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A Review on Engineering Approaches to Reverse Osmosis Brine Management: Disposal, Volume Reduction and Emerging Resource Recovery

Oluwasegun Emmanuel Babajide[1,2,3*], Mustafa Burak Doğanay[1], Aydın Cihanoğlu[1,4],
Mehmet Kamil Meriç[5], Nalan Kabay[1]
[1]Ege University, Faculty of Engineering, Department of Chemical Engineering,
İzmir, Türkiye
[2]Ege University, Graduate School of Sciences, Division of Environmental Sciences,
İzmir, Türkiye
[3]Ege University, Graduate School of Sciences, Institute of Nuclear Sciences,
İzmir, Türkiye
[4]Ege University, Aliağa Vocational School, İzmir, Türkiye
[5]Ege University, Bergama Vocational School, İzmir, Türkiye

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ABSTRACT

Reverse osmosis (RO) desalination generates concentrated brine streams whose management remains a primary technical and regulatory constraint on system performance and sustainability. This review evaluates current and emerging RO brine management strategies with emphasis on operational feasibility, energy demand, and compliance drivers. Conventional disposal options remain dominant in practice but are increasingly limited by discharge regulations and environmental impact. Membrane-based, thermal, and hybrid processes can achieve significant brine volume reduction and support near-zero liquid discharge; however, these gains come with substantial energy penalties, fouling risks, and operational complexity. Resource recovery from seawater RO brines has progressed for major ions such as magnesium, calcium, and bulk salts, yet most pathways remain at laboratory or pilot scale, while recovery of trace elements is constrained by low concentrations, selectivity limits, and unfavorable process economics. Across all advanced options, the lack of long-term performance data, uncertain cost structures, and site-specific regulatory requirements continue to impede scale-up. The review concludes that near-term brine management is best achieved through incremental integration of volume reduction, energy recovery, and compliant discharge within existing treatment trains, rather than through standalone recovery systems.

Keywords: Reverse osmosis; desalination; brine management; volume reduction; energy demand; environmental regulation

1.0 INTRODUCTION

Reverse osmosis (RO) reject brine represents a persistent and intensifying challenge in desalination due to its high salinity, density, and chemical load. Brine effluents commonly exhibit salt concentrations well above ambient seawater and contain residual pretreatment chemicals, antiscalants, and trace contaminants. These characteristics increase the risk of

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[*] Corresponding to: O.E. Babajide (email: emmybabajide31@gmail.com)

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salinity shock, density driven stratification, and localized toxicity in receiving waters. Brine discharge is therefore widely recognized as one of the principal environmental pressures associated with seawater desalination, particularly in semi enclosed or low circulation coastal zones [1,2]. Documented impacts include disruption of benthic communities, osmotic stress in marine organisms, and long-term habitat degradation in areas where brine accumulates [3,4].

From an engineering perspective, RO recovery is fundamentally constrained by osmotic pressure and scaling phenomena. As salinity increases along the membrane modules, osmotic pressure rises nonlinearly and progressively offsets the applied hydraulic pressure, ultimately limiting water flux. In parallel, elevated concentrations of sparingly soluble salts promote inorganic scaling that compromises membrane performance and lifespan. As a result, seawater RO systems typically operate at 40 to 55 percent recovery, while brackish water systems may reach 60 to 85 percent under favorable conditions. Exceeding these ranges requires additional treatment stages or hybrid configurations, each imposing higher capital costs, energy consumption, and operational complexity [5,6].

Regulatory scrutiny of brine disposal is increasing across major desalination regions. Discharge permits progressively incorporating stricter limits on salinity elevation, mixing zone dimensions, chemical residuals, and ecological monitoring requirements. These developments reflect growing concern over cumulative impacts from clustered desalination facilities and the long-term resilience of coastal and marine ecosystems [1,7]. In response, recent literature frequently frames brine management within broader narratives of valorization and circular economy integration, emphasizing mineral recovery and zero liquid discharge concepts as pathways toward sustainability [6,7,8,9].

Despite the rapid growth of this literature, a critical gap remains in how brine management options are comparatively assessed. Many existing reviews treat technologies in a largely neutral or aspirational manner, with limited differentiation based on operational limits, energy penalties, scaling and fouling behavior, or technology readiness. Recovery pathways are often discussed in isolation from the hydraulic, chemical, and regulatory constraints of real-world plant operation, producing conclusions that are conceptually informative but rarely actionable.

This review addresses that gap through a constraint-driven comparison of RO brine management strategies. Rather than cataloguing all proposed recovery routes, the analysis prioritizes technologies with demonstrated or near-term deployability and evaluates them against practical limits including salinity tolerance, scaling control, energy demand, operational robustness, and regulatory compliance. Resource recovery is treated as a secondary and conditional objective, viable primarily where it aligns with volume reduction, discharge requirements, or process integration within existing treatment trains. Structured as a narrative synthesis rather than a systematic review, literature selection was guided by relevance to these core evaluation dimensions, with priority given to peer-reviewed publications from the past decade and sources reporting demonstrated or near-term deployable technologies under representative operating conditions. The review is intended as a decision-oriented synthesis for engineers, utility planners, and regulators seeking practically grounded guidance, rather than as a mineral economics assessment of brine valorization potential.

2.0 CHARACTERISTICS OF RO BRINE

SWRO brines are characterized by elevated salinity, increased density, and enrichment of sparingly soluble ions relative to the feed seawater. Reported total dissolved solids typically fall in the range of 60 to 85 $g \cdot L^{-1}$, corresponding to approximately 1.5 to 2 times ambient seawater, with Na^+ and Cl^- accounting for roughly 85 to 90 percent of the dissolved salt mass [8,9]. This concentration directly governs discharge behavior, as higher density brines tend to sink and spread along the seabed, increasing the risk of localized salinity accumulation and ecological stress in poorly mixed environments [10]. The TDS range of 60–85 $g \cdot L^{-1}$ cited in Section 2 reflects a broad literature-derived range across multiple SWRO systems and geographic settings, while the narrower range of 58–72 $g \cdot L^{-1}$ in Table 1 represents measured values from a specific regional case study of SWRO plants in the Canary Islands [10]. These values are complementary, with the case study range falling within the broader reported range and illustrating site-specific variability.

The relative enrichment of divalent ions such as Mg^{2+}, Ca^{2+}, and SO_4^{2-} has limited influence on discharge salinity but strongly constrains treatment and volume reduction options. Elevated concentrations of calcium sulfate, calcium carbonate, and magnesium hydroxide increase scaling potential at higher recovery, restricting the applicability of HPRO, MD, and thermal processes without intensive scaling control. [5, 6]. These compositional characteristics therefore define practical recovery ceilings and drive the need for additional pretreatment or intermediate softening steps when advanced brine management strategies are considered.

Residual treatment and cleaning chemicals represent a secondary but operationally relevant brine characteristic. Antiscalants, coagulants, disinfectants, and pH control agents are commonly present at low but variable concentrations, depending on pretreatment design and cleaning frequency. While quantitative reporting is inconsistent, these residuals can affect toxicity assessments for discharge and limit compatibility with downstream processes such as crystallization, adsorption, or electrochemical treatment [7,11]. Trace metals have also been reported sporadically, typically reflecting site specific corrosion or intake conditions rather than systematic enrichment through RO [12].

Table 1 summarizes the key physicochemical parameters of RO brine that are most relevant to management decisions. Salinity and density primarily control discharge impacts and outfall design, while ionic composition and residual chemicals constrain the feasibility, energy demand, and operational stability of further treatment or volume reduction. Higher water recovery reduces brine volume but increases salinity, scaling risk, and energy demand, narrowing the range of viable downstream management options. [4, 6].

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* Corresponding to: O.E. Babajide (email: emmybabajide31@gmail.com)

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Table 1. Physicochemical characteristics of reverse osmosis brine reported in recent literature, including salinity, ionic composition, residual treatment chemicals, and brine volume relative to system recovery

Parameter	Typical / reported value	Notes	References
Salinity (TDS)	58–72 g·L^{-1} reported for SWRO brines in coastal, high recovery systems (Canary Islands case study)	Brine salinity depends on feed salinity and recovery ratio. Values approaching ~70 g·L^{-1} have been reported under high recovery operation	[10, 12]
Major ionic composition (% of TDS)	Cl^- ~55%; Na^+ ~29.5%; SO_4^{2-} ~8%; Mg^{2+} ~4%; Ca^{2+} ~1.5%; K^+ ~1.2%; HCO_3^- ~0.5%	Fractional composition reported as relatively stable across ten SWRO plants within a single regional study; absolute concentrations scale with TDS	[10]
Residual treatment chemicals	Antiscalants, coagulants, disinfectants, acids, and bases	Chemical identity and residual levels depend on pretreatment strategy, operating regime, and cleaning frequency. Quantitative residual data are rarely disclosed	[7, 11]
Trace metals and contaminants	Detected sporadically; concentrations rarely quantified	Isolated case studies report trace enrichment of Cu, Fe, Ni, and Cr. Data are inconsistent, site specific, and often below routine regulatory reporting thresholds	[12]
Brine volume relative to recovery	SWRO recovery typically 40–55%, yielding ~45–60% brine fraction; brackish RO recovery 60–85%, yielding ~15–40% brine fraction	Increasing recovery reduces brine volume but increases salinity and scaling risk	[6, 4]
EC–TDS conversion factor	EC to TDS factor ~0.73–0.76 at 25 °C for seawater derived brines (Canary Islands plants)	Empirical correlation applicable to seawater derived brines; conversion factor varies with ionic composition	[10]

Note: Reported values reflect seawater reverse osmosis systems and are influenced by feedwater composition, recovery ratio, and pretreatment strategy. Values should not be interpreted as universal design inputs.

* Corresponding to: O.E. Babajide (email: emmybabajide31@gmail.com)
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3.0 CONVENTIONAL BRINE DISPOSAL PRACTICES

Reverse osmosis (RO) desalination produces a concentrated brine waste stream that must be managed to avoid adverse environmental and hydrological effects. The most widely practiced disposal routes are marine discharge, sewer disposal, and subsurface injection. Each approach has distinct operational contexts, advantages, and limitations grounded in physical behavior and system interactions.

3.1 Marine Discharge

Marine discharge remains the most widely applied disposal option for SWRO facilities due to its logistical simplicity and cost effectiveness where sufficient dilution and mixing can be achieved. In practice, brine is commonly released through diffuser systems that promote rapid mixing with ambient seawater and aim to minimize localized salinity gradients. Nevertheless, concentrated SWRO brine has a higher density than surrounding seawater and, if mixing is insufficient, tends to sink and spread along the seabed. This behavior can generate localized salinity anomalies that alter water chemistry and affect benthic habitats. Field investigations have reported measurable brine influence extending from tens to several hundreds of meters from discharge points, with observed effects on benthic fauna, sediment characteristics, and near bed biogeochemical processes within the mixing zone [13, 14].

3.2 Sewer Disposal

Sewer disposal involves routing RO brine to a wastewater collection system for conveyance to a municipal wastewater treatment plant rather than direct discharge to surface waters. This approach is most applied where desalination facilities are located inland or near urban infrastructure capable of receiving saline effluents. Discharge of RO brine into sewer networks can provide dilution through mixing with domestic wastewater, thereby moderating short term salinity fluctuations. However, the salinity of RO reject brine typically exceeds that of municipal wastewater by an order of magnitude, and elevated chloride concentrations can disrupt biological nutrient removal processes and alter microbial community structure in activated sludge systems [15, 16]. High chloride levels have been shown to inhibit microbial metabolism, reduce treatment efficiency, and increase the risk of process instability. As a result, sewer disposal is generally feasible only when brine volumes and salinity loads are sufficiently controlled through dilution or pretreatment prior to entry into the sewer system. The literature further indicates that quantitative field data on long term impacts of desalination brine on wastewater treatment performance remain limited, and many treatment plants have minimal operational experience with sustained high salinity inflows.

3.3 Subsurface Injection

Subsurface injections involve placing concentrated RO brine into deep geologic formations or saline portions of coastal aquifers rather than releasing it to surface waters. In systems where marine or surface disposal is impractical or carries unacceptable

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ecological risk, injections can isolate brine from immediate ecological receptors. Numerical modeling has shown that injected brine forms persistent high-salinity plumes that push the freshwater interface landward and elevate aquifer salinity, with effects persisting decades after injection ceases. For example, Stein *et al.* [17] demonstrated through groundwater flow and solute transport simulations that sustained brine injection can significantly salinize coastal aquifers and delay aquifer recovery, although injection depth, rate, and simultaneous saline groundwater pumping can moderate plume migration and interface displacement. Such formation responses indicate that careful hydrogeological characterization and management of injection operations are required to avoid long term degradation of aquifer quality and withdrawal zones. Less common conventional practices include evaporation ponds, surface water discharge to inland rivers or lakes, and land application, though these options are increasingly constrained by land requirements, hydrogeological risks, and environmental regulation. Below are concise, descriptive subsections for the three conventional disposal routes: marine discharge, sewer disposal, and subsurface injection. Each subsection explains typical locations of use, main advantages, and main drawbacks, with recent, verifiable citations. To contextualize the environmental and operational implications of reverse osmosis brine management, Tables 2 and 3 synthesize both conventional disposal practices and reported field evidence from representative case studies. Table 2 provides a comparative overview of the main disposal routes currently applied in practice, highlighting typical application settings, perceived advantages, and structural limitations. Table 3 compiles measured and modeled observations from diverse settings to illustrate how salinity impacts and system constraints vary locally, while remaining governed by common process-level controls. The regulatory implications of each disposal route are examined systematically across key desalination regions in Section 6.1.

Table 2. Overview of conventional reverse osmosis brine disposal practices, summarizing typical application settings, main advantages, and principal drawbacks for marine discharge, sewer disposal, and subsurface injections

Disposal route	Typical application settings	Advantages	Drawbacks	References
Marine discharge	Coastal SWRO facilities and island systems with direct ocean access, including systems in the Middle East, Mediterranean, Canary Islands, Australia, and the United States	Low capital cost: effective natural dilution when appropriately sited and designed with outfall diffusion	Localized salinity and thermal impacts; performance highly dependent on-site specific hydrodynamics; cumulative effects require monitoring and assessment	[10, 11]
Sewer disposal	Inland and small coastal RO plants connected to municipal wastewater treatment plants, primarily brackish water systems	Avoid direct marine discharge; operationally convenient for small scale installations	Can disrupt biological treatment processes; often require dilution or pretreatment; constrained by municipal hydraulic capacity and salinity tolerance	[6]

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* Corresponding to: O.E. Babajide (email: emmybabajide31@gmail.com)
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Disposal route	Typical application settings	Advantages	Drawbacks	References
Subsurface injection	Regions with suitable confined geological formations, commonly applied for industrial brines in the United States, Australia, and selected sedimentary basins	Isolates brine from surface ecosystems; controlled subsurface containment	Risk of brine migration under inadequate confinement; high capital cost; long term monitoring and regulatory requirements	[18]

Note: Applicability of disposal routes is site specific and depends on local hydrodynamics, receiving water sensitivity, geological conditions, and regulatory requirements; listed settings are illustrative rather than exhaustive.

Table 3. Representative case study data illustrating measured salinity levels, plume extents, and system constraints associated with conventional RO brine disposal routes, highlighting the variability of impacts under different environmental and operational conditions (Data represented reported case study measurements and should be interpreted as site-specific rather than universal values)

Disposal route	Location	Key observations	Implication	References
Marine discharge	Mostaganem, Algeria	Salinity up to ~9% above ambient, plume ~200 m	Local salinity elevation remains spatially limited; impact magnitude is controlled by hydrodynamic conditions	[19]
	Hadera & Sorek, Israel	Elevated salinity ~1–10% over ~0.5–1.5 km^2	Outfall depth, diffuser configuration, and ambient mixing govern impact footprint	[20]
	Candelaria & Nueva Atacama, Chile	Salinity increments <5% within ~50–100 m	Rapid dilution where currents and diffusers are effective	[21]
	Red Sea, Gulf of Aqaba	Elevated salinity near outfall; loss of seagrass in high-salinity zone	Persistent salinity elevation can cause localized habitat exclusion	[22]
	Pacific coast, South America	Salinity elevation and biomarker stress in macroalgae	Sub-lethal biological effects may occur even where physical dilution is achieved	[23]

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Disposal route	**Location**	**Key observations**	**Implication**	**References**
Sewer disposal	Global field synthesis	Recurrent benthic impacts reported across sites	Observed effects reflect systematic process-level responses rather than site-specific anomalies	[1]
	General WWTP context (various)	Typical brine salinity ~50–70 $g \cdot L^{-1}$ vs WWTP tolerance <5–7 $g \cdot L^{-1}$	Undiluted RO brine exceeds biological treatment capacity and requires dilution or pretreatment	[24]
	Zolkiewka Commune, Poland	Small-diameter sewers (25–100 mm) operating since 2015 with septic pretreatment	Pretreatment and controlled hydraulics reduce operational failures in low-flow systems	[25]
	Yangon, Myanmar	Decentralized systems scored higher than centralized systems in multi-criteria sustainability assessment	Decentralized treatment offers adaptive capacity where centralized expansion is constrained	[26]
	USA	Eight community case studies comparing onsite, cluster, and centralized systems	Decentralized and cluster systems provide viable alternatives where centralized sewerage is limited	[27]
	Ropice Czech Republic	Legacy systems identified as non-compliant under updated regulations	Infrastructure modernization is required to meet evolving regulatory standards	[28]
	Indiana, USA	Sewer network operating at ~90% of design capacity	Capacity saturation necessitates system upgrades and long-term planning	[29]
Subsurface injection	El Gouna, Egypt	Local groundwater salinity reached ~60 $g \cdot L^{-1}$	Inadequate geological confinement can lead to severe aquifer salinization	[30]
	Coastal aquifer, Egypt	Modeled increase in aquifer salt mass and expansion of saline zone	Combined abstraction and injection increase long-term salinization risk	[31]

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Disposal route	**Location**	**Key observations**	**Implication**	**References**
	El-Dabaa area, Egypt	Simulated salinity increase up to ~41 g·L⁻¹ within several hundred meters	Localized but severe degradation of groundwater quality	[32]
	Sharm El-Sheikh, Egypt	Modeled saline plume development following brine disposal	Requires careful well placement and hydraulic control	[33]
	Cross-site synthesis	Salinity plume development consistently governed by aquifer confinement, injection rate, background abstraction, and hydraulic conductivity rather than geographic location	Environmental risk is process driven and transferable across arid coastal settings with similar hydrogeological conditions	[30- 33]

Note: Marine discharge salinity changes are reported as percentage increase relative to ambient seawater. Subsurface and sewer disposal salinities are reported as total dissolved solids in g·L⁻¹. Sewer disposal case studies include decentralized and cluster sanitation systems that are not exclusively designed for RO brine management but are presented as analogs to illustrate infrastructure tolerance, dilution capacity, and operational constraints relevant to saline wastewater handling. Although several subsurface injection studies originate from Egypt, the reported impacts are governed by hydrogeological controls rather than geographic location, indicating transferability to comparable arid coastal aquifer systems.

4.0 BRINE TREATMENT AND VOLUME REDUCTION TECHNOLOGIES

Brine treatment and volume reduction technologies are applied to limit discharge volumes and comply with environmental and regulatory constraints as RO recovery increases. Their applicability is governed primarily by feed salinity, scaling propensity, energy demand, and operational robustness rather than theoretical recovery potential. The following subsections summarize the principal technologies currently deployed or under advanced evaluation, emphasizing where each approach becomes constrained in practice, and fouling mechanism under hypersaline conditions.

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* Corresponding to: O.E. Babajide (email: emmybabajide31@gmail.com)

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4.1 Membrane-based Concentration Processes

4.1.1 High-pressure Reverse Osmosis (HPRO)

HPRO extends conventional RO by operating at elevated hydraulic pressures to overcome increased osmotic pressure in concentrated brines. It remains a pressure-driven process and therefore inherits the same salinity-dependent limitations as standard RO [5,34]. HPRO can incrementally increase water recovery using familiar membrane infrastructure and control systems. It is most applicable where brine salinity remains below the mechanical and fouling limits of commercial RO elements.

As salinity increases, osmotic pressure and energy demand rise sharply, while scaling risk intensifies. Membrane compaction, reduced flux, and frequent chemical cleaning limit sustainable operation at high concentration factors. These constraints restrict HPRO to moderate brine concentration and preclude its use as a standalone route to near-ZLD [35]. Figure 1 depicts High-pressure reverse osmosis (HPRO) System.

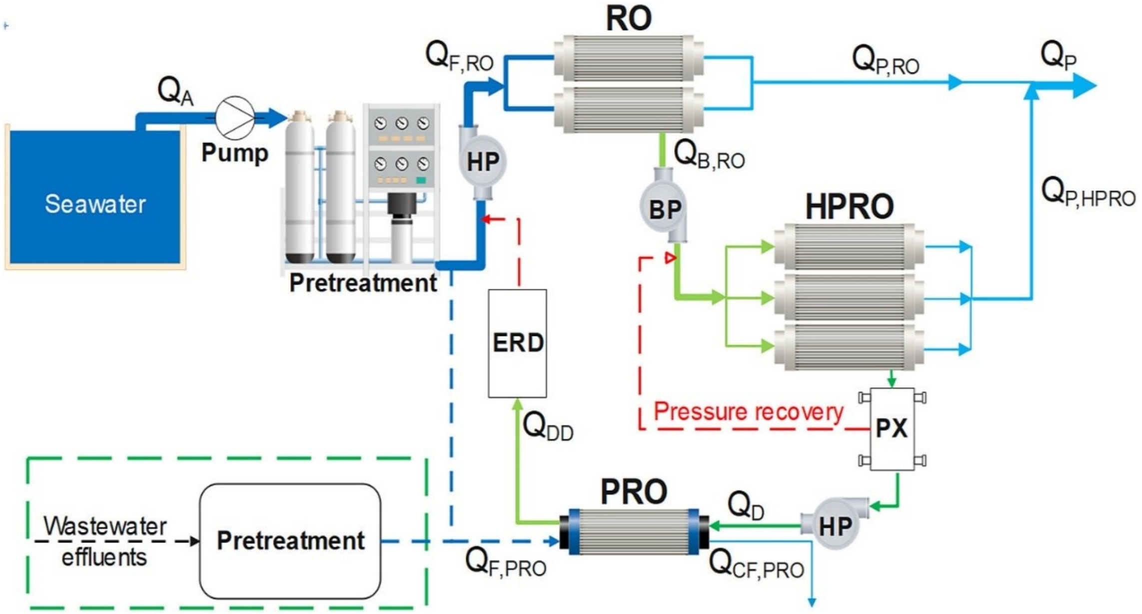

Figure 1. High-pressure reverse osmosis (HPRO) System (Adapted with permission from [34])

4.1.2 Membrane Distillation (MD)

MD uses a vapor pressure gradient across a hydrophobic membrane to separate water vapor from saline feed, allowing operation at salinities where RO is no longer feasible [36]. MD tolerates very high salinity and is therefore suited to late-stage brine concentration. It is most attractive where low-grade thermal energy is available. Low flux, membrane wetting, and scaling limit long-term operation. Without reliable heat sources, overall energy demand remains high. Industrial-scale deployment is still limited, and durability under continuous high-salinity operation remains a key uncertainty [37]. Figure 2 depicts Membrane distillation system.

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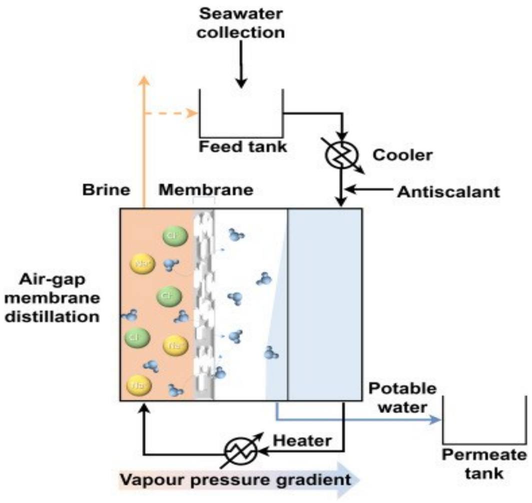

Figure 2. Membrane distillation (MD) System (Adapted with permission from [36])

4.1.3 Electrodialysis (ED)

ED applies an electric field to transport ions through selective membranes, concentrating salts electrically rather than hydraulically [38]. ED performs best at moderate salinity and is suited to partial desalting or selective ion management within hybrid treatment trains. Electrical resistance increases with salinity, sharply raising energy consumption at high concentrations. Multivalent ion scaling and membrane fouling restrict ED performance in concentrated RO brines, limiting its role near ZLD unless combined with other technologies [35]. Figure 3 depicts Electrodialysis system.

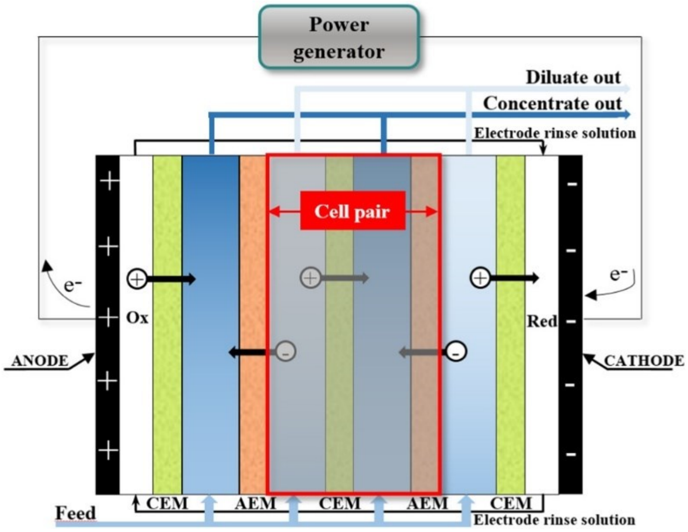

Figure 3. Electrodialysis (ED) System (Adapted with permission from [38])

* Corresponding to: O.E. Babajide (email: emmybabajide31@gmail.com)
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4.2 Thermal and Evaporation-based Processes

4.2.1 Evaporation Ponds

Evaporation ponds rely on solar-driven water loss over large surface areas. They are applied where land availability and arid climate permit passive volume reduction with minimal mechanical complexity. Large land requirements, slow kinetics, climate dependence, and regulatory concerns related to seepage and salt management restrict applicability, particularly near populated or environmentally sensitive areas [5,6]. Figure 4 depicts evaporation ponds.

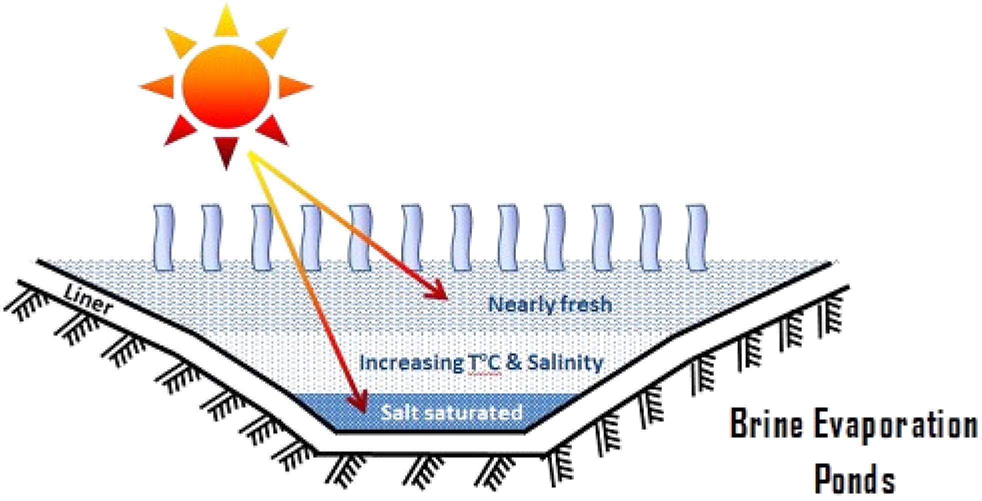

Figure 4. Evaporation Ponds (Adapted from [6])

4.2.2 Crystallizers

Crystallizers use forced evaporation to precipitate salts, producing solid residues and minimizing liquid discharge. They represent the terminal step in ZLD systems where liquid disposal is prohibited. Very high capital cost and energy demand dominate system economics. Scaling, corrosion, and solid handling impose additional operational burdens. Crystallizers are therefore deployed primarily under strict regulatory mandates rather than as routine brine management solutions [39]. Figure 5 depicts crystallizer system.

4.3 Hybrid Systems

4.3.1 RO–MD Hybrids

RO pre-concentrates brine to moderate salinity, followed by MD for high-salinity polishing. Hybridization allows each process to operate within its feasible salinity range, increasing overall recovery relative to single-stage systems. Thermal integration, membrane fouling management, and system complexity limit scalability. Most reported systems remain at pilot scale [37].

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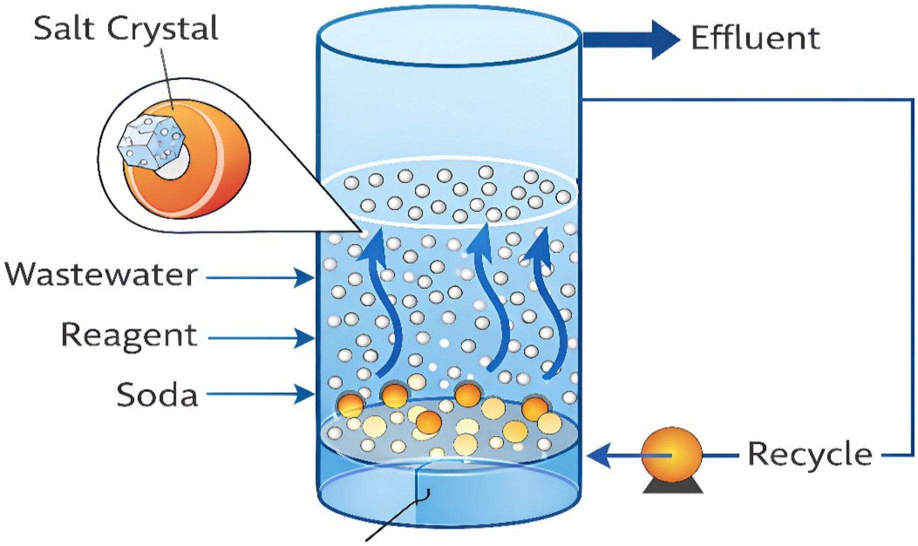

Figure 5. Crystallizer System

4.3.2 RO–thermal Hybrids

RO is combined with evaporation or crystallization to progressively reduce brine volume. These systems underpin most near-ZLD configurations for desalination plants facing strict discharge limits. High energy consumption, capital intensity, and operational complexity confine application to sites with strong regulatory or disposal drivers [38, 39]. Table 4 summarizes the functional operating range, recovery performance, and dominant constraints of the principal brine treatment and volume reduction technologies discussed. Across all options, increasing salinity and scaling propensity ultimately impose energy and cost penalties that define practical deployment limits. Under these conditions, treatment selection is governed by disposal requirements and operational feasibility rather than maximum theoretical recovery. Among the technologies reviewed, practical deployment is governed by operational feasibility, energy demand, and scalability rather than theoretical maximum recovery. High-pressure RO and hybrid RO–thermal systems currently offer the most viable near-term options for brine volume reduction, balancing established infrastructure compatibility with achievable concentration ranges. Thermal-only methods, membrane distillation, and electrodialysis are generally constrained by energy intensity, scaling sensitivity, or limited large-scale deployment experience. Resource recovery is secondary and only technically feasible under these constrained operating conditions. To complement the functional comparison in Table 4, Table 5 presents approximate CapEx and OpEx ranges for each brine treatment technology reviewed, drawn from available techno-economic assessments in the peer-reviewed literature. Where published cost data are limited or highly site-specific, this is explicitly acknowledged within the table.

* Corresponding to: O.E. Babajide (email: emmybabajide31@gmail.com)
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Table 4. Functional comparison of brine treatment and volume reduction technologies based on operating principle, applicable salinity regime, practical concentration limits, energy intensity, and dominant operational constraints relevant to RO brine management

Technology	Operating Principle	Salinity Operating Range & Practical Concentration	Practical Recovery Range	Typical Specific Energy Demand (SEC)	Strengths	Limitations	References
High-pressure RO (HPRO)	Operates RO at elevated pressures to further extract water from hypersaline brine beyond conventional RO limits	Feed salinity 70–130 $g\cdot L^{-1}$ TDS; operates above ≥100 bar; up to ~130 $g\cdot L^{-1}$ demonstrated at pilot scale	~50% per pass; ~70–85% overall when integrated with SWRO	~3.6–5.4 kWh/m^3 with energy recovery device; up to ~5.3 kWh/m^3 at high salinity	Mature membrane platform, compatible with existing RO infrastructure, lower thermal footprint than evaporative methods	Rapid increase in osmotic pressure, membrane compaction and fouling at extreme salinity	[46]
Membrane distillation (MD)	Uses vapor pressure gradient across a hydrophobic membrane driven by temperature difference	Feed salinity up to ~260 $g\cdot L^{-1}$; operates effectively above 70 $g\cdot L^{-1}$ where RO is no longer feasible	40–72% additional recovery from RO brine; near-ZLD with feed recirculation	~49–801 kWh/m^3 depending on configuration; reduces to ~3–22 kWh/m^3 when low-grade waste heat is available	Can handle very high salinity, near-ZLD potential, tolerant to feed salinity variations	Thermal energy requirement, membrane wetting, limited large-scale deployment	[36, 37]
Electrodialysis (ED)	Applies electric potential to selectively transport ions through ion-exchange membranes	Most effective at 1–35 $g\cdot L^{-1}$; demonstrated up to 75–100 $g\cdot L^{-1}$ under optimized conditions	43–80% water recovery; salt removal 60–80% at moderate salinity	~1–3.5 kWh/m^3 at moderate salinity; increases sharply at high concentration	Selective ion separation, suitable for moderate salinity brines	Decreased efficiency at very high salinity, membrane scaling, electrical energy demand	[35, 38]
Evaporation ponds	Natural evaporation using solar energy in lined basins	No upper salinity limit; suitable from ~35 $g\cdot L^{-1}$ to	Near-complete water removal over extended residence times;	Negligible electrical input; solar-driven passive process	Low operational energy input, simple operation	Large land requirement, climate dependent, risk	[5]

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Technology	Operating Principle	Salinity Operating Range & Practical Concentration	Practical Recovery Range	Typical Specific Energy Demand (SEC)	Strengths	Limitations	References
		saturation (~260 $g \cdot L^{-1}$ NaCl)	highly climate dependent			of leakage and salt accumulation	
Mechanical or thermal crystallizers	Forced evaporation to induce salt crystallization and solid recovery	Feed salinity typically ~150–250 $g \cdot L^{-1}$; terminal concentration step toward ZLD	Approaches 100% water removal; brine concentrators reduce feed volume by up to 98%	~40–60 kWh/m^3 electrical; brine concentrators typically ~20–25 kWh/m^3	Complete liquid elimination, controlled salt recovery	Extremely high energy consumption, high capital and operating costs	[5, 40]
RO–MD hybrid systems	RO pre-concentrates brine followed by MD for high-salinity polishing	RO stage: 35–70 $g \cdot L^{-1}$; MD stage: 70–260 $g \cdot L^{-1}$	>90% overall water recovery combined	~6.5–23.2 kWh/m^3 depending on waste heat availability	Synergistic use of pressure and thermal driving forces, reduced brine volume	System complexity, heat integration challenges, membrane durability	[41]
RO–thermal hybrid systems	RO coupled with evaporation or crystallization units	RO stage: 35–85 $g \cdot L^{-1}$; thermal stage: up to saturation	Near-ZLD; overall system water recovery typically >95%	~10–17.5 kWh/m^3 for MLD/ZLD configurations	Enables maximum water recovery, suitable for strict discharge regulations	Very high energy and cost footprint, best suited for niche applications	[38, 39]

Note: Specific energy demand values reflect reported ranges under representative operating conditions and vary with feed salinity, recovery ratio, system configuration, and availability of low-grade or waste heat. Salinity operating ranges are indicative and may vary with membrane type, pretreatment strategy, and system design. Direct comparison across technologies should account for differences in inlet salinity, recovery stage, and system boundary.

* Corresponding to: O.E. Babajide (email: emmybabajide31@gmail.com)

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Table 5. Approximate CapEx/OpEx Ranges for Brine Treatment Technologies

Technology	Approximate CapEx	Approximate OpEx ($/m³)	Notes	References
Conventional SWRO	~$800–$1,100/m³/day installed capacity	$0.5–$1.5/m³	Varies significantly with plant scale, location, and energy prices	[39, 42]
High-pressure RO (HPRO)	Higher than conventional RO due to specialized high-pressure equipment (>100 bar)	$1.8–$7.4/m³ LCOW depending on feed salinity and recovery	Cost-optimal LCOW increases sharply with feed salinity; formal CapEx data remain limited	[43]
Membrane distillation (MD)	Moderate-high; DCMD with heat recovery projected at ~$1.1/m³ at 24,000 m³/day; reduces to $0.5/m³ with low-cost waste heat	$0.5–$2/m³ depending on heat source availability	Economics improve substantially with low-grade waste heat integration	[44]
Electrodialysis (ED)	Moderate; scale and salinity dependent; limited published data for brine-specific applications	$0.7–$1.5/m³ at moderate salinity	CapEx data for high-salinity brine applications are limited in peer-reviewed literature	[42]
Evaporation ponds	Low mechanical CapEx but high land cost; site-specific	Negligible electrical OpEx; dominated by land and maintenance costs	Not suitable for land-scarce or regulated environments; cost data are highly site-specific	[5]
Thermal crystallizers / ZLD	High; evaporation/crystallizer module typically accounts for 60–70% of total ZLD CapEx; full ZLD system ~$25–$50 million at 1,000–3,000 gpm	$0.7–$2.1/m³ for ZLD configurations; energy cost dominates OpEx	Highest cost option; justified only under strict ZLD mandates	[42, 45]
RO–MD hybrid	Moderate-high; combines membrane and thermal capital requirements	~$2.0/m³ for MEE-MD hybrid	17% lower cost than standalone thermal configurations	[42]
RO–thermal hybrid (MLD/ZLD)	High; MLD system estimated at $0.7/m³; ZLD system at $0.7/m³ in Eastern Mediterranean context	$0.7–$0.7/m³ (MLD vs ZLD); LCOW ~$1.9–$2.6/m³ for solar-assisted ZLD	ZLD costs increase with brine salinity and absence of renewable energy integration	[42]

CapEx — Capital Expenditure; OpEx — Operating Expenditure; SWRO — Seawater Reverse Osmosis; HPRO — High-Pressure Reverse Osmosis; MD — Membrane Distillation; ED — Electrodialysis; ZLD — Zero Liquid Discharge; MLD — Minimal Liquid Discharge; LCOW — Levelised Cost of Water; DCMD — Direct Contact Membrane Distillation; MEE-MD — Multi-Effect Evaporation — Membrane Distillation Hybrid; gpm — Gallons Per Minute; m^3 — Cubic Metre; USD ($) — United States Dollar; TDS — Total Dissolved Solids; RO — Reverse Osmosis; kWh — Kilowatt Hour.

Note 1: Specific energy demand, salinity operating ranges, and recovery values are indicative and vary with feed salinity, recovery ratio, system configuration, and availability of low-grade or waste heat. Direct comparison across technologies should account for differences in inlet salinity, recovery stage, and system boundary.

Note 2: CapEx and OpEx values are drawn from modelled techno-economic assessments rather than reported operational data and vary substantially with plant scale, local energy prices, regulatory requirements, and site-specific conditions. These figures should not be used as design inputs without site-specific feasibility assessment.

4.4 Fouling and Scaling Mechanisms under Hypersaline Operating Conditions

Fouling and scaling represent the most critical operational constraints limiting membrane performance in hypersaline brine treatment systems. Under elevated salinity conditions characteristic of RO brine, the mechanisms governing scale formation become more complex and severe than those encountered in conventional desalination, owing to higher ionic concentrations, increased supersaturation ratios among cationic and anionic species (e.g., Ca^{2+}, Mg^{2+}, CO_3^{2-}, SO_4^{2-}), and the synergistic interactions between multiple scalants [46,47].

Inorganic scaling occurs when the concentrations of sparingly soluble salts exceed their solubility limits at the membrane surface, driving precipitation through two principal pathways: heterogeneous crystallization at the membrane interface, where the surface reduces the free energy barrier for nucleation, and homogeneous bulk crystallization in the feed solution with subsequent deposition onto the membrane. Heterogeneous nucleation is thermodynamically and kinetically favorable, but homogeneous crystallization plays an increasing role in feeds with higher supersaturation, making the relative contributions of these two pathways intricate and dependent on operating conditions [46]. The dominant scalants in hypersaline RO brine systems are calcium carbonate ($CaCO_3$) [48], calcium sulfate ($CaSO_4$) [49], magnesium silicate hydrate complexes, and amorphous silica [50]. A wide range of minerals including calcium carbonate, calcium sulfate, and silica precipitate during membrane-based desalination, limiting water recovery and reducing process efficiency [46].

Among these, $CaCO_3$ scaling is the most prevalent under moderate salinity and alkaline conditions, forming dense crystalline layers along the feed channel in the direction of water flow. $CaCO_3$ scaling can be reduced through proper control of pH and temperature. Maintaining these parameters within appropriate limits helps regulate the equilibrium among CO_3^{2-}, HCO_3^-, and H_2CO_3, which are the main species responsible for calcium carbonate precipitation [51].

Calcium carbonate scale precipitates when Ca^{2+} becomes supersaturated with CO_3^{2-} or HCO_3^-, according to the following reactions [52]:

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* Corresponding to: O.E. Babajide (email: emmybabajide31@gmail.com)
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$$Ca^{2+}(aq) + CO_3^{2-}(aq) \rightarrow CaCO_3(s) \quad (1)$$
$$Ca^{2+}(aq) + 2HCO_3^{-}(aq) \rightarrow CaCO_3(s) + CO_2(g) + H_2O(l) \quad (2)$$

Several studies have investigated the use of $CaCO_3$ scale inhibitors. Both conventional chemical inhibitors and environmentally friendly alternatives (green types) have been examined, including polyaspartic acid (PASP) [53], polyepoxysuccinic acid (PESA) [54], and carboxymethyl inulin (CMI). In addition, the use of natural organic molecules, which are considered more eco-friendly, has also been documented. Examples include humic acid and fulvic acid [55]. $CaSO_4$ scaling, typically occurring as gypsum ($CaSO_4 \cdot 2H_2O$), becomes critical at higher concentration factors and follows a multistage crystallization pathway that involves the formation of amorphous calcium sulfate nanoparticles before the development of gypsum crystals. Gypsum and silica are two common types of scaling formed through crystallization and polymerization, respectively, and differences in their formation mechanisms significantly influence thermodynamics, kinetics, mineral morphology, and the strategies used for their mitigation [49]. Unlike $CaCO_3$ scaling, $CaSO_4$ scaling cannot be effectively controlled by adjusting pH or temperature. Instead, it is primarily mitigated using chemical inhibitors, commonly referred to as antiscalants [56]. Several effective inhibitors have been reported in the literature, including pectin-based graft copolymers [57], polycitric acid [58], and mixtures of phosphonate scale inhibitors [59]. Silica scaling is particularly problematic under hypersaline conditions because silica polymerizes rather than crystallizes, forming amorphous, gel-like deposits that are chemically resistant to conventional acid cleaning and difficult to remove once established [50]. Silica scales are considered among the most difficult to remove due to their hard structure and their insolubility in common acids and alkalis. As a result, they are resistant to many conventional inhibitors, and further research has been recommended to develop specialized inhibitors specifically for silica control [52, 60].

The formation of silica fouling occurs through a process known as dimerization. This process can take place under both neutral or acidic conditions ($pH < 7.5$) and alkaline conditions ($pH > 7.5$), through two main reactions [61]:

$$2Si(OH)_4 \rightarrow (HO)_3Si–O–Si(OH)_3 + H_2O \quad (3)$$
$$Si(OH)_4 + SiO(OH)_3^{-} \rightarrow (HO)_3Si–O–Si(OH)_3 + OH^{-} \quad (4)$$

Under the high-pressure conditions typical of HPRO systems, scaling is further intensified by concentration polarization at the membrane surface. This phenomenon locally increases ion concentrations well above those in the bulk solution, creating favorable conditions for heterogeneous nucleation and scale formation [62, 63]. Flux decline in RO systems has largely been attributed to the progressive coverage of the membrane surface by laterally growing gypsum crystals. These crystals originate from heterogeneous nucleation at the membrane interface and expand across the surface, gradually blocking active membrane areas and reducing permeate flux [64]. In membrane distillation, the temperature gradient across the hydrophobic membrane creates an additional driving force for scaling. Interfacial supersaturation, caused by both concentration and temperature polarization, promotes rapid scale deposition at the membrane surface [65]. Calcium-induced scaling represents a major operational challenge in MD systems. Under these conditions, gypsum can form thick crystalline layers on the

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* Corresponding to: O.E. Babajide (email: emmybabajide31@gmail.com)
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membrane surface due to the high supersaturation at the interface. The presence of silicon and iron compounds can further accelerate scale formation by acting as nucleation bridges, facilitating the deposition and growth of mineral crystals [66, 67].

Organic and biological fouling can further aggravate inorganic scaling under hypersaline conditions. Residual antiscalants, natural organic matter, and extracellular polymeric substances may interact with mineral scalants and modify nucleation behavior as well as the morphology of the resulting deposits, sometimes promoting crystallization on membrane surfaces while slowing crystallization in the bulk solution [63]. Studies have also shown that humic acid can enhance the early stages of surface scaling while simultaneously inhibiting bulk crystallization processes. In hypersaline desalination systems operating at high pressure, bulk crystallization of $CaSO_4$ and magnesium–silicate complexes has been identified as a major scaling pathway, often leading to pore blocking and cake layer formation on the membrane surface [68].

Current mitigation strategies for scaling in reverse-osmosis brine systems rely largely on conservative operating conditions, antiscalant dosing, intermediate softening or pretreatment, and periodic chemical cleaning. These approaches are widely applied because antiscalants remain one of the most practical and cost-effective methods for controlling mineral precipitation in RO systems, although their effectiveness depends strongly on dosing strategy and feed chemistry [69]. However, the effectiveness of chemical cleaning tends to decline under hypersaline conditions as scale layers become denser and more strongly attached to membrane surfaces. This is particularly evident for silica scales, which are known to form hard deposits that are difficult to remove once established and can significantly reduce membrane flux and system efficiency [70, 71]. Owing to these limitations, several advanced mitigation approaches are currently being explored. These include surface-modified antifouling membranes, improved antiscalant chemistries, and novel monitoring or suppression strategies aimed at preventing scale formation before it occurs. Nevertheless, many of these methods remain at the laboratory or pilot-scale stage, and further development is needed before they can demonstrate reliable performance in full-scale desalination operations [69, 72].

4.5 Membrane Material Limitations under Hypersaline Operating Conditions

The performance of membrane-based brine treatment technologies is fundamentally constrained not only by fouling and scaling but also by the material limitations of the membranes themselves under the extreme operating conditions characteristic of hypersaline brine processing. These limitations are distinct for each membrane type and represent critical barriers to long-term operational reliability.

4.5.1 Polyamide Membranes in HPRO

Thin-film composite (TFC) polyamide membranes, which are widely used in SWRO and high-pressure RO (HPRO) systems, can undergo structural changes when operated at the high pressures required for hypersaline brine concentration. Studies have shown that at pressures above 100 bar, mechanical compaction can occur within the membrane structure, leading to densification of the porous polysulfone support layer and changes in the polyamide selective layer. These structural changes are associated with reduced permeability and are often only partially reversible after the pressure is lowered [73-75]. Experimental studies on commercial thin-film composite (TFC) membranes operated

* Corresponding to: O.E. Babajide (email: emmybabajide31@gmail.com)
DOI: https://doi.org/10.11113/jamst.v30n1.344

under high-pressure RO conditions (up to 200 bar) with feeds around 70 g/L NaCl have reported substantial structural compaction of the membrane. Measurements showed reductions in the thickness of the polysulfone support layer of about 42–61% and decreases in the height of the polyamide surface features of about 15–22%. These structural changes were accompanied by noticeable declines in membrane performance, including lower water permeability and reduced salt rejection, and the losses were not fully recovered when the operating pressure was reduced. In some of the tested membranes, water permeability decreased from about 1.63 to 0.39 L m^{-2} h^{-1} bar^{-1}, while salt rejection declined from approximately 97.5% to 95.0% during high-pressure operation [76]. Also the performance of three commercial RO membranes was evaluated at feed pressures up to 207 bar (3000 psi) using five different permeate carrier materials. Compaction was observed as soon as the membranes were pressurized (minimum 14 bar) and increased with higher pressures. When the pressure was reduced from the maximum, water permeance partially recovered but did not return to its original value. This indicates that while a small portion of compaction may be reversible, most of the structural changes are permanent [74]. In related studies, Davenport *et al*. [73] reported a 35% reduction in water permeability and a 60% decrease in membrane cross-sectional thickness after exposing SWRO membranes to 150 bar (2175 psi). Similarly, Pendergast *et al*. [77] studied hand-cast TFC RO membranes at pressures up to 35 bar (500 psi) and observed 20–30% reductions in thickness and up to 50% loss of water permeability.

Embossing is a mechanical damage mechanism observed in high-pressure reverse osmosis that differs from general membrane compaction. Under very high operating pressures, the thin-film composite membrane can be pressed against the structure of the permeate carrier located beneath it. As pressure increases, the surface of the membrane may take on the shape of the carrier mesh, leaving permanent deformation patterns that correspond to the geometry of the support material. This effect has been reported at the high pressures used for hypersaline brine concentration and can contribute to long-term performance decline in RO membranes [74]. The study by Wu *et al.* [78] shows that embossing is a major mechanical limitation in ultrahigh-pressure RO systems. Under pressures of about 80–120 bar, the membrane is forced against the permeate carrier, causing deformation patterns that follow the carrier mesh and increasing hydraulic resistance in the permeate channel. With continued operation at these pressures, the polyamide selective layer and the polysulfone support layer can rupture, leading to irreversible loss of salt rejection. Kleffner *et al.* [79] operated a commercial 4-inch HPRO element at 120 bar for 800 h at 30 °C and observed that the permeate-carrier pressure drop became more than three times higher than during operation at 30 bar, providing clear evidence that embossing can significantly affect permeate-side hydraulics in high-pressure RO modules. The study by de Roever *et al.* [80] showed that operating SWRO membranes can develop visible imprint patterns that match the geometry of the permeate spacer. These patterns indicate that the membrane is pressed into the spacer structure under pressure, providing clear physical evidence of embossing caused by membrane intrusion and compaction.

4.5.2 Hydrophobic membranes in MD

Membrane distillation operates using microporous hydrophobic membranes that maintain a liquid–vapor interface at the pore entrance. These membranes are commonly

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* Corresponding to: O.E. Babajide (email: emmybabajide31@gmail.com)
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fabricated from polyvinylidene fluoride (PVDF), polypropylene (PP), or polytetrafluoroethylene (PTFE) because their low surface energy and hydrophobicity prevent liquid water from entering the pores while allowing water vapor transport across the membrane [81]. The membranes used in membrane distillation operate differently from those used in pressure-driven processes such as reverse osmosis, and their surface properties can lead to different scaling and wetting behavior in the presence of natural organic matter (NOM).

Pore wetting in membrane distillation can occur through several mechanisms. One pathway is direct pore intrusion, where large osmotic pressure differences allow liquid to enter the membrane pores [82]. Wetting can also occur due to surfactants or surface-active compounds in the feedwater, which reduce the surface tension of the solution, lower the membrane's liquid entry pressure, and allow water to penetrate the pores [83, 84]. Another mechanism is scaling-induced wetting, where inorganic crystals form and grow on the membrane surface or inside the pores, altering the pore structure and promoting liquid penetration [85, 86]. In MD systems, this type of wetting is closely related to the rate of crystal formation and growth on the membrane surface, and natural organic matter in the feedwater may interfere with this process, thereby influencing how and when membrane wetting occurs [87].

Mineral scaling, especially from gypsum and silica, is one of the main causes of membrane wetting in hypersaline membrane distillation systems. As these minerals crystallize, they grow on the membrane surface or inside the pores. Over time, this crystal growth can deform the pores or create pathways that allow liquid water to enter the membrane, leading to wetting and loss of separation performance [88, 89]. Once wetting occurs in membrane distillation, it is difficult to fully reverse and often requires intensive chemical cleaning. Repeated cycles of wetting and cleaning can gradually damage the membrane by reducing its hydrophobicity and weakening its structure, which shortens its operational lifespan [90]. To address this issue, researchers have developed advanced membrane designs such as omniphobic, Janus, and superhydrophobic membranes that show better resistance to wetting in laboratory studies. However, these membranes have not yet demonstrated stable long-term performance under full-scale operational conditions [91, 92].

Jacob and Gupta [93] showed that hydrophobic MD membranes are prone to wetting when exposed to surfactants and high salinity. Even 0.1 mM sodium dodecyl sulfate with NaCl above ~1.2 M (~70 g/L) accelerates wetting by lowering surface tension at the pore interface. The study emphasizes that hypersaline, surfactant-containing feeds increase wetting risk in MD systems. Doguwa et al. [94] fabricated six different membranes and reported that the Janus membrane with a stable interfacial layer maintained strong separation performance during prolonged Water Gap Membrane Distillation (WGMD) operation. The membrane sustained a flux of 36.23 kg m^{-2} h^{-1} and a salt rejection of 99.97% for more than 60 h, indicating good resistance to membrane wetting. Liao *et al.* [95] showed that the #PVDF-NA membrane maintained high flux (34.6 kg·m^{-2}·h^{-1}) and excellent salt rejection, similar to the original PVDF membrane. Its combined dissolution-diffusion and pore-flow transport enabled strong anti-scaling performance under 20 wt% NaCl and 25 mM gypsum feeds. The membrane also resisted wetting when exposed to surfactant- and ethanol-containing feeds, preserving structure despite a gradual flux decline.

* Corresponding to: O.E. Babajide (email: emmybabajide31@gmail.com)
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Elahi *et al*. [96] developed robust superhydrophobic PP membranes using a thermally induced phase separation (TIPS) method. The membranes maintained a stable flux and achieved 99.99% salt rejection for a range of feeds, including 35 g/L and 100 g/L NaCl solutions and simulated seawater RO brine, during 24 hours of DCMD operation. This approach produces durable, superhydrophobic coatings on PP membranes, providing excellent stability and performance for MD desalination. Xie *et al*. [97] developed an omniphobic membrane using a simple one-step dip-coating method. During 80 hours of continuous MD operation with actual RO brine, the membrane maintained a permeate flux of around 14 kg m^{-2} h^{-1} and conductivity below 3 μS cm^{-1}, achieving over 99% salt rejection. The membrane showed excellent resistance to both scaling and wetting. Rezaei *et al*. [98] found that recharging air bubbles on a superhydrophobic MD membrane surface prevented wetting and maintained nearly 100% salt rejection, even with up to 0.8 mM SDS in highly concentrated NaCl feeds, without affecting permeate flux.

4.5.3 Ion- exchange membranes in ED

Ion-exchange membranes (IEMs) used in electrodialysis can experience both reversible fouling and irreversible chemical degradation when treating hypersaline brines. Fouling occurs when inorganic scale, organic matter, and colloidal particles accumulate on or inside the membrane. Over time, exposure to electric current, chemicals, and cleaning agents can also damage the polymer structure and ion-exchange functional groups, leading to permanent loss of membrane performance [99, 100]. Reversible fouling in electrodialysis membranes often occurs when multivalent ions such as Ca^{2+} and Mg^{2+} accumulate on cation exchange membranes [101]. Organic matter can also foul anion exchange membranes, especially humic acids and other negatively charged macromolecules. These deposits increase the electrical resistance of the membrane and reduce the efficiency of ion transport. Membrane fouling is also affected by several operating conditions, including electric current, the presence of other components in the solution, temperature, pH, and the duration of operation [102].

Long-term exposure to hypersaline brines can damage commercial cation exchange membranes. In a 30-day study, the membrane surface structure and charged functional groups gradually degraded, and the mono to divalent ion selectivity dropped from 16.60 to 5.67. This decline was linked to the buildup of ions at the membrane–brine interface, which disrupted the ionic interactions between the membrane's charged groups [103]. Liu *et al*. [104] developed a polymer ion exchange membrane using ionic crosslinking between polystyrene sulfonate and 2 hydroxypropyltrimethyl ammonium chloride chitosan to separate Cl^- from SO_4^{2-}. The membrane initially showed a permselectivity of 2.8, but its performance declined during operation, dropping to about 1.0 after 30 h. White *et al*. [105] modified Nafion ion exchange membranes using a layer-by-layer approach based on ionic crosslinking between poly(4-styrene sulfonate) and protonated poly(allylamine). The modified membrane initially showed very high selectivity, reaching a permselectivity of about 1000 for Li^+ over Co^{2+}. However, the membrane was not stable over time, and the permselectivity dropped to about 25 after 48 hours of operation.

Kazemabad *et al*. [106] reported a PEMM nanofiltration membrane that contained crown ether groups in its structure to achieve monovalent salt selectivity. The membrane initially showed selective separation of Li^+ over K^+, but this selectivity lasted for only about

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* Corresponding to: O.E. Babajide (email: emmybabajide31@gmail.com)
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90 min. After that time, the crown ether sites became saturated and the membrane lost its selectivity, although it still maintained high overall salt rejection. Virga *et al*. [107] studied polyelectrolyte multilayer membranes and found that even chemically stable layers like PDADMAC/PSS can be partially removed by charged surfactants. Tested on synthetic produced water with CTAB and SDS stabilized oil-in-water emulsions, the membranes achieved nearly 100% oil removal, about 97% reduction in organic content, and retained 75 to 80% of divalent ions. They also showed high flux recovery, 100% for CTAB and 80% for SDS, with minimal fouling, demonstrating effective simultaneous deoiling, organics removal, and ion retention while remaining easy to clean.

5.0 RESOURCE RECOVERY FROM RO BRINES

Desalination brines contain elevated concentrations of major salts and trace constituents relative to feed seawater. Although this has motivated interest in resource recovery, the practical relevance of such approaches for seawater reverse osmosis (SWRO) systems remains limited. For most facilities, recovery options are constrained by low absolute concentrations, complex brine chemistry, and integration requirements. Consequently, resource recovery from SWRO brines should be interpreted as a byproduct of high recovery or zero liquid discharge (ZLD) operation, not as a primary brine management strategy [108-110]. Resource recovery should be considered a secondary benefit of high recovery or ZLD systems rather than a primary driver of brine management design.

5.1 Realistic Recovery Targets

Among constituents present in SWRO brines, magnesium and calcium are the only elements with demonstrated technical relevance under representative desalination conditions. Magnesium concentrations typically increase from approximately 1.2–1.4 g L^{-1} in seawater to around 2–3 g L^{-1} in RO brines depending on recovery ratio, while calcium is similarly enriched and frequently addressed due to scaling control requirements [108, 109]. These concentration ranges allow pilot scale recovery through precipitation or crystallization when brines are further concentrated within high recovery or ZLD configurations. In contrast, lithium and other critical elements occur in SWRO brines at microgram per liter levels, several orders of magnitude lower than concentrations found in continental salar brines. Under these conditions, recovery remains restricted to laboratory or early pilot studies and lacks commercial relevance [111].

5.2 Technical and Operational Constraints

Despite salinity enrichment, SWRO brines remain dilute compared to conventional mineral resources. High ionic strength, mixed ion matrices, residual antiscalants, and scaling tendencies impose significant selectivity, fouling, and energy penalties on recovery processes. These constraints limit most recovery pathways to site specific pilot applications integrated within high recovery or ZLD desalination systems rather than independent operation [108, 112]. Operational feasibility is further constrained by reagent consumption, membrane durability, and product purity control, particularly for precipitation-based approaches targeting divalent ions.

* Corresponding to: O.E. Babajide (email: emmybabajide31@gmail.com)
DOI: https://doi.org/10.11113/jamst.v30n1.344

5.3 DevelopmentStatus and Risk Profile

Most reported resource recovery systems for SWRO brines remain at laboratory or pilot scale. Pilot demonstrations indicate that magnesium and calcium recovery can be technically achieved when integrated downstream of high recovery or ZLD oriented desalination trains. However, full scale implementations are rare and typically embedded within broader brine minimization strategies rather than deployed for resource production alone [113, 114]. Recovery pathways targeting lithium, rubidium, or in situ acid and base generation remain noncommercial, characterized by low technology readiness levels, high energy demand, and unfavorable economics. These pathways should therefore be regarded as exploratory and high risk, with no implication of near-term deployment. Table 6 presents a TRL-based, risk-oriented assessment of representative recovery options, highlighting their integration context and key technical and economic constraints.

Table 6. Technology readiness level and risk-oriented assessment of resource recovery options from seawater reverse osmosis brines

Resource	Recovery method	Estimated TRL	Integration context	Key limitations	References
Magnesium (Mg^{2+})	Alkaline precipitation as $Mg(OH)_2$; selective ion exchange	TRL 6–7 (pilot)	Downstream of high recovery or ZLD SWRO systems	High reagent demand, complex brine chemistry, energy penalty	[113]
Calcium (Ca^{2+})	Alkaline precipitation as $CaCO_3$; membrane assisted crystallization	TRL 5–6 (pilot)	Concentrated brine streams in ZLD configurations	Scaling control, fouling risk, product purity	[114, 115]
Lithium (Li^{+})	Selective membranes; sorbents; electrochemical extraction	TRL 3–5 (laboratory to early pilot)	Highly concentrated or synthetic brines within ZLD studies	Extremely low concentration, poor economics	[116, 117]
Rubidium (Rb^{+})	Ion exchange; ionic liquid extraction; MD coupled sorption	TRL 2–3 (laboratory)	Synthetic or highly concentrated brines	Very low abundance, low selectivity	[118, 119]
HCl and NaOH	Bipolar membrane electrodialysis; electrosynthesis	TRL 5–6 (pilot)	Internal chemical reuse in ED or ZLD systems	High energy demand, membrane degradation	[120, 121]

TRL- technology readiness level

Note: In this review, pilot scale refers to site specific or short-term demonstration studies conducted under representative operating conditions. This designation does not imply sustained commercial operation or long-term economic viability. Furthermore, TRL assignments presented in this table represent the authors' assessments based on a synthesis of the cited literature, informed by reported experimental scale, demonstrated operating conditions, and deployment status. They are not directly derived from any single source and should be interpreted as indicative rather than definitive classifications.

* Corresponding to: O.E. Babajide (email: emmybabajide31@gmail.com)
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6.0 CHALLENGES AND FUTURE PERSPECTIVES

6.1 Regional Regulatory Frameworks for Brine Discharge

Regulatory requirements governing RO brine discharge vary substantially across regions and represent one of the most site-specific constraints on brine management system design. Rather than converging toward a unified global standard, brine regulation continues to be shaped by local environmental conditions, institutional capacity, and the degree of dependence on desalination for water supply.

In the Gulf Cooperation Council (GCC) region, which accounts for nearly 50% of global desalination capacity and an estimated 70% of global brine production, regulatory frameworks are primarily structured around salinity quality thresholds and monitoring requirements rather than absolute discharge prohibitions [125]. Brine has been formally identified as a major environmental concern in countries such as Qatar, with regulatory responses focused on discharge infrastructure, technology-based management, and threshold monitoring systems. However, enforcement mechanisms remain inconsistent across the region, and the deep reliance on large-scale desalination infrastructure limits the pace of regulatory tightening [126-129].

In the European Union, brine discharge from coastal desalination facilities is subject to the Marine Strategy Framework Directive (MSFD, 2008/56/EC), which requires Member States to achieve and maintain Good Environmental Status (GES) in marine waters. Discharge of brine into inland or surface water bodies additionally conflicts with the objectives of the Water Framework Directive (2000/60/EC), which has driven interest in ZLD approaches for inland desalination systems, particularly in Spain. Environmental Impact Assessment requirements for desalination plants are well established in the EU, though difficulties with monitoring indicators and enforcement specificity have been reported, particularly in Mediterranean member states [130, 131]

In the United States, brine discharge from desalination facilities is regulated under the Clean Water Act through the National Pollutant Discharge Elimination System (NPDES) permit program, which prohibits discharge of pollutants to surface waters except as permitted. Permits are issued on a case-by-case basis by state water boards, with salinity limits typically expressed as relative deviations from ambient background rather than fixed absolute thresholds. California, one of the most active desalination markets in the US, has developed specific regulatory guidance for concentrate management through its Ocean Plan framework, though permitting uncertainty and the absence of uniform salinity objectives across jurisdictions continue to create challenges for project developers [132-134].

In Australia, desalination brine discharge is regulated through state-level environmental impact assessment processes, with independent environmental authorities overseeing compliance separately from water supply regulators. Economic regulators such as water pricing authorities are increasingly engaged in scrutinizing the full costs of desalination, including brine management, as desalination becomes a significant component of urban water supply contingency planning [135, 136].

In many developing regions, formal regulations governing brine discharge are either absent or only weakly enforced. As a result, decisions about brine management are often shaped more by practical site considerations such as available infrastructure, disposal

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* Corresponding to: O.E. Babajide (email: emmybabajide31@gmail.com)
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options, or operational costs than by regulatory compliance. This creates a noticeable imbalance in the global regulatory landscape and highlights the importance of designing brine treatment systems that are modular and adaptable. Such systems can respond to changing regulatory expectations as environmental oversight strengthens over time.

Overall, the variation in regulatory frameworks across regions shows that brine management strategies cannot assume a unified or converging global standard. In the near term, engineering decisions should focus on meeting the regulatory requirements that are currently in force using reliable discharge control methods and gradual volume-reduction strategies. At the same time, system designs should retain enough flexibility to accommodate stricter environmental standards when they are introduced.

6.2 Major Challenges

Despite advances in desalination and brine management, several technical and systemic challenges continue to limit efficiency gains and broader implementation. The most critical constraints relate to energy demand, fouling and scaling control, and the lack of long-term performance data under representative operating conditions. Near term progress is therefore more likely to arise from incremental improvements and conservative system integration rather than disruptive technology shifts. Energy consumption remains a defining limitation in both desalination and advanced brine management. While RO is less energy intensive than thermal desalination, pushing recovery beyond conventional ranges substantially increases energy demand (recovery above ~85% typically requires >10 kWh/m^3) due to rising osmotic pressure and the need for secondary concentration steps. Recovery increases above approximately 85% typically require additional treatment trains or thermal processes, resulting in nonlinear energy penalties [39]. As a result, near term system design favors energy recovery optimization, pressure management, and staged concentration rather than aggressive pursuit of full zero liquid discharge. Fouling and scaling continue to constrain operational stability in hypersaline systems. Elevated salinity accelerates inorganic scaling, particularly calcium carbonate and sulfate precipitation, while organic and biological fouling further reduces membrane performance and increase cleaning frequency [122, 123]. Current mitigation strategies rely primarily on conservative operating envelopes, improved pretreatment, and periodic cleaning rather than advanced control algorithms. While data driven monitoring tools are under development, their deployment at full scale remains limited. A persistent limitation across advanced brine management technologies is the lack of long-term, full-scale performance data. Many emerging approaches are supported primarily by laboratory or short-term pilot studies, which restricts robust comparison of energy consumption, fouling behavior, and environmental performance. In addition, the absence of standardized reporting metrics for recovery, uptime, and operational reliability limits cross study benchmarking and risk assessment [124]. Addressing these gaps is essential for conservative engineering design and regulatory confidence. Regulatory requirements for brine discharge and reuse differ widely across regions and are often addressed on a case specific basis. This variability favors modular, adaptable treatment configurations that can meet local discharge limits without relying on speculative future regulatory standards. Near term system designs therefore prioritize compliance with existing regulations through dilution, controlled discharge, or incremental concentration rather than assumptions of rapid regulatory

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* Corresponding to: O.E. Babajide (email: emmybabajide31@gmail.com)

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convergence [5]. In the near term, progress in brine management is expected to be driven by incremental integration of proven technologies rather than large scale deployment of novel recovery schemes. Hybrid configurations that combine conventional RO with supplementary concentration or polishing steps are more likely to be adopted when they improve water recovery, process uptime, or discharge compliance within conservative design margins. Resource recovery, where present, is expected to remain a secondary outcome of high recovery or near zero liquid discharge systems rather than a primary design objective. Table 7 summarizes the principal challenges constraining advanced brine management and their implications for near term system design.

Table 7. Key challenges and implications for brine management

Challenge	Description	Implications for future brine management	References
Energy penalties	Increased recovery and multistage treatment raise specific energy demand	Emphasis on energy recovery, staged concentration, and conservative recovery targets	[39]
Fouling and scaling	Inorganic and organic fouling under hypersaline conditions reduce performance	Improved pretreatment, fouling resistant materials, and conservative operating envelopes	[122, 123]
Data gaps	Limited long-term full-scale performance data	Constrains benchmarking, risk assessment, and design confidence	[124]
Regulatory variability	Site specific discharge and reuse requirements	Favors modular and adaptable system configurations	[5]

7.0 CONCLUSIONS

This review assessed current practices and emerging strategies for reverse osmosis desalination brine management, focusing on disposal pathways, treatment and volume reduction technologies, and conditional resource recovery options. Conventional disposal routes, including marine discharge, sewer disposal, and subsurface injection, remain the most widely implemented due to their technical maturity and operational reliability, although they face increasing environmental and regulatory scrutiny. Advanced brine treatment approaches, such as membrane-based concentration, thermal processes, and hybrid configurations, can significantly reduce brine volumes but introduce higher energy demand and operational complexity. Resource recovery from seawater reverse osmosis brines is feasible for selected major ions, particularly magnesium and calcium, when integrated within high recovery or near zero liquid discharge systems. In contrast, recovery of trace elements such as lithium and rubidium remains constrained by low concentrations and is largely limited to laboratory or pilot scale investigations. Across all management

* Corresponding to: O.E. Babajide (email: emmybabajide31@gmail.com)
DOI: https://doi.org/10.11113/jamst.v30n1.344

strategies, fouling, scaling, energy penalties, and the scarcity of long-term full-scale performance data continue to limit broader adoption. From a practical perspective, engineers and regulators should prioritize conservative, site specific brine management solutions that emphasize incremental recovery increases, energy efficiency improvements, and reliable discharge compliance. Near-term efforts are best directed toward modular system integration and optimization of established technologies, rather than speculative standalone recovery schemes.

DECLARATION OF COMPETING INTEREST

The authors declare no competing interests.

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* Corresponding to: O.E. Babajide (email: emmybabajide31@gmail.com)

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* Corresponding to: O.E. Babajide (email: emmybabajide31@gmail.com)

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* Corresponding to: O.E. Babajide (email: emmybabajide31@gmail.com)
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* Corresponding to: O.E. Babajide (email: emmybabajide31@gmail.com)

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* Corresponding to: O.E. Babajide (email: emmybabajide31@gmail.com)
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