Environmental Science & Technology

pubs.acs.org/est

Critical Review

Impacts of Desalination Brine Discharge on Benthic Ecosystems

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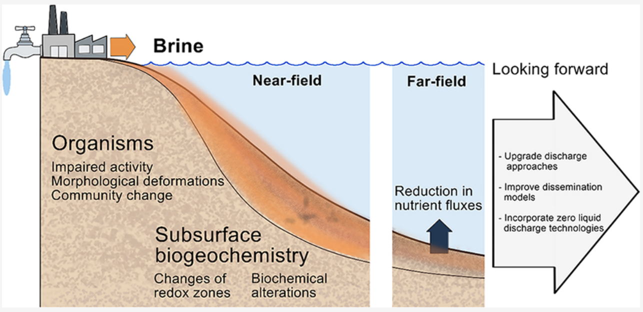
Cite This: *Environ. Sci. Technol.* 2024, 58, 5631−5645

ABSTRACT: Seawater reverse osmosis (SWRO) desalination facilities produce freshwater and, at the same time, discharge hypersaline brine that often includes various chemical additives such as antiscalants and coagulants. This dense brine can sink to the sea bottom and creep over the seabed, reaching up to 5 km from the discharge point. Previous reviews have discussed the effects of SWRO desalination brine on various marine ecosystems, yet little attention has been paid to the impacts on benthic habitats. This review comprehensibly discusses the effects of SWRO brine discharge on marine benthic fauna and flora. We review previous studies that indicated a suite of impacts by SWRO brine on benthic organisms, including bacteria, seagrasses, polychaetes, and corals. The effects within the discharge mixing zones range from impaired activities and morphological deformations to changes in the community composition. Recent modeling work demonstrated that brine could spread over the seabed, beyond the mixing zone, for up to several tens of kilometers and impair nutrient fluxes from the sediment to the water column. We also provide a possible perspective on brine's impact on the biogeochemical process within the mixing zone subsurface. Desalination brine can infiltrate into the sandy bottom around the discharge area due to gravity currents. Accumulation of brine and associated chemical additives, such as polyphosphonate-based antiscalants and ferric-based coagulants in the porewater, may change the redox zones and, hence, impact biogeochemical processes in sediments. With the demand for drinking water escalating worldwide, the volumes of brine discharge are predicted to triple during the current century. Future efforts should focus on the development and operation of viable technologies to minimize the volumes of brine discharged into marine environments, along with a change to environmentally friendly additives. However, the application of these technologies should be partly subsidized by governmental stakeholders to safeguard coastal ecosystems around desalination facilities.



KEYWORDS: *desalination brine, SWRO, benthic organisms, biogeochemical cycles, environmental impacts*

■ INTRODUCTION

The Desalination Industry: The Paradigm of "Dr. Jekyll and Mr. Hyde". Socioeconomic conditions and geopolitical stability in many regions of the world depend on freshwater availability, much of which is currently produced by seawater desalination.[1,2] However, the discharge of desalination effluents to adjacent coastal waters may alter nearby marine environments, especially in confined areas with limited mixing, such as lagoons and semienclosed basins.

Globally, two billion people suffer from constant water stress, and about four billion people live in areas that undergo severe water scarcity for at least one month each year.[3,4] Models predict that freshwater scarcity will sharply increase in the near future due to excessive freshwater withdrawal, seawater intrusion, and the salinization of coastal aquifers, while the global population continues to increase and living standards rise.[5,6] Currently, seawater desalination is the leading technology used to bridge the widening gap between natural freshwater supply and the growing demand, with a daily global production rate of 99 million m^3 day^{-1}.[7−9]

To date, ∼70% (and growing) of the desalination industry worldwide uses seawater reverse osmosis (SWRO),[7,10] which is the focus of this review. Reverse osmosis desalination is a membrane separation process in which highly saline feedwater is pressurized through specially structured membranes. These membranes are based on semipermeable polymers that reject salts and minerals while being highly permeable to water. Despite progress in desalination technology, reverse osmosis (RO) membranes still require extensive pretreatment steps to

Received: September 19, 2023
Revised: February 16, 2024
Accepted: February 16, 2024
Published: March 22, 2024

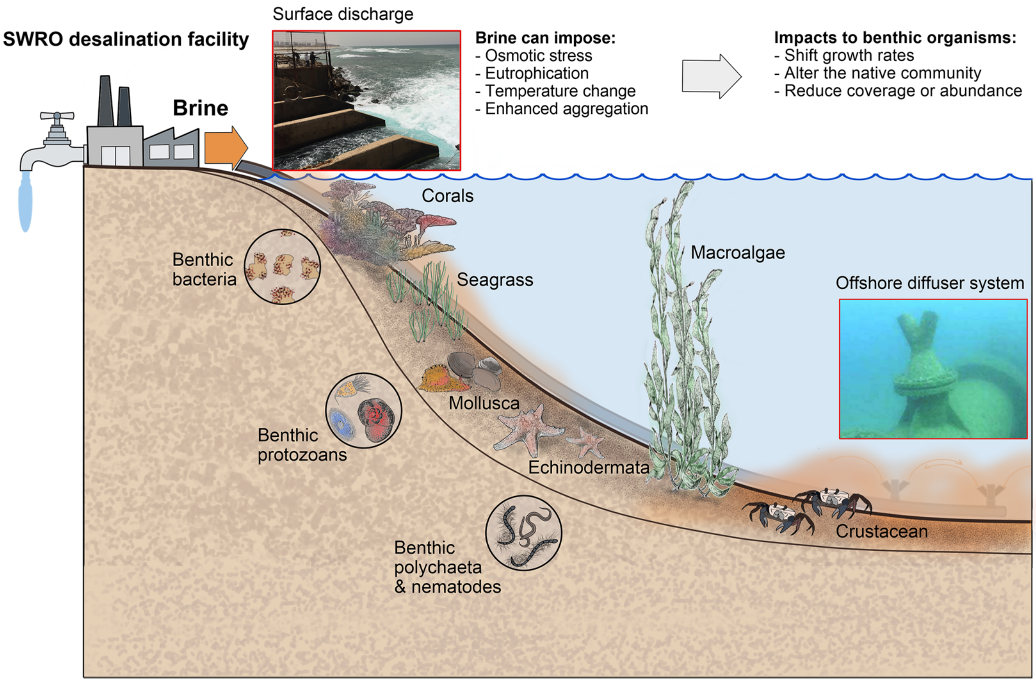


Figure 1. Nexus between desalination brine in the mixing zone and benthic fauna and flora. Shown are surface discharge and offshore diffuser systems, the two most common practices for brine discharge by large-scale desalination facilities. Insets include examples of marine benthic organisms that could be affected by this process, including primary producers (macroalgae and seagrasses), alongside a suite of benthic invertebrates (corals, crustaceans, worms, echinoderms, and molluscs), protozoans, and bacteria. The diffuser image is courtesy of Prof. Iigo J. Losada.

minimize fouling and maintain constant freshwater production. To this end, coagulants are often added (1−15 mg L^{-1}), typically in the form of aluminum or iron salts to induce the aggregation of negatively charged colloids (mostly organic compounds) and facilitate their removal by gravity filtration.[11−16] Antiscalants, such as polyphosphate, polyphosphonate, and polycarboxylates, which are acidic, are also added at the pretreatment stages (doses range from 2−5 mg L^{-1}) to minimize scale formation on the RO membrane surface.[14,17−19] After the addition of antiscalants, the pH of the remaining brine is adjusted prior to discharge to reduce pH and alkalinity alterations in the receiving water.[20] Following SWRO desalination, freshwater is distributed to end-users, while the brine byproduct (also known as concentrate or reject), which consists of highly concentrated saline water, is discharged to the coastal environment via open beach channels or different designs of offshore diffuser systems (Figure 1).

RESULTS AND DISCUSSION

Discharge of Brine from Large-Scale SWRO Facilities.

Brine produced as a byproduct of SWRO desalination facilities is characterized as a hypersaline stream (up to 102% higher than the ambient salinity).[21] The brine may often contain elevated concentrations of inorganic and organic matter[22−26] with similar or slightly reduced pH values than the receiving environment, depending on feedwater properties, pretreatment procedures, and/or RO performance (Table 1).[19,22,27,28] SWRO brine, the focus of this review, differs from that produced by desalination facilities that use other available technologies, such as multistage flashing (MSF) and multi-effect distillation (MED), since both of these methods discharge the brine at higher temperatures and often leach heavy metals (e.g., Cu & Ni) together with different biocides (chlorine and trihalomethanes).[26,29−31] Regardless of the source, disposed brine is normally diluted based on various discharge projections (e.g., MIKE3-HD and\or CORMIX), which include, but are not limited to, near-field, far-field, and biogeochemical models.[12,30,32−34] These projections should also include biological parameters such as ecotoxicity tests that entail both acute and chronic effects.[12] These projections also compute the ambient salinity of the receiving waters, the water recovery efficiency of the specific desalination facility, the brine's salinity, and the distance of brine discharge. These site-specific projections take into account the concentrations allowed in both the near-field and the far-field, which are based on environmental impact assessments (EIAs) and local regulations before the facility is constructed.[12,30,32,35,36]

Brine from large-scale SWRO desalination facilities is typically dispersed into the coastal environment via open beach channels (i.e., surface discharge) or through offshore diffuser systems using underwater nozzles (Figure 1). The area impacted by the discharged brine depends on various factors, including discharge volumes, brine and seawater densities, dilution factors, discharge technology, coastal bathymetry, water currents, and tidal and wave activity.[19,36,46,64,71]

Surface brine discharge via human-made canals or short pipelines[12,57,59,72,73] is a simple and cheap approach, as the brine is directly disposed at the shoreline where the water depth is shallow (<5 m)[48,64] (Figure 1). It has been shown that brine disposed using this technology can affect a coastal area of up to 5 km^2.[48,64,74] The brine is typically diluted with the cooling water of an adjacent power plant to achieve neutral buoyancy and enhance the mixing of the brine plume in the receiving environment, thus minimizing its environmental footprint.[12,75] The brine discharge mixed with the cooling water is often warmer (by 0.5−15 °C) than the receiving

Table 1. Typical Physicochemical and Biological Characteristics of Desalination Brine As Measured in the Mixing Zone (≤ 350 m away from the Discharge Site) Reported from Selected Studies (n = 39, Mean Value and Range Are Reported) around the World[a]

Parameter	Units	Mean ± SD	Range	Ambient mean ± SD	Refs
Salinity	g L^{-1}	40.69 ± 4.99	19.2–75	37.63 ± 2.75	19–22,28,37–67
Temperature	°C	23.89 ± 4.61	11–38.35	22.58 ± 3.94	19,20,22,37,38,41,43,45–47,50,51,55–57,59,60,62–70
pH		7.86 ± 0.67	4.3–8.55	8.15 ± 0.29	19,20,28,37,42–44,49,51,54,59,60,62,63,67,69,70
Suspended solids	mg L^{-1}	14.39 ± 9.84	2–25.1	40.69 ± 4.102	37,43
Total dissolved solids (TDS)		51043 ± 21317	26593–90000	34082 ± 8521	19,22,48,58,63,69,70
Suspended particulate matter (SPM)		1.58	0.59–4.91	1.48	22
Total organic carbon (TOC)		2.8 ± 0.57	1.9–3.5	2.21 ± 0.34	37
Dissolved organic carbon (DOC)	μM	422	95.4–1086.9	NA	64
Dissolved inorganic carbon (DIC)		2553	2140–3270	40.7 ± 4.1	67
HCO_3^-	mg L^{-1}	157 ± 10.59	150–182	158	19,70
Cl^-		27807 ± 4812	21480–34260	23274 ± 1026	19,58,69,70
Na^+		15840 ± 2859	12010–22400	12370	19,58,70
Mg^{2+}		1645 ± 335	1200–2438	1425 ± 80	19,58,60,70
Ca^{2+}		527 ± 93.4	375–840	461 ± 35.8	19,58,60,70
K^+		521 ± 76.4	444–625	530 ± 109.4	60,70
Br^-		88.6	80–103	86.6	70
Sr^{2+}		8.19 ± 0.63	7.25–9.4	8.18 ± 0.23	60,70
SO_4^-		4003 ± 1127	3206–4800	3236	19,70
Total P		0.08 ± 0.08	0.002–0.3	0.004 ± 0.0004	22,45,54
Total organic P (TOP)	μM	0.23	0.017–0.711	0.28 ± 0.25	22,54
Dissolved organic phosphorus (DOP)		4.05 ± 1.65	~1.5–~12	NA	54
Inorganic P		0.2	0.015–~9.7	0.05 ± 0.03	22
Orthophosphate	mg L^{-1}	3.12 ± 2.66	0.323–9.68	NA	60,68
PO_4^{3-}		0.11 ± 0.17	0.0001–0.38	0.005 ± 0.003	22,37,45,54,70
Total N		0.09	0.07–0.13	0.09 ± 0.0003	22
NO_x	μM	4.24 ± 3.58	<0.06–20.8	0.17 ± 0.03	22,45
NO_2^-	mg L^{-1}	0.12 ± 0.22	<0.001–0.651	0.003 ± 0.005	37,42,70
NO^{3-}		1.32 ± 2.19	<0.001–5.57	0.007 ± 0.009	21,37,42,70
$NH_{3/4}^+$		0.02 ± 0.02	<0.001–0.127	0.01 ± 0.01	22,37,42,60,70
Zn	μg L^{-1}	10.4 ± 4.58	0.02–28	12.9 ± 4.93	22,43,60
Fe		24.7 ± 53.7	0.018–290	4.1 ± 2.4	22,37,54,60
Ni		1.2 ± 0.7	0.1–3	0.2 ± 0.1	22,37,43
As		3.79 ± 3.07	0.5–<7	NA	22,43
Cu		3.41 ± 2.92	0.1–10	1.05 ± 0.93	22,37,43
Mn		4.48	0.02–8.93	NA	22
Cr		0.76 ± 0.31	<2.1	0.1 ± 0.001	22,37,43
Pb		1.29 ± 0.95	0–5	NA	22,43,54
Cd		3.36 ± 4.25	<8.01	NA	22,43,54
Ba		8250	7750–8750	8234	60
Al		169.2	3.3–335	NA	54
V		<10	<10	NA	54
Se		<7	<7	NA	22
Hg		0.04 ± 0.05	<0.1	NA	22,43,54
Ag		<0.1	<0.1	NA	22
Si	μM	2.5	1.42–5.15	1.05	70
SiO		3.03	<6.11	NA	64
SiO_2	mg L^{-1}	17.6	17.6	NA	19
$Si(OH)_4$	μM	2.67 ± 1.04	0.36–4.16	1.71	22,45
ClO^-	mg L^{-1}	<2	<2	NA	43
$Na_2S_2O_5$		812	123–1500	NA	44
Bromoform	ug L^{-1}	25	22–28	NA	37
Chl a	μg L^{-1}	663 ± 904	<0.001–3900	764 ± 556	22,37,45,64,65

[a] Note that studies that collected brine from within the facility or did not specify where the parameters were measured are not included. All data in the table are for SWRO plants except for ref 19, which is an MED/RO hybrid desalination facility, and ref 37, which has brine from MSF and SWRO facilities deposited into the same canal.

environment (especially during wintertime), leading to an increase in temperature around the mixing zone.[48,64] The combination of high seawater temperatures and the hypersaline brine can reduce O_2 saturation near the discharge point,

Table 2. Environmental Footprints of Desalination Brine Disposal Using Various Technologies[a]

Discharge approach	Discharge point	Affected area (km^2)	Environmental impacts	Refs
Coastal discharge	On the beach, at depths ≤5 m	~0.04−23	Development of density currents along the seabed Accumulation of pollutants in nearshore environment Increased turbidity Coastal erosion	[12,44,52,88]
Coastal discharge mixed with cooling water	On the beach, at depths ≤5 m	0.1−1.9	Increased seawater temperature, Coastal erosion	[12,81,89]
Diffuser with a single outflow pipe	<0.5 km from the shoreline at 4−10 m depths	2.4−4.3	Costly to construct, maintain, and operate (compared to surface discharge) Development of density currents near the benthic community Localized accumulation of brine and other chemicals	[12,21,62,90]
Diffuser system with multiple outlets	0.6 km from the shoreline at 5−33 m depths	<0.1−2.6	Costly to construct, maintain, and operate (compared to surface discharge)	[22,91,92]

[a] The affected area is defined as the area in which salinity is ≥2% above ambient seawater.

Table 3. Identifying Knowledge Gaps Concerning the Impacts of SWRO Desalination Brine on Marine Benthic Organisms[a]

Organisms	Number of papers	Percentage of reports	References
Bryozoans	2	2	50,74
Sponges	2	2	50,74
Foraminifera	2	2	48,70
Bacteria	2	2	46,89
Fish	3	4	44,92,149
Others	4	5	49,64,116,135
Macroalgae	5	6	21,42,55,74,122
Anthozoans	7	8	30,51,64,66,74,75,100
Echinoderms	8	10	41,52,53,57,64,90,122,135
Polychaetes	9	11	20,49,51,60,64,74,122,135,149
Mollusks	10	12	28,39,41,49–51,63,64,90,135
Crustaceans	11	13	40,41,49–51,74,79,90,122,135,149
Seagrasses	18	22	21,38,44,47,52,57,62,67,108–112,114–116,150

[a] The color scale represents the number and percentage of total papers analyzed for this review reporting the effects of SWRO desalination brine on benthic fauna and flora. Note that publications and reports that examined more than one organism are counted more than once.

while at the same time, provide a competitive advantage to organisms that thrive in warmer waters,[76−78] promoting the success of invasive tropical species.[79]

Offshore discharge by diffuser systems includes various configurations, such as single nozzle, multiport, or rosette diffusers.[12,30,80] These diffuser systems distribute the brine further away from the coastline (up to a few km) and at greater depths (~20 m) to avoid potential impacts on sensitive shallower coastal habitats and enhance the mixing with offshore currents[12,48,81] (Figure 1). Outfall systems that utilize rosette or multiport diffusers have numerous nozzles (4−12), which are oriented in the direction of the prevailing currents (angled generally from 30−60°) to maximize the dilution.[81,82] However, it was reported that in some occasions, diffuser systems can affect an area as large as 13 km^2 around the discharge point in which the salinity of the brine plume that gravimetrically spreads downslope along the sea bottom is ≥1% above the ambient.[12,39,41,50,61,83] Although the impacted area can be larger than that of the direct discharge, it has been shown that using a diffuser system can enhance the brine dilution efficiency and reduce the environmental impact.[39,41,44,50,61,84]

Regardless of the applied disposal methods, it has been indicated that the brine can still sink and spread on the seabed as a hyperpycnal flow (Table 2). It has been suggested that this dense boundary layer will reduce the nutrient fluxes from the seabed, thus impacting the natural benthic-pelagic nutrient cycle in coastal waters.[34] Moreover, hypersaline brine and the accompanying chemical additives can impose osmotic shock, as well as alter nutrient stoichiometric ratios, thus directly affecting benthic organisms.[47,85,86] Following the tight nexus of desalination with the coastal environment, brine discharge must be highly regulated by local guidelines to minimize its ecological footprint.[87]

Potential Far-Field Impacts from Large-Scale Brine Flow. Most studies assessing the impacts of desalination brine on the marine environment have focused on the visible mixing zone where the concentrations of the salts and additives are high enough to be directly measured or produce a physiological response in marine biota.[28,39,41,48,49,64] However, recent modeling work suggested that SWRO brine may also have a far-field impact that may influence large coastal water areas.[34] Following the discharge of brine into the coastal zone, hydrodynamic model simulations have indicated that while not physiologically significant at the organism level, the diluted plumes could have far-field dynamic effects. Simulated brine flow showed that gravity currents and the Coriolis force will cause the dense plume to spread along the seabed down-

https://doi.org/10.1021/acs.est.3c07748
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slope.[34] It should be noted that the density differences between the diluted brine and the ambient seawater required to support the formation and propagation of gravimetric density currents are quite small.[93] The above-mentioned study argued that the far-field propagation (<13 km^2) of desalination brines will form a higher density layer above the seabed that can impede the vertical mass transfer of nutrients from the sea bottom to the overlying water,[22,34] similarly to reports from the mixing zone.[54]

Previous studies have shown that the recycling of organic matter and remineralization of nutrients in coastal-shelf sediments are vital processes that support up to 40% of primary production in coastal waters.[94,95] Considering the observed and modeled far-field dynamic effects of seawater desalination brine discharge discussed above, it is likely that the propagating density currents may transport recycled nutrients that are emitted from the sea bottom downslope and away from the shore. Furthermore, in light of the current knowledge on the effects of seasonal thermal stratification on coastal water productivity,[96−98] it is also likely that the vertical transport of recycled nutrients from the seabed into the dense brine plume to overlying water would also be impaired. The reduced nutrient supply to the overlying water column would limit coastal water productivity.[34]

Benthic Fauna and Flora: Ecological Functions and Brine Discharge Impacts. To date, little attention has been paid to the specific impacts of brine discharge on benthic organisms,[22,37,43,48,53,99] and only a handful of papers have reported impacts on porewater chemistry.[51,53,67] Nearly all (~93%) of these studies addressed the effects of salinity or brine effluent, while only a very few focused on the chemical additives used in the desalination process.[44,75,100] By compiling the latest literature, we provide a detailed overview of benthic organisms that were reported to be impacted by SWRO brine (Table 3).

Heterotrophic bacteria play a central role within the benthic fauna assemblage as they regulate various biochemical processes, such as the decomposition of dissolved organic matter and mineralization of nutrients in the sediment.[101−103] Remineralized nutrients can then be released back into the water column and taken up by primary producers, which, in turn, fix biomass for secondary consumption at higher trophic levels. Heterotrophic bacteria are also important contributors to the marine food web as they assimilate organic matter that is consumed by bacterivores and ultimately utilized by higher trophic levels.[104] Currently, very few studies (Table 3; *n* = 2; 2%) have reported on the impacts of brine from SWRO desalination facilities on benthic bacteria's activity or microbial diversity.[46,89] A short benthocosm experiment (48 h) indicated that exposure to salinities >5% above the ambient caused drastic reductions (60%) in bacterial abundance, but surprisingly, there were no differences in the bacterial community structure.[89] Another study indicated that benthic bacteria's activity and growth efficiency in the vicinity of the brine outfall (1.4 km^2) were higher (up to 2.6-fold) compared to a control (unaffected) site.[46] In addition, the bacterial community structure near the hypersaline brine outfall point included more halophytic species than the bacterial community at the control site.[46] It was also suggested that a reduction in bacterivore abundance (e.g., nematodes) caused by the brine indirectly contributed to the proliferation of benthic bacteria within the area impacted by the brine.[46]

Seagrasses are a unique group of marine flowering plants (angiosperms) that thrive worldwide on shallow sedimentary shorelines. Seagrasses are keystone species with important ecological services evaluated to be worth at least \$2.8 million km^{-2} year^{-1}.[105,106] Seagrasses are important primary producers that enrich their surrounding water with oxygen while sequestering large amounts of atmospheric carbon dioxide ("blue carbon"[107]). In addition, seagrasses act as nurseries for juvenile fish and invertebrates as well as a food source for various herbivores. Seagrass meadows can also protect shorelines through the attenuation of waves and sediment stabilization, thereby preventing coastal erosion. A total of 18 studies on desalination brine's impacts on seagrass have been performed, yet all of them focused on seagrass species residing in temperate/subtropical waters (*Posidonia oceanica* [*n* = 12], *Posidonia australis* [*n* = 2], *Cymodocea nodosa* [*n* = 4]) (Table 3). These studies have reported that seagrasses are negatively impacted by desalination brine.[21,44,47,67,108−112] Specifically, it was found that the hypersaline brine caused a reduction in seagrass coverage[21,112] (~40%), increased leaf necrosis,[67,109,110,112] decreased leaf and shoot size (≤75% and 17−66%, respectively), reduced growth rates (26%),[47,62,109,110,112,113] and reduced shoot abundance (12−45% reduction).[62,110,112] An increase in the amount of nitrogen found within the leaves and rhizome was linked to the reduction in glutamine synthetase activity due to brine exposer.[67] Brine discharges were shown to decrease net photosynthetic rates by 12−33%[108,109,111] and to increase the dark respiration (up to 98%).[108,109,114,115] *P. oceanica* leaves and rhizomes exposed to hypersalinities (116% above the ambient) for 1−3 months had increased carbohydrate concentrations; however, after three months of exposure followed by one month of recovery, the carbohydrate concentrations decreased by 35 and 28%, respectively.[109] An additional study reported that only the concentration of sucrose within *P. oceanica* tissue significantly increased when exposed to two different elevated salinities.[116] One study reported that two different seagrass species (*P. oceanica* and *C. nodosa*) from shallow (5−7 m) and deep (18−20 m) populations increased their Chl a, b and carotenoid concentrations after exposure to high salinity treatment.[114] However, it was found that these species were able to osmoregulate and tolerate the hypersaline exposure by accumulating organic solutes.[114] Interestingly, continuous seagrass meadows of *P. oceanica* were able to mitigate the salinity in the porewater compared to patchy ones.[67] Most of the impacts listed above may be attributed to osmotic stress, as *P. oceanica* species showed altered K^+:Na^+ and Ca^{2+}:Na^+ ratios during the 1−3-month-long exposure to higher salinities;[109,115] however, those exposed for only one month were able to recover, although such recovery was not observed after exposure for three months.[109] It should be noted that some of *P. oceanica*'s physiological measurements, such as the number of leaves per shoot and shoot size, were shown to be unaffected by the salinity increases (116% above the ambient) found at the outfall of these specific desalination facilities.[108] When increased salinity was coupled with elevated water temperature (e.g., when power plants' cooling water is mixed with the brine), increased seagrass mortality and decreased growth rates were documented.[38] It was also reported that exposure to increased salinity (only), as well as desalination brine at different concentrations, reduced the relative water content by up to 20%.[116] Seedlings exposed to 50% and 100%

brine for 50 days also decreased leaf shoot and root biomass.[116] In rare occasions, exposure to a biocide reagent used in some desalination facilities to clean RO membranes (e.g., sodium metabisulphite at low concentrations of <1 ppm) was found to reduce shoot survivability, leaf growth, and leaf surface area, and increase the frequency of leaf necrosis;[44] however, this concentration is above the reported values used in many other desalination facilities (0.7 g m^{-3} and 0.05−1.5% (w/w).[117,118] Altogether, it is possible to use the enhanced production of organic matter including some amino acids (e.g., proline) and sugars, as well as photosynthetic damages and other molecular signals (e.g., upregulation of oxidative stress markers, antioxidant defenses, detoxification enzymes), as biological markers for osmotic stress in seagrasses.[47,115]

Macroalgae are commonly found living as epiphytes or on rocky shores at high biomasses. Macroalgae play a central role in coastal environments as primary producers and pioneer species.[119] They also constitute an important habitat and food source for a variety of plankton species, fish, and invertebrates.[120,121] About 6% of the published studies on the impacts of SWRO desalination have focused on macroalgae (Table 3, n = 5). One study found that the thalli of the macroalga *Caulerpa prolifera*, located near the brine diffuser system, disappeared or were in a poor physiological state.[21] It was also reported that brown algae (*Ectocarpus* sp.), found in close vicinity (<30 m) to a brine discharge pipe, expressed severe oxidative stress responses, possibly due to the reduction of several photosynthetic parameters.[55] In contrast to the above, an ecotoxicology report on the germination and growth of *Macrocystis pyrifera* showed a high resilience to salinities up to 30% above ambient salinities.[122] Lastly, algae from control and impacted sites within the Mediterranean Sea showed no statistical differences in δ^{13} C and δ^{15} N values between brine-impacted and control sites,[74] indicating species-specific resilience to desalination brine.

Foraminifera are unicellular protists that are found in most marine environments, including the benthos.[123,124] These microorganisms are considered bioindicators of environmental stressors and pollution.[125−131] To the best of our knowledge, only two studies (Table 3) have examined the impacts of desalination facilities on Foraminifera.[48,70] It has been reported that the higher brine temperatures (after mixing with the cooling water of adjacent power plants) further reduced the abundance and species richness of local foraminifera, with two threshold temperatures at 30 and 35 °C. The two most common species found within the warm brine plume were *Lachlanella* sp. and *Pararotalia calcariformata*.[48,70] Other species common to the area have rarely been found in the vicinity of the brine plume. In addition, it was recently reported that an increase of only 2−3 salinity units over the ambient salinity had a negative effect on organic-cemented foraminifera species, but only a minor impact on calcareous benthic foraminifera assemblages.[48,70] Others reported that impacts of hypersaline brine (5 to 10 salinity units above the ambient) included reduced calcification and photosynthesis, as well as increased bleaching in symbiont-bearing foraminifera.[48,70] Overall, it can be expected that brine, combined with other stressors (temperature, antiscalants, and coagulants), will negatively impact foraminifera within the discharge mixing zone of desalination facilities.

Polychaetes are small (up to a few cm long), segmented worms, ubiquitously found in subsurface marine environments.[28,132] Polychaetes play a key role in benthic nutrient recycling and sediment bioturbation, thus affecting organic matter remineralization and sedimentation.[133] Overall, increased salinity levels negatively impacted benthic polychaetes, with a marked decrease in their abundance, richness, and diversity.[28,39,41,49−51] On the other hand, increased salinity levels provided a competitive advantage to unique Polychaeta families (such as Onuphidae, Paraonidae, and Magelonidae) that are more resilient and can survive at higher salinities.[39,41,64] It should be noted that *Syllidae* and *Capitellidae* populations recovered rapidly when pipeline discharge was switched to a diffuser system as a mitigation measure for brine dissemination into the coastal environment.[39] Since the abundance and species richness of polychaetes are high and different families have different salinity tolerances, they could be used to monitor further impacts of brine effluent.[90]

Echinoderms can be found in a variety of coastal environments and consist of sea urchins, sea cucumbers, and starfish. They are considered ecosystem engineers, with a high impact on bioturbation.[134] Echinoderms were found to be highly sensitive to salinity variations from coastal discharge, especially during their larval stages.[53] Multiple studies reported negative impacts of increased salinity from brine effluent on echinoderm abundances (Table 3).[41,52,53,64,90,135] However, other studies indicated that some specific species, such as the brittle star *Ophiothrix* spiculata, the sand dollar *Dendraster excentricus*, and the purple sea urchin *Strongylocentrotus purpuratus*, showed no significant impacts on arm growth,[64] development,[122] fertilization[122] or mortality[64] when exposed to salinities up to 10% above the ambient.[64] SWRO desalination facilities with mitigation strategies, such as rapid diffusion or diffuser installation, do not seem to impact echinoderm abundance or growth, and indeed, the recovery of impacted areas was observed within a year.[90]

Crustaceans play a central role in the food web with some species functioning as filter feeders and others as herbivores or carnivores. Most studies show that increased salinity from brine dramatically reduces the abundance (~82%−100%) of crustaceans near various types of desalination outflows.[40,41,49,51,90,135] For example, most amphipod species were absent from the impact zone; however, some species, such as *Ampelisca diadema*, *Ampelisca typica*, and *Photis longipes*, were more resilient to salinity changes and were found close to the impact zone, suggesting that some species are more resilient to salinity changes (pipeline discharge) than others.[40] Nevertheless, amphipod abundance returned to pre-exposure conditions six months after the open-discharge system was replaced by diffusers.[40] An ecotoxicology test, looking at the survival and growth of mysid shrimp *Americamysis bahia*, showed their tolerance to salinity above the ambient concentrations (34‰).[122] Lastly, a combination of the brine discharge and the construction/installation of intake and outfall pipes resulted in the proliferation of an invasive skeleton shrimp (*Paracaprella pusilla*) in Mediterranean waters off the coast of Israel.[79] The numbers of the invasive skeleton shrimp increased from two female specimens found in the spring of 2010 to 1669 specimens found in the spring of 2016.[79]

Hard (hermatypic) corals form complex holobionts that include the coral host, endosymbiotic algae (*Symbiodiniaceae*; zooxanthellae), and associated bacteria and archaea.[136−138] Hard corals are reef-building organisms (precipitating calcium carbonate skeletons) that provide habitat and shelter for many organisms. Corals are sensitive to changes in salinity,[139−141]

Table 4. Physical and Chemical Properties of Sedimentary Porewater and Sediments Impacted by Desalination Brine Discharged into the Coastal Waters (< 350 m away)[a]

Parameter	Unit	Mean ± SD	Range	Ambient mean	Refs
Salinity	g L^{-1}	40 ± 0.6	36.4−45.6	37.5	51,67
Temperature	°C	23.1	22.4−23.7	23.3	67
pH		7.5	7.47−7.5	NA	53
Total P	mg kg^{-1}	143 ± 194	3.13−280	145.5	51,99
Total N		1.06	<1−1.2	NA	51
Zn		9.5 ± 5.3	1−18	9.8 ± 5.1	30,43,99
Fe		5057 ± 3455	2590−7500	1567 ± 1850	30,44,99
Fe_2O_3	wt %	1.17 ± 1.32	0−3.71	<0.001	48
Ni	mg kg^{-1}	14.4 ± 3.4	10−16.8	10.3 ± 6	30,44,99
As		2 ± 0.26	1.4−3	2.2 ± 0.7	43
Cu		5.6 ± 5.98	0.5−15	2.14 ± 0.96	30,41,44,99
Mn		263 ± 340	50−934	237 ± 134.7	48
Cr		33 ± 66	1.9−240	24.3 ± 34	30,41,44,47,99
Pb		7.2 ± 5.4	0.5−13	7.3 ± 5.5	30,43,99
Cd		0.23 ± 0.2	0−0.5	1 ± 1.2	30,43,99
V		16	16	10.4 ± 0.5	99
Bromoform		0.3	0.27−0.33	NA	37

[a] Data assembled from select studies ($n = 8$) around the world. All data in the table are for SWRO plants except for that from ref 37, which combines the brine from MSF and SWRO facilities.

temperature,[142−144] and nutrients.[145−147] An early field study reported that most corals around a brine discharge area in the Red Sea (where salinity was 42% over the ambient) disappeared.[69] Another study performed in the Arabian Gulf showed that corals within several tens of meters from the discharge were extensively damaged or dead.[30] However, more recent studies have indicated that some coral species seem to be more resilient to high salinity. Specifically, *Fungia granulosa* were found to be resilient to rapid and prolonged changes in salinity units (25 to 50), and their algal symbionts also exhibited wide plasticity with regard to salinity changes (pipeline discharge).[66] An ex-situ experiment involving polyphosphonate and polymer-based antiscalants showed negative impacts on *Montipora capricornis*, including decreased polyp activity (25%), increased tissue damage (41% for polymer-based and 30% for polyphosphonate), increased bacterial abundance (~40%), and decreased photosynthetic efficiency (~3−6%).[100] Specifically, the polyphosphonate antiscalant caused a 39% decrease in the endosymbiotic algae, increased chlorophyll a concentrations, and upregulated the host's antioxidant capacity by 45%.[100] The polymer antiscalant also decreased the productivity of symbiotic bacteria.[100] Similarly, the combination of polyphosphonate antiscalants and brine significantly impaired the physiology of three coral species and their associated symbionts with decreased calcification rates (20−90%, species dependent), reduced associated algal and bacterial abundance, increased bacterial productivity, and decreased protein concentrations in two of the three coral species.[75]

Table 3 summarizes the reports of the main benthic organisms that were impacted by the desalination industry, indicating the current gaps of knowledge. The fact that this list is relatively short highlights the need for additional studies, particularly those that investigate the combined effects of the different components found in brine effluents. Although we call for more studies on this topic, it should be noted that comparing different studies is not straightforward, since the impacts of brine may strongly depend on the discharge method, with surface discharge[46] causing chronic near-field effects while different diffuser systems induce mild[40] or negligible[66,148] responses. Nonetheless, much is still unclear regarding the effect of multiple stressors (e.g., the combination of high temperatures and hypersalinities) and common chemicals (e.g., coagulants and antiscalants) used in the treatment process. More importantly, we emphasize that additional long-term studies are needed to determine the effects of brine on porewater chemistry,[51−53,61,67] sediments,[37,43,48,51,99] and the ecophysiology of a wider range of benthic organisms.[22,39,40,50,53,57]

The Black Box: Effects of Desalination Effluent on Subsurface Biogeochemistry. Currently, little is known about the impacts of brine effluents on subsurface (sediment porewater) biogeochemistry within the desalination mixing zone (Table 4). The subsurface is considered a hotspot of organic carbon remineralization and hence, a source of nutrients that diffuse through the sediment-water interface into the water column.[151,152] Desalination brine that flows as a concentrated plume on the seafloor can infiltrate into fine sediments by gravity flows,[153] accumulate in the porewater, and potentially alter various biogeochemical processes (Figure 2A). The infiltration rate into the subsurface will be greater when the sediment is sandy (grain sizes are larger than a few hundreds of micrometers), which is often found around the discharge sites of large-scale desalination facilities.[48,64,154,155] Although the above scenario is highly possible, there is little information about the brine concentrations that are found in porewater around desalination facility outfalls. Here we suggest a unitless diagram that highlights the biogeochemical transformations that may occur as brine infiltrates into the sandy subsurface (Figure 2).

Under typical coastal conditions, microbes within the sediment and porewater can use a variety of electron acceptors during the oxidation of organic matter. The order in which these electron acceptors are used largely reflects their relative availability and the free energy yield associated with their reduction.[156] The highest energy yield is associated with aerobic respiration (O_2), followed by denitrification (NO_3^-), manganese, iron, then sulfate (SO_4^{2-}) reduction, and finally,

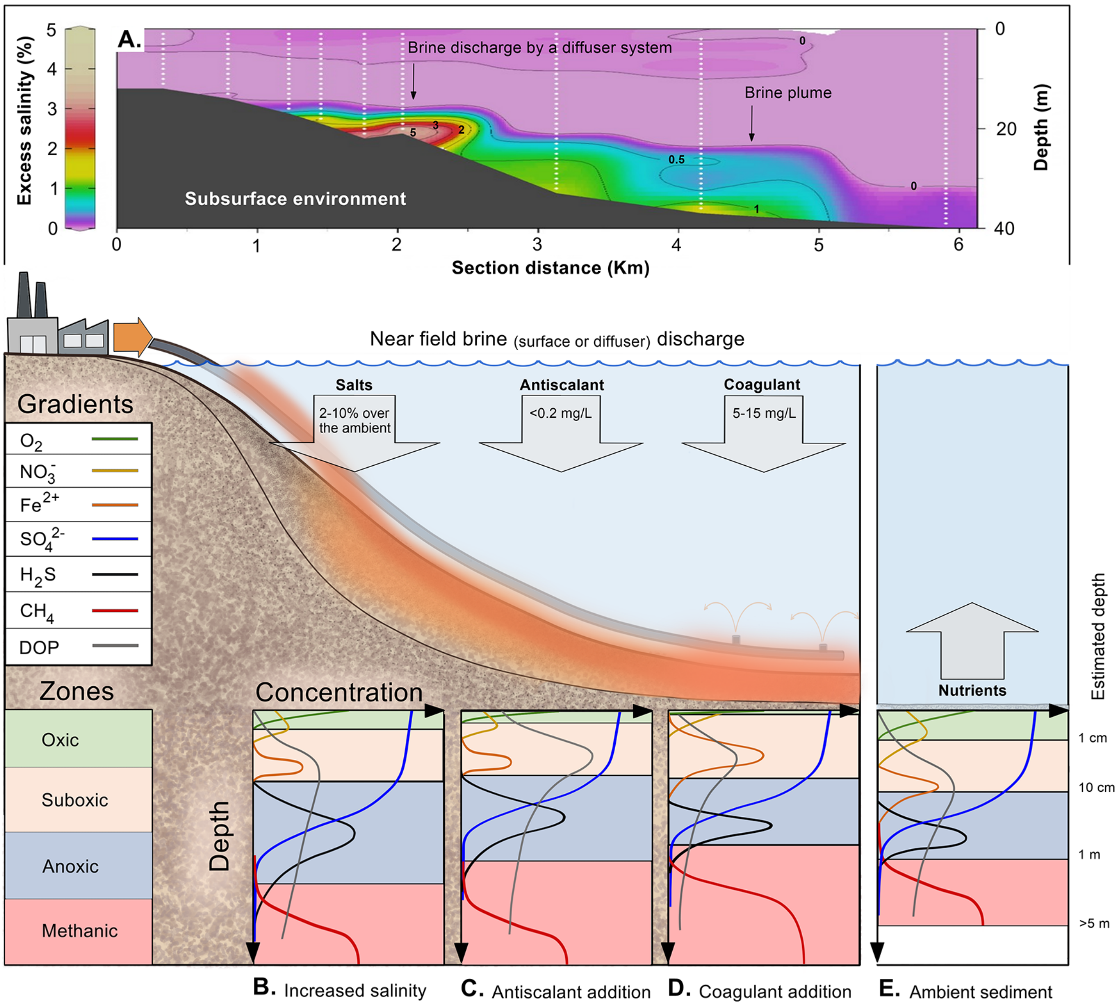

Figure 2. (A) Measurements of brine dispersion from a large-scale SWRO desalination facility that was discharged via an offshore diffuser system.[54] Schematic illustration of potential changes in the sediment redox zonation in the mixing zone due to (B) increased salinity and (C) the addition of polyphosphonate-based antiscalants or (D) ferric-based coagulants. (E) Changes in the different layers of the sediment, as well as inorganic and organic matter content, indicate plausible changes in an unaffected, ambient coastal sediment and hence are unitless. Note: These concentrations and depths are schematic, and actual values will depend on various environmental factors such as geographic location, depth, and sediment type.

organic fermentation into methane (methanogenesis).[156,157] Although benthic ecosystems, including subsurface communities, are vital to many marine processes,[158,159] the impacts of brine on these subsurface communities have been poorly studied.

Salinization of porewater (>5%) may impose osmotic stress on benthic microbes, impair their activity, and alter community structure,[39,46,75,89,160] thus leading to changes in various biogeochemical cycles (Figure 2B). Around the Canary Islands, Spain, porewater salinity as high as 24.6% above ambient was measured close to the discharge point. This salinity dropped to 5.7% above the ambient 15 m away from the discharge site before returning back to ambient levels at ~30 m away.[51] Another study reported porewater salinity within *P. oceanica* seagrass beds that was 0.5−2.6 higher than ambient levels.[67] The degree of porewater salinization (salinity levels and the area affected) will likely depend on the discharged brine volumes, brine salinity, the discharge technology used, and the sediment type (e.g., rocky, sand, pebbles, etc.). Within the sediment, porewater salinization will reduce dissolved oxygen (DO) concentrations as gas solubility decreases with increasing salinity.[161] Lack of oxygen in areas of high sedimentary organic matter will stimulate microbial organic matter decomposition through sulfate reduction[162−167] and will allow the buildup of hydrogen sulfide.[160] Under these conditions, the anoxic sulfate reduction zone will expand, potentially driving the methanogenesis zone deeper (Figure 2B).

Polyphosphonate-based antiscalants are frequently added to SWRO feedwater[22] and are often discharged with the brine (Figure 2C). Polyphosphonate-based antiscalants are not considered to be a form of phosphorus used by organisms. However, a recent study that sampled sediment and porewater from the discharge area of a large-scale desalination facility indicated that these antiscalants can be degraded, leading to the release (~40x higher than the intake water) of dissolved organic phosphate, DOP.[54] This additional load of organic phosphate has been shown to enhance bacterial metabolism at the diffusive boundary layer.[54] The addition of DOP from antiscalants to the environment may also enhance bacterial respiration in the sediment, consuming oxygen, and possibly leading to a shift in the depth of sulfide and methane production closer to the sediment-water interface (Figure 2C). Moreover, a recent study by Hasanin et al. (2023) showed that phosphate, a more readily bioavailable phosphorus form, is also present in some polyphosphonate-based antiscalants,[168] which may upregulate microbial activity.

Coagulants are also added to desalination feedwater, especially when organic and nutrient loads are high in the feedwater. These chemical additives are used to facilitate the aggregation of organic colloids by the formation of ion bridging to increase the removal efficiency of gravity filters.[11,16] Coagulants such as ferric chloride or ferric sulfate, applied in some large-scale facilities, are often mixed and discharged with the brine after backwashing the gravity filters,[36,37,169,170] and thus, may also infiltrate and accumulate in the porewater. Indeed, it has recently been reported that iron concentrations within the sediments near a discharge site (Arabian Gulf coast) were 9-fold higher than at a control site.[37] Similarly, an early study showed that the levels of Fe, Cd, Cu, P, Ni, Zn, and Hg significantly increased near the discharge zone of desalination brine, yet gradually decreased further (3 km) from the discharge point.[99] Off the coast of Algeria, the concentrations of Cr, Pb, and Cd around the discharge site were somewhat elevated but still lower than the environmental threshold.[42] Collectively, these results indicate that both organic loads and iron oxides will accumulate in the top sedimentary layer near the discharge point, reducing the level of the oxic layer and expanding the suboxic zone (Figure 2D). We also hypothesize that the addition of ferric iron will drive sulfate reduction and methanogenesis upward in the sedimentary column.

Collectively, it is expected that desalination of brine and chemical additives will alter the biogeochemical cycles that occur in the subsurface in coastal environments impacted by brine discharge (Figure 2E). Moreover, the fact that the brine plume may reduce nutrient fluxes from the sediment into the water column can potentially impact primary producers, causing cascading changes in the food-web dynamics along wider, far-field regions.

Nexus of Brine Discharge and Marine Environments: Current Challenges to Possible Mitigation Strategies. Models predict that global desalination capacity, especially via large-scale SWRO facilities, will increase 3.2-fold during the 21st century as freshwater demand increases.[171,172] It can therefore be expected that brine discharge will increase, exacerbating the stress to benthic coastal environments. Moreover, it is plausible that the impact of brine on subsurface ecosystems will increase over time due to the accumulation of salts and chemical additives within the sediments. It should be noted that benthic coastal habitats are already under great environmental pressure by anthropogenic activities and climate change,[173,174] and are thus highly sensitive to additional stressors. Therefore, construction of large-scale desalination facilities should be approved by regulators only after high-resolution hydrodynamic models (e.g., MIKE3-HD or Deft3D) have been used to provide detailed estimations of brine propagation in the near- and far-fields.[12,34,65,175] These models should consider the brine volume and discharge rates and how they change throughout the year as well as the disposal method, coastal bathymetry, and hydrodynamics, and potential cumulative contributions from adjacent facilities. These model results should be compared to field observations for validation.[30,34,61,65,175] This could be done, for example, by combining the use of autonomous underwater vehicles to obtain accurate salinity, temperature, and current profiles and couple these with discharge models such as the Cornell Mixing Zone Expert System (CORMIX^2) to get a better understanding of how the brine effluent will impact the near to far-field areas.[65] Monitoring the benthic community should also be performed because brine propagation models can occasionally deviate from realistic conditions, causing damage to the benthos.[50] This emphasizes the importance of detailed surveys of the benthos within the proposed mixing zone before, during, and after the facility's construction to establish an environmental baseline and document the ecological changes. This site-specific baseline should include physiochemical and biological parameters of both the sediment and the water column. Seasonal surveys of benthic epifauna and flora could be carried out by divers, remotely operated vehicles, or remote sensing methods.[155] In addition, porewater chemistry and site-specific bioindicators that include infauna (e.g., nematodes) and epifauna (e.g., foraminifers and bryozoans), as well as other benthic organisms such as corals and seagrass meadows, should be monitored seasonally for at least two years before discharge. The water column, with emphasis on the sediment-water interface, should be monitored for inorganic nutrient levels as well as biomass and physiology of sessile organisms, phytoplankton, and zooplankton species. After the facility's construction, monitoring at different distances from the discharge site, at least seasonally, should be conducted to record any deviation from the baseline parameters. Salinity should be mapped at high resolution (e.g., 0.5 × 0.5 km) to obtain a spatial dynamic of the brine plume. The biochemical parameters should be collected from the discharge point and along the salinity gradients at >5%, 3%, and 1% above the ambient salinity. The results should be compared to NOAA's Screening Quick Reference Tables (SQuiRTs) to estimate the potential environmental toxicity of the brine, and local regulations regarding salinity limits; they should also be evaluated against the EIA.[35,36,176,177]

Minimizing the impact of SWRO desalination brine on benthic marine environments should be a target of this industry and could be achieved by one or more of the following actions: (A) The brine should be discharged in areas of least concern (e.g., barren seascapes, deep waters, within outflow currents, etc.), the brine should be considerably diluted before discharge, and brine should be discharged through underground or offshore diffuser systems to maximize mixing and minimize the affected area.[37,41,57] (B) Chemical additives, such as antiscalants and coagulates, should be replaced by environmentally friendly products.[100,178] Specifically, we suggest reducing the use of phosphate-based antiscalants, especially if these additives are discharged with the brine into oligotrophic, phosphorus-poor marine environments. Some of the newly developed antiscalants and coagulants, designed to reduce environmental impacts, have had mixed results. For example, some biodegradable antiscalants were found to impact the bacterial community,[178] facilitate membrane biofouling[179,180] or only partially remove scaling.[181−183] Regarding the addition of coagulants, it is possible to use liquid ferrate (Fe(VI) in 10x lower doses than $FeCl_3$, which removes adenosine triphosphate (ATP) to >99% and reduces the operating expenses by 62%[184] or to add titanium salts ($TiCl_4$) and polytitanium tetrachloride, which removed more dissolved organic carbon at similar doses as $FeCl_3$.[185] Nevertheless, it is still recommended to collect, concentrate, and land-treat the backwash slurry from the gravity filters, as it includes high concentrations of organic matter and coagulants used in the process. (C) Environmentally friendly approaches should be adopted, such as "building with nature" concepts that incorporate natural processes with beneficial outcomes (e.g., forming artificial reefs from the diffuser architecture).[81,186] Another avenue could be the use of bioflocculators (microbial communities that form bioflocs) instead of adding chemical additives.[187] (D) Further efforts are also needed in the following areas to enhance the proposed methods and designs: (i) Environmental impact studies with increased focus on regional ecotoxicological investigations, which involve analyzing the characteristics of local species and assessing their susceptibility to local effluent attributes. (ii) Validation studies, conducted in laboratory settings, are needed to readjust the numerical models for the near-field region, particularly in terms of refining formulations of boundary impingement and considering the influence of ambient currents on the mixing efficiency and dispersal of the brine. The models for the far-field region require additional data on winds, ambient currents, and stratification to establish more accurate boundary conditions. These measurements, combined with modeling, are immensely valuable for addressing coastal zone management concerns. Also, large-scale field studies incorporating local and regional features are crucial for validating the proposed brine disposal methodologies and EIA recommendations.[30] (E) Finally, it is crucial to minimize the volumes of discharged brine, as well as other byproducts such as sand filter backwash-waste, through the development of minimal liquid or zero discharge strategies[188] and to incorporate these into hybrid systems such as pressure-retarded osmosis[189] and forward osmosis.[190] It must be stressed that these approaches can become viable only if governmental bodies and other stakeholders partially subsidize the integration and operational costs of these systems within desalination facilities.

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This paper was supported by a grant to E.B.Z from the Middle East Regional Cooperation (MERC) Program (M39-011). This article is in partial fulfillment of the Ph.D. thesis by R.S. at Ben-Gurion University of the Negev.

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