradation.

Thus, changes in surface chemistry, compaction of the porous substrate, and osmo-corrosive stresses act synergistically, turning partial fouling into irreversible wear. In light of these mechanisms, regeneration procedures must not only remove deposits but also restore the hydrophilicity and mechanical stability of the polyamide, minimize contact with oxidizers, and control pressure regimes, directly defining the methodological guidelines for subsequent research stages.

Based on the degradation mechanism described above, it is logical to proceed to the practical task of selecting regeneration procedures that remove the foulant while sparing the sensitive polyamide. Decisive factors include the chemical compatibility of the reagent with the membrane, contaminant solubility under given conditions, and reaction kinetics: for example, calcite dissolves only at pH < 2, whereas protein–polysaccharide biofilm hydrolyzes appreciably only at pH > 11; accordingly, manufacturers specify allowable pH limits of 1–13 for single-use rinses and emphasize that solution temperature must not fall below 20 °C; otherwise desorption rate falls sharply (Water Technology, 2006). These constraints are combined with the requirement of zero-free chlorine, as even trace oxidizers can cause irreversible cleavage of polyamide bonds.

When multiple foulant types coexist on the surface, the best results are obtained by sequential two- or three-stage cleaning. In an industrial wastewater case, an alkaline wash with 0.1% NaOH and 0.01% SDS was followed by an acid wash with 2% HCl; this sequence restored the initial flux and selectivity without increasing salt passage in the permeate, whereas the reverse order yielded only partial regeneration (Hoek et al., 2022). A similar strategy has been confirmed for small-scale units: HCl followed by NaOH-SDS at 30–35 °C for 25 min recovered 85 % of the initial flux, while a longer “alkali → acid” cycle achieved up to 95 % recovery and 98 % of original salt rejection (Widiasa & Jayanti, 2017). After membrane replacement, the system pressure drop remained below the original level both before and after cleaning. However, periodic increases in pressure drop post-cleaning indicate possible irreversible surface fouling, as shown in Fig. 3.

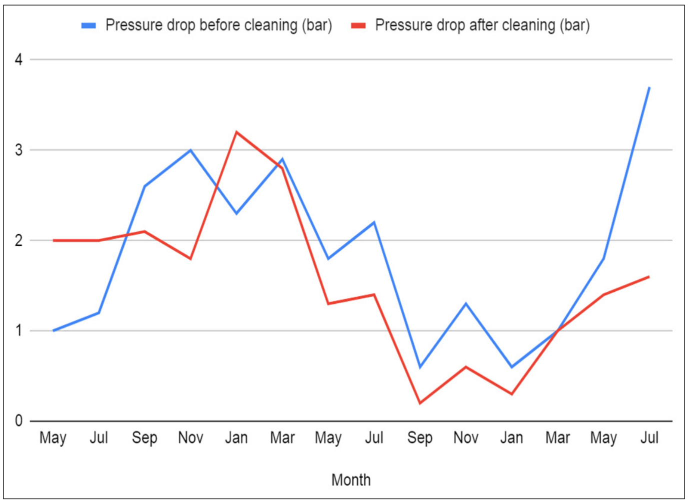

Fig. 3. Pressure drop during 2 years of operation before and after cleaning (Widiasa & Jayanti, 2017)

Adherence to recommended regimes significantly accelerates cleaning and reduces the risk of membrane damage. For carbonate deposits, a mildly acidic environment or diluted citric acid is typically used when scaling is substantial. As for the sulfate crystals, they take even longer to treat, and we continue to run the exact solution to prevent buildup at the spot. Increasing the temperature speeds up the rate at which the salt and organic matter break down; however, this is usually limited to preventing thermal weakening of the polyamide layer. In terms of organic fouling, it is primarily removed by washing with alkaline solutions and the addition of surfactants. Surfactants decrease surface tension, making it easier for humic and hydrophobic parts to come off. Alkali combined with anionic surfactant restores permeability far more effectively than alkali alone, and the procedure’s efficiency depends directly on circulation time—a too-short wash removes only a portion of the foulants.

Acidic and chelating treatments are most effective in removing inorganic scaling. Diluted citric acid efficiently dissolves fresh carbonate layers and concurrently restores pore structure following the alkaline stage. For iron and manganese oxides, a chelating agent is added to the solution, enabling near-complete flux restoration. Moderate heating accelerates the reaction.

Biological fouling requires not only cell removal but also disruption of the microorganisms’ polymeric matrix. Oxidative reagents, followed by alkaline washing, are commonly employed; however, these methods affect only the surface. The addition of specialized enzymes after chemical treatment significantly reduces residual biomass and extends trouble-free operation. At higher enzyme concentrations, the desired cleaning level is achieved much faster, allowing for procedure optimization based on downtime.

Thus, methodologically grounded regeneration relies on type-specific reagent selection, sequential alternation of alkaline, acidic, and enzymatic stages, and precise control of pH, temperature, and cycle duration; meeting these conditions consistently restores most performance while limiting mechanical and chemical wear, thereby slowing damage accumulation.

In actual operation, the key constraint is maintaining a continuous permeate supply; therefore, cleaning cycles are selected to fit within short process windows without prolonged line shutdowns. On systems with a circulation loop, mineral deposits are removed within one to two standard work shifts. At the same time, more persistent organic and mixed layers may require extended cleaning times if preventive measures are insufficient. The wash-solution volume is calculated based on the number of membrane elements and the geometry of the housings. A portion of the fresh mixture is continuously discharged to remove loose deposits, and the remainder is recirculated until the conductivity parameters stabilize. Indeed, the requirement for a substantial reagent volume often dictates the size of the CIP tank and the capacity of the pump more than the required chemical concentration.

To minimize downtime and eliminate operator error, modern plants are equipped with fully automated cleaning stations. A programmable controller maintains temperature, flow rate, and the sequence of alkaline and acid phases with high precision, preventing excessive differential or back-pressure on the permeate. Automation not only reduces labor requirements but also minimizes the risk of polyamide-layer damage by keeping operating conditions within optimal limits.

Experience shows that upgrading to fouling-resistant membranes, combined with properly configured automation, more than doubles the intervals between cleanings. The additional hours of continuous operation directly translate into increased annual throughput while maintaining stable permeate quality (Dupont, 2022).

Economic analysis confirms the advantage of regeneration over premature element replacement. The main fouling-related costs arise from increased energy consumption and the forced purchase of new cartridges, whereas the cost of a single CIP cycle is comparatively low (Feo-García et al., 2024). By restoring operating permeability to its original values, even partial regeneration pays for itself more quickly than acquiring new modules, especially at sites with substantial total filtration volumes. Therefore, a correctly designed cleaning process—supported by automated control and type-specific reagent selection—remains the most effective strategy for reducing operating costs and extending the service life of reverse osmosis membranes.

Thus, this study demonstrates that the effective regeneration of reverse-osmosis membranes under industrial conditions is possible only by accounting for the complementary actions of organic, inorganic, and biological foulants on the various components of the thin-film polyamide composite. The proposed methodological approaches—from early diagnostics and controlled alternation of alkaline, acid, and enzymatic stages to optimization of pH, temperature, and pressure parameters—make it possible not only to restore up to 95% of the original permeability and selectivity but also to minimize irreversible structural changes in the membranes. This process, when integrated into automated CIP systems, ensures stable permeate quality, lowers energy consumption, and operational risks. Economic analysis confirms the high profitability of regeneration compared to complete module replacement. The next phase of work will present detailed practical recommendations for implementing the developed protocols and assessing their long-term effects on the service life of membrane elements.

CONCLUSION

This study confirmed that the successful regeneration of thin-film composite reverse-osmosis membranes in industrial environments is achievable only by addressing the complex, type-specific nature of organic, inorganic, and biological fouling. Analysis of the interaction mechanisms between surfactants, scaling compounds, and biofilms has demonstrated that a single cleaning protocol cannot fully restore performance due to variations in adsorption, crystallization, and adhesion kinetics. Initiating cleaning before critical flux decline prevents the formation of difficult-to-remove foulant layers, and selecting reagents according to the predominant fouling type ensures maximum recovery efficiency.

The developed methodological approaches demonstrate that a two- or three-stage sequence of alkaline, acid, and enzymatic treatments, with precise control of pH (1–13), temperature (not below 20 °C), and cycle duration, can restore up to 95% of the original permeability and 98% selectivity. The use of mildly acidic and chelating solutions for inorganic scales, NaOH–SDS for organic foulants, and specialized enzymes for biofilms enables gentle removal of deposits without damaging the polyamide layer. Limiting oxidizer exposure and controlling transmembrane pressure prevent irreversible structural deformation and minimize mechanical wear.

The integration of these procedures into automated CIP systems with a programmable controller can more than double the cleaning intervals compared to manual methods, while maintaining stable permeate parameters at reduced energy consumption and operational risk. Economic analysis has shown that even partial regeneration recoups its costs faster than complete module replacement, particularly at high filtration volumes, thanks to lower energy expenses and less frequent membrane procurement.

In conclusion, careful consideration of fouling specifics, flexible adaptation of cleaning-stage order and composition, and process automation constitute a robust strategy to extend reverse-osmosis membrane service life and reduce overall operating costs. Future work should develop practical guidelines for implementing the proposed protocols across various industrial installations and evaluate their long-term impact on membrane-element durability and economic performance.

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