

Article

Brine Discharge from Desalination Plants: Environmental Contaminants, Pollution Control Processes and Mitigation Strategies

Elmahdi Belhadj ¹, Cherif Rezzoug ^{2,*}  and Youcef Benmoussa ¹

¹ Department of Hydraulics, Faculty of Technology, University of Tahri Mohamed, Bechar 08000, Algeria; elhadjdz@yahoo.fr (E.B.); benmoussa.youcef@univ-bechar.dz (Y.B.)

² Chemistry and Environmental Sciences Laboratory, University of Tahri Mohamed, Bechar 08000, Algeria

* Correspondence: cherifrezzoug@yahoo.fr; Tel.: +213-550-716-365

Abstract

Desalination is an urgent response to global freshwater shortages, serving more than 300 million people by 2025. However, it is a technology that still raises several sustainability concerns. Through this study, we aim to propose a systematic review based on the PRISMA methodology, analyzing 45 studies published between 2015 and 2026. Quantitative synthesis of 45 studies showed brine salinity ranging from 40 to 75 g/L, boron and bromate concentrations of 1.8 mg/L and 25 µg/L, respectively, and energy consumption of 3–5 kWh/m³ for membrane systems, reaching 15 kWh/m³ for thermal technologies. Economically, the levelized cost of desalinated water remains high (USD 0.5–2.0/m³) due to the high energy consumption of up to 15 kWh/m³ in thermal processes. This study proposes several mitigation strategies, including diffuser optimization, integration of renewable energies, and brine recovery through the extraction of strategic minerals. The originality of this study lies in its integrated approach, combining health, environmental, energy, and economic dimensions, all addressed together in previous reviews. These results demonstrate the need for regional governance and consistent international standards to achieve sustainable water desalination that combines water security and ecosystem conservation.

Keywords: desalination; public health; brine; carbon footprint; SEC; LCOW

1. Introduction

Freshwater poverty is a major global problem today, particularly in arid and semi-arid regions where demand for water resources far exceeds supply. Desalination is now considered a strategic solution to ensure water security, as is the case in the MENA (Middle East and North Africa) region, where over 50% of drinking water is supplied using desalination technology [1,2].

However, this technology still poses significant environmental, health, and economic challenges. Freshwater production through reverse osmosis or thermal processes is often accompanied by highly saline discharges, called brines, and the frequent addition of chemicals such as chlorine, biocides, and antiscalants [3,4]. These discharges disrupt saline and thermal stratification, causing biodiversity loss, the deterioration of seagrass beds such as *Posidonia oceanica* in the Mediterranean, and the death of sensitive benthic organisms [5,6].

On the other hand, desalinated water can contain chemical by-products such as boron and bromate, which pose significant health risks. Desalination plant workers are



Academic Editor: Otman
El Mountassir

Received: 5 June 2026

Revised: 18 July 2026

Accepted: 22 July 2026

Published: 24 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

also exposed to hazardous chemicals on a daily basis, increasing their risk of developing occupational diseases [7,8]. In addition to these environmental and health risks, there are other energy and economic aspects: the production of desalinated water consumes a lot of energy (3–4 kWh/m³ for reverse osmosis and approximately 15 kWh/m³ for thermal processes), resulting in significant costs and a significant carbon footprint [9–11].

To address these challenges, an integrated approach must be developed, combining hypersaline plume modeling, health risk assessment, and energy and economic analysis, with the goal of sustainable water desalination.

Figure 1 presents the original conceptual framework of this study, linking desalination, brine discharge, and their environmental, health, energy, and economic impacts.

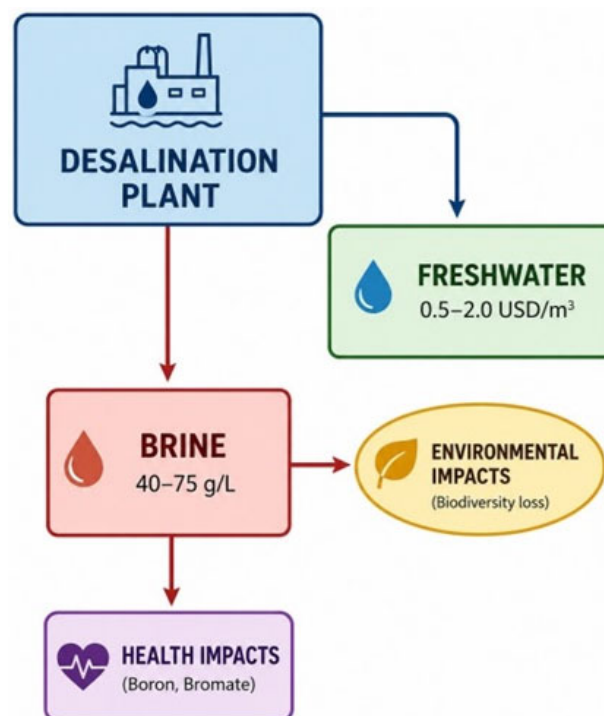


Figure 1. Original conceptual framework of this study showing interactions between freshwater production, brine discharge, and associated environmental and health impacts.

While previous reviews on desalination mainly addressed isolated aspects such as brine salinity, energy demand, or economic cost, this study provides a more comprehensive perspective by integrating environmental, public health, occupational, energy, and economic dimensions. This study adopts a hybrid framework combining a PRISMA-based review with a numerical modeling case study. The review provides global evidence, while the simulation validates plume dispersion under Algerian Mediterranean conditions.

2. Materials and Methods

2.1. General Approach

This study adopts the principle of a systematic and critical review of the international scientific literature published between 2015 and 2026 in high-impact journals. The methodological objective of the work is to reassess the potential impacts of desalination plants from a health, environmental, and economic perspective, drawing on

- Experimental data;
- Quantitative analyses;
- Documented regional case studies.

Integration of Review and Modeling Components

This study integrates a systematic review and a numerical modeling case study to synthesize global evidence and validate findings under Mediterranean conditions.

2.2. Source Selection Criteria

Throughout this study, all sources were selected based on specific inclusion and exclusion criteria, ensuring the validity and relevance of the analyzed data (Table 1).

Table 1. Reproducible inclusion and exclusion criteria for study selection.

Inclusion Criteria	Exclusion Criteria
Peer-reviewed articles indexed in Scopus or Web of Science (2015–2026)	Non-peer-reviewed documents (editorials, opinions, and blogs)
Studies reporting quantitative data on brine salinity, contaminants, energy use, or environmental impacts	Studies without measurable quantitative data
Studies with clearly described methodology and reproducible results	Studies with incomplete or unclear methodology
Official reports from recognized institutions (WHO, FAO, IEA, and IRENA)	Unverified local reports or non-citable sources
Studies directly related to desalination sustainability, brine management, or risk assessment	Studies unrelated to desalination impacts

2.3. PRISMA-Based Literature Search Strategy

This systematic review followed the PRISMA 2020 guidelines to ensure transparency and reproducibility. The study selection process included four stages: identification, screening, eligibility, and final inclusion.

A literature search was conducted in Scopus, Web of Science, and ScienceDirect for studies published between 2015 and 2026, using keywords such as *desalination plant*, *brine discharge*, *environmental impact*, *public health*, and *energy consumption*, combined with Boolean operators. This search identified 612 records.

After removing 124 duplicate records, 488 articles were screened based on titles and abstracts. Of these, 351 studies were excluded because they were unrelated to desalination impacts or lacked quantitative data.

The full texts of 137 articles were then assessed according to the inclusion and exclusion criteria presented in Table 1. Studies without peer review, measurable indicators, or sufficient methodological detail were excluded.

Finally, 45 studies were retained for qualitative and quantitative synthesis, including eight representative studies selected for detailed comparative analysis. Figure 2 presents the PRISMA flow diagram summarizing the study selection process.

Among the 45 selected studies, eight representative studies were chosen for comparative analysis (Table 2).

Table 2. Summary comparing representative studies on the impacts of brine discharges and modeling (2015–2026).

Reference	Location/Methodology	Key Results	Recommendations
[12]	Ténès, Algeria—CORMIX + GIS modeling	Dilution ≥ 20:1 required; dense plume in low current	Multi-nozzle diffuser

Table 2. Cont.

Reference	Location/Methodology	Key Results	Recommendations
[13]	Tipaza, Algeria—GIS + statistics	Strong spatiotemporal variability	Permanent monitoring
[14]	Eastern Mediterranean—Benthic monitoring + modeling	Reduction in biodiversity; sensitive corals	Maintain $\Delta S < 2$ g/L
[15]	Chile—Hydrodynamic model + terrain	Rapid dilution in high-energy zone	Regulation by site
[16]	Morocco—Regional analysis	Lack of MENA integration	Valorization (brine mining)
[17]	Arabian Gulf—CORMIX + Delft3D	Dense plume persisting at the bottom	Deep discharge systems and monitoring
[18]	Spain—Monitoring <i>Posidonia oceanica</i>	High sensitivity $> +1$ g/L	Limit discharges near seagrass beds
[19]	Global—Technology analysis	SWRO best practices	Optimized diffusers and deep discharges

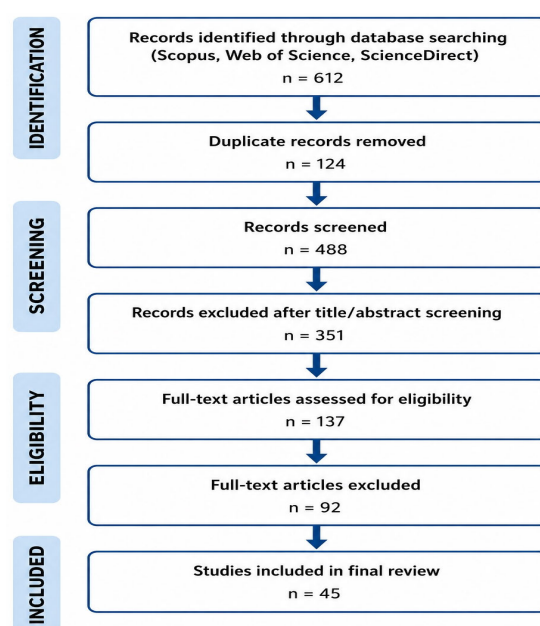


Figure 2. PRISMA flow diagram of study selection process.

This review highlights the need for minimal dilution and appropriate regulation, as well as improved diffuser systems with continuous monitoring and brine recovery.

2.4. Data Analysis Methods

2.4.1. Energy Analysis

The energy analysis aims to compare the specific energy consumption (SEC) of different technologies to measure their sustainability (as shown in Figure 2). These analyses show that the wide variation in energy consumption rates is due to the type of technology used. Reverse osmosis (RO) consumes an average of 3 to 4 kWh/m³, while multi-stage distillation (MSF) consumes up to 12 kWh/m³ [20,21].

SEC, expressed in kWh/m³, was calculated using Equation (1):

$$SEC = \frac{E_{tot}}{V_{water}} \quad (1)$$

where

- E_{tot} = total energy consumed (kWh);
- V_{water} = volume of desalinated water (m³).

The SEC values presented in Table 3 and Figure 3 were derived from the 45 studies included in the PRISMA dataset. For each desalination technology, reported SEC ranges from peer-reviewed studies published between 2015 and 2026 were collected and averaged. The representative SEC values shown in Figure 3 correspond to the arithmetic mean of the reported ranges for each technology. This approach was adopted to provide a comparative overview while minimizing bias from individual case studies.

Table 3. Typical energy consumption by desalination technology (according to recent studies).

Technology	SEC (kWh/m ³)	Reference
Reverse osmosis (RO)	2.5–4.0	[8,20]
Multi-effect distillation (MED)	6–12	[22,23]
Multi-stage distillation (MSF)	10–16	[8,23]
Hybrid desalination (RO+MED)	3–5	[8,20,23]

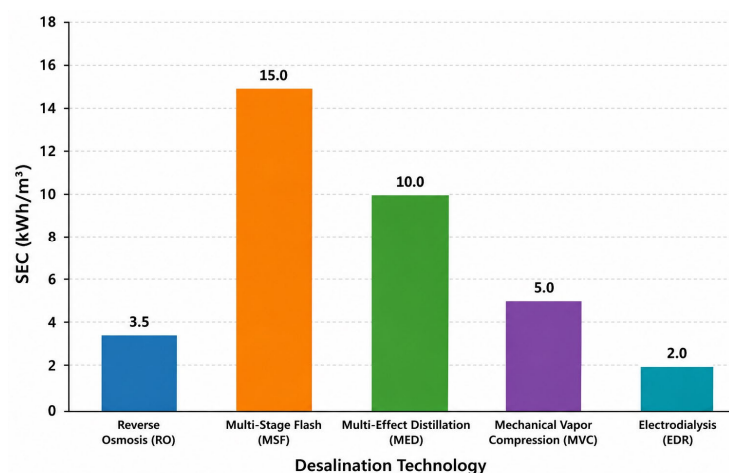


Figure 3. Comparison of specific energy consumption (SEC) by desalination technology (kWh/m³).

SEC depends on both desalination technology and operating conditions, particularly salinity, recovery rate, and energy recovery efficiency.

The data for Figures 3–7 were extracted from 45 PRISMA-selected studies and official reports (WHO, IEA, and FAO), standardized to common units, and synthesized using ranges or arithmetic means for comparative visualization. No additional modeling was applied. To better illustrate the performance gaps, Figure 3 provides a comparison of specific energy consumption (kWh/m³) between the different desalination technologies currently in use.

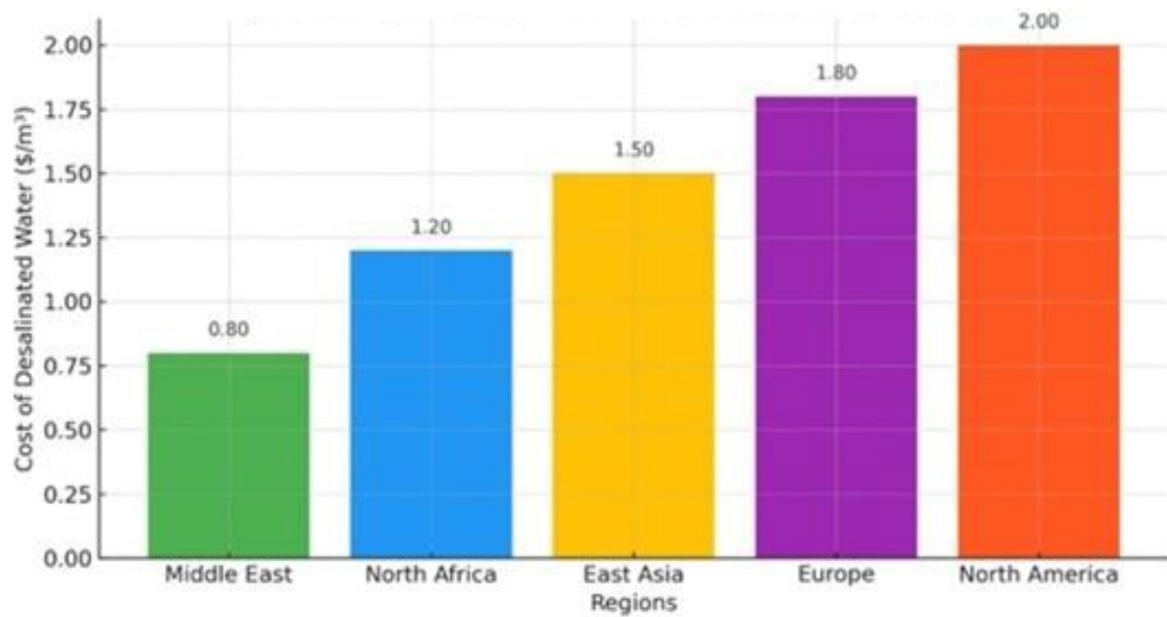


Figure 4. Regional comparison of desalinated water costs (USD/m³).

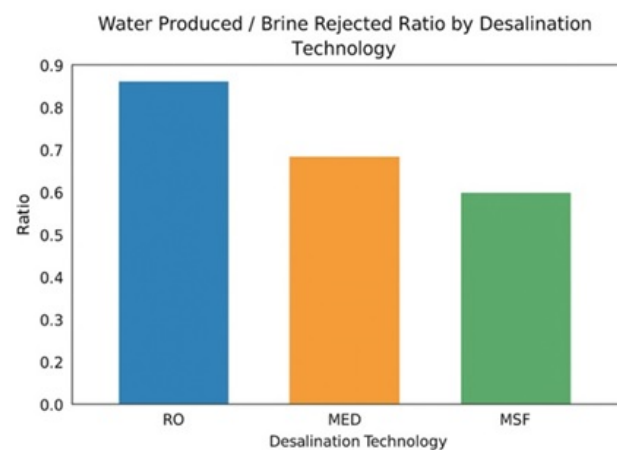


Figure 5. Ratio of produced water to discharged brine according to technology.

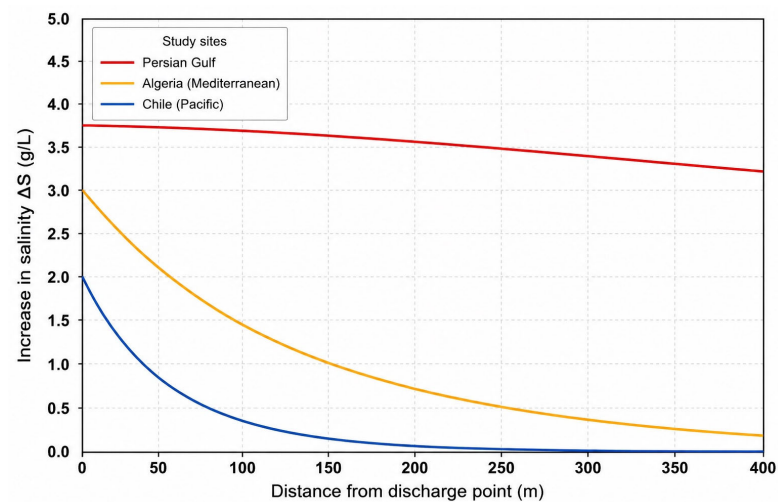


Figure 6. Dilution and extension of brine plumes with distance from outfall.

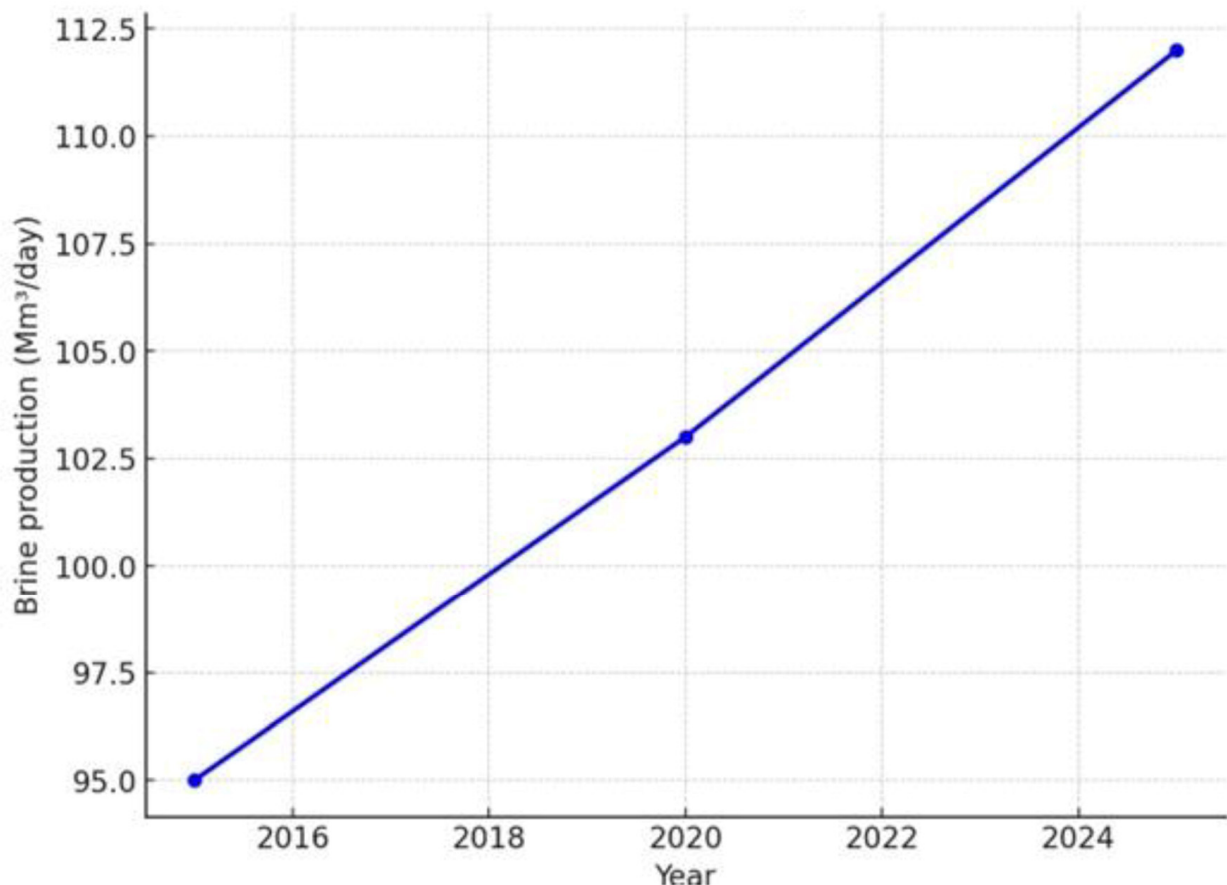


Figure 7. Global evolution of brine production (2015–2025).

Figure 3 illustrates the mean SEC values calculated from the ranges found in the literature and reported in Table 3, enabling a comparative visualization of the energy performance of major desalination technologies.

Thermal technologies remain energy-intensive, which limits their sustainability in energy transitions.

2.4.2. Economic Analysis

The economic analysis is based on the levelized cost of water (LCOW) study, which provides a regional comparison (Figure 3). The levelized cost of desalinated water was estimated in USD/m³ according to the International Energy Agency [24] and was calculated using Equation (2):

$$LCOW = \frac{\sum_{t=1}^n \frac{C_t}{(1+r)^t}}{\sum_{t=1}^n \frac{V_t}{(1+r)^t}} \quad (2)$$

where

- C_t = total annual costs (investment, operation, and maintenance);
- V_t = volume of water produced;
- r = discount rate;
- n = lifetime of the facility.

Table 4 presents the levelized cost of desalinated water (LCOW) by main production area.

Table 4. Average production costs of desalinated water (according to recent studies).

Region	LCOW (USD/m ³)	Reference
Middle East (Saudi Arabia and UAE)	0.50–1.20	[9]
North Africa (Algeria and Morocco)	0.80–1.50	[22]
Mediterranean Europe (Spain and Italy)	0.90–1.60	[25]
Australia	1.20–2.00	[26]

As shown in Figure 4, there is significant variation in the cost of desalinated water by region, for a number of reasons, reflecting significant differences in energy availability, technology used and available support policies.

2.4.3. Environmental Analysis

Based on the environmental analysis, we focus on the volumes and salinity of brine discharges.

The discharged brine volumes were calculated according to (3):

$$Q_{brine} = Q_{product} \left(\frac{1 - R}{R} \right) \quad (3)$$

where

- Q_{brine} : brine discharge (m³/day);
- R = recovery rate (40–50% in RO, 25–35% in MED/MSF);
- MED = multi-effect distillation;
- MSF = multi-stage flash distillation.

Table 5 gives the average brine discharge volumes and associated salinities for various major desalination technologies.

Table 5. Brine discharge volumes by technology.

Technology	Brine Volume (m ³ Discharged/m ³ Produced)	Average Salinity (g/L)
Reverse osmosis (RO)	1.2–1.5	60–75
MED	2–2.5	70–85
MSF	2.5–3	80–90

Figure 5 highlights that membrane processes have a better ratio between produced water and discharged brine compared to thermal processes, which is better in terms of environmental sustainability.

2.4.4. Health Analysis

The health analysis is based on the epidemiological and toxicological literature on chemical by-products and nanoparticles. A set of epidemiological and toxicological data was collected on

- The presence of chemical by-products: chlorine, bromates, and trihalomethanes (THMs);
- The toxicity of nanoparticles from membranes;

- The effects of concentrated brine on marine organisms.

Quantitative values for brine salinity, boron, bromate, and energy consumption were extracted from 45 PRISMA-selected studies using validated measured data. Brine salinity is reported as an interquartile range, while the other parameters are presented as median or mean values.

3. Results

The main objective of this study is to illustrate the potential and multidimensional impact of desalination plants in terms of public health, the environment, and the economy.

3.1. Discharge Volumes and Salinities

- Desalination plant output varies on average by 1.5 L of saline solution for every liter of freshwater [22,27].
- In the MENA region, discharges could exceed 55 Mm³/day, or about half of the total global discharge [22].
- Salinity measured in plumes ranges from 45 to 70 g/L, with maximum salinity levels above 75 g/L recorded in the Arabian Gulf [27,28].

3.2. Plume Dilution and Extension

- According to hydrodynamic models (CORMIX, Delft3D, and MIKE 21), the minimum acceptable dilution ranges from 20:1 to 50:1, depending on local hydrodynamics [12].
- In the Algerian Mediterranean (Ténès and Tipaza), hypersaline plumes can extend over a distance of 100 to 300 m from the discharge point under slow current conditions (<0.05 m/s) [3,29]. Desalination brine discharges may cause ecological disturbances in marine ecosystems exposed to high-salinity conditions [29].

Figure 6 highlights the key role of coastal hydrodynamics in plume dispersion, with weak currents causing persistent salinity and stronger currents promoting rapid dilution. On the Chilean coast, which is exposed to strong currents, the dilution is less than 50 m [15]. Hypersaline brine discharges can significantly affect marine benthic diatom diversity and coastal microbial ecosystems [19].

The ecological thresholds used in this study ($\Delta S = +1$ and $+2$ g/L) were selected based on widely reported marine sensitivity limits. The $+1$ g/L threshold corresponds to the tolerance limit of sensitive seagrass ecosystems such as *Posidonia oceanica*, while $+2$ g/L is associated with measurable disturbances in benthic communities under prolonged exposure [30]. These thresholds are consistent with previous Mediterranean and Gulf desalination studies and are commonly used to define ecological risk zones [30].

3.3. Comparative Ecological Impacts

- The salinity of *Posidonia oceanica* meadows exceeds a critical threshold of >1 g/L above ambient levels [31].
- There is a significant decrease in benthic communities exceeding $+2$ g/L [14,32].
- Due to cumulative discharges into the Arabian Gulf waters, this has led to an increase in coastal salinity of 2 to 3 g/L, with a lasting impact on macrofauna [28].

3.4. Trends 2015–2026

- Overall increase: According to recent estimates, global brine production was expected to increase from 95 Mm³/day in 2015 to over 110 Mm³/day in 2025 [27,33].

Figure 7 shows the global increase in desalination-related brine discharges recorded through 2025. It highlights a continued upward trend, driven by the increased use of desalination technologies, particularly in arid and semi-arid regions [22].

- Diversity of methods, with a significant increase in geographic information systems (GIS) and multivariate statistical methods for spatiotemporal assessment [13,21].
- Towards recovery: Several studies have recommended the recovery of minerals (lithium and magnesium) as an alternative to simple dilution [34,35].

3.5. Synthetic Regional Comparison

Table 6 summarizes the observed regional variations in brine discharges, taking into account volumes, salinity, dilution, and environmental impacts. The Arabian Gulf tops the list, with brine discharge rates exceeding 35 Mm³/day and salinity levels reaching 75 g/L. The 20:1 ratio remains elusive, resulting in a serious impact on benthic organisms [36].

Table 6. Regional summary of brine impacts.

Region	Brine Volume (Mm ³ /Day)	Average Salinity (g/L)	Typical Dilution	Main Impact
Arabian Gulf	>35	50–75	20:1 hard to reach	Accumulation; affected macrofauna
Algerian Mediterranean	2–3	40–55	20:1 à 30:1	Stress on Posidonia; local variability
Morocco (Atlantic)	1–2	38–50	Rapid dilution (strong currents)	Moderate impacts but poorly monitored
Chile (Pacific)	~1	40–50	Dilution < 50 m	Localized; mitigated impacts
Australia	~0.5	38–45	Variable	Reduction in benthic diversity
Overall	>110	40–75	Very variable	Need for harmonized standards

However, the Algerian (2–3 Mm³/day) and Moroccan (1–2 Mm³/day) coasts are the least affected but still at risk, particularly for *Posidonia oceanica* meadows. Chile and Australia, meanwhile, record moderate discharge levels (≤ 1 Mm³/day), with rapid mitigation and limited impacts, highlighting the urgent need for unified international standards.

Quantitative synthesis shows brine salinity ranging from 40 to 75 g/L, with dilution requirements of 20:1–50:1. Plume extension varies from <50 m in high-energy coasts to >400 m under weak currents, while thermal processes generate 45–70% more brine than RO.

Figure 8 compares the volumes and salinity of saltwater discharges by region. The highest levels are in the Persian Gulf, with over 35 Mm³/day, followed by the Mediterranean coast of Algeria and Morocco, with around 1 to 3 Mm³/day. In contrast, Chile and Australia record low levels of brine, with rapid dilution. With global production exceeding 110 Mm³/day, this illustrates the scale of the problem.

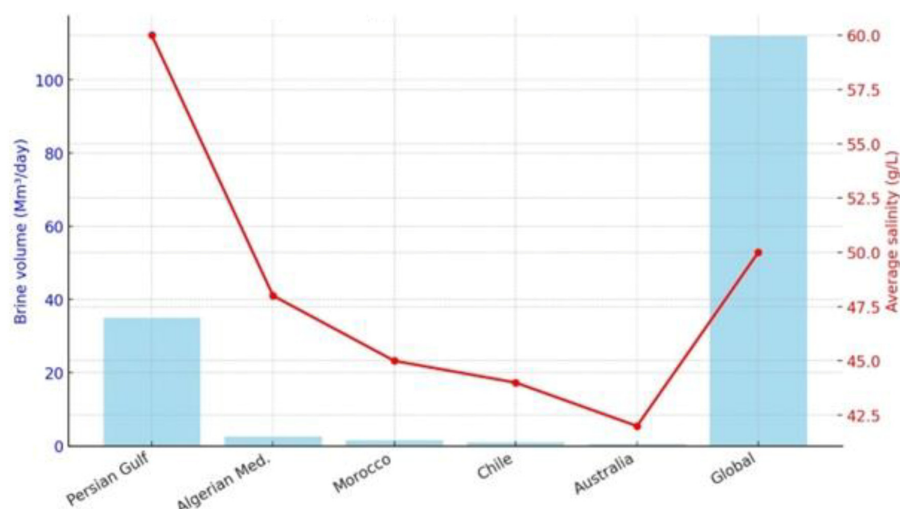


Figure 8. Regional comparison of brine volumes and salinities.

The strong contrast between the Arabian Gulf and Pacific systems indicates that environmental risk depends not only on discharge volume but also on local mixing capacity and ecosystem resilience.

Cross-Study Comparative Analysis

Brine impacts vary significantly across regions due to hydrodynamics and discharge conditions. The Arabian Gulf shows the highest impacts, whereas Chile and Australia experience rapid dilution; Mediterranean sites show intermediate effects.

3.6. Brine Production and Impacts on the Marine Ecosystem

The amount of brine discharged by desalination plants is 1.5 L for every liter of freshwater produced, resulting in high salinity in the presence of high concentrations of chlorine, copper, and antiscalants [28,32].

The following formula gives the ratio of produced water to infiltrated brine (4):

$$R = \frac{Q_{water}}{Q_{brine}} \quad (4)$$

where

- Q_{water} = volume of water produced (m^3/day);
- Q_{brine} = volume of brine discharged (m^3/day).

Table 7 shows the ratios between produced water and brine discharged for several technologies, highlighting the low efficiency of thermal processes compared to reverse osmosis.

Table 7. Ratios between produced water and brine discharged for desalination technologies.

Technology	Produced Water (m^3)	Brine Discharged (m^3)	Report (R)
RO	1	1.2–1.5	0.67–0.83
MED	1	0.8–1.0	1.0–1.25
MSF	1	1.5–2.0	0.5–0.67

These discharges cause local oxygen shortages, high mortality rates among marine animals, and a significant decline in biodiversity [37].

3.7. Impacts on Public Health

Halogenated disinfection by-products formed during the chlorination and chloramination of desalinated water may pose significant toxicological risks [38]. Desalinated water generally meets all drinking water standards, but the presence of residual by-products can pose serious health risks if not managed properly.

- In the Gulf region, bromate (BrO_3^-) formation during ozonation depletion has been detected at levels up to 25 $\mu\text{g/L}$, exceeding the World Health Organization's recommended limit of 10 $\mu\text{g/L}$.
- The residual boron concentration in reverse osmosis-treated water ranges from 1.5 to 2.5 mg/L , which is very high compared to the WHO maximum limit (0.5 mg/L) and can have negative effects on reproductive health [39].
- Some studies in Gulf countries suggest possible associations between long-term consumption of inadequately remineralized desalinated water and kidney-related disorders. However, evidence remains limited and influenced by multiple confounding factors [8,40].

Table 8 summarizes the main contaminants detected in desalinated water, their average concentrations and possible exceedances of WHO standards, and the associated health risks.

Table 8. Main contaminants detected in desalinated water and associated health risks.

Contaminant	Average Concentration (mg/L)	WHO Standard (mg/L)	Potential Health Risk
Boron	1.8	2.4	Possible reproductive effects
Bromate	0.025 (25 $\mu\text{g/L}$)	0.01 (10 $\mu\text{g/L}$)	Potential carcinogenic risk
Chloride	450	250	Hypertension

3.7.1. Evolution of Cancer Diseases Following the Proliferation of Desalination Plants

Although desalinated water is generally safe, concerns remain regarding disinfection by-products such as bromate and N-nitrosodimethylamine (NDMA), which may pose long-term health risks when guideline limits are exceeded. However, current evidence is insufficient to establish a direct link with cancer. Several studies have shown the presence of disinfection by-products (DBPs), such as bromates and nitrosamines (NDMA), which are produced following oxidative treatments of bromide-rich seawater (chlorination and ozonation) [29,41]. For example, in Kuwait, high bromate levels are associated with a cancer risk of up to 3.9×10^{-4} , which exceeds international limits [1]. In contrast, a study conducted in the occupied territories did not show a significant increase in colorectal cancer but recommended long-term monitoring [42]. Therefore, the association of desalination and cancer risk still requires further study and monitoring. This requires improved treatment processes, strict monitoring at all stages of desalination, and the establishment of stricter standards to mitigate potential health risks [29,43].

Table 9 shows the concentrations and presence of disinfection by-products (DBPs) in several locations around the world.

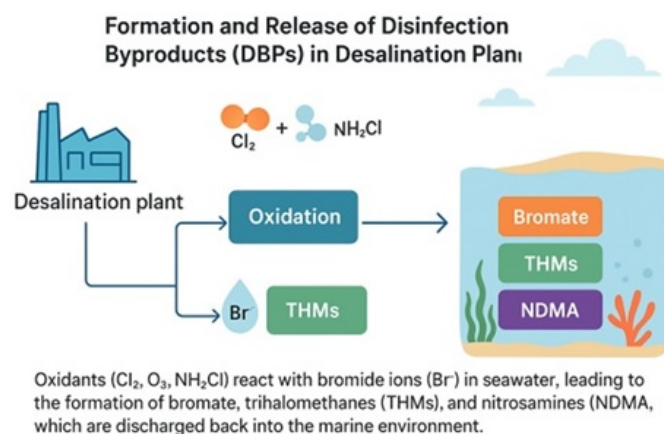
Table 9. Concentrations of disinfection by-products (DBPs) detected in desalinated water in different regions.

Region/Country	Dominant By-Product	Measured Concentration (µg/L)	WHO Guideline Value (µg/L)	Estimated Lifetime Cancer Risk	Reference
Kuwait	Bromate	18–28	10	3.9×10^{-4}	[1]
Saudi Arabia	Bromate	12–20	10	2.5×10^{-4}	[44]
Occupied Territories	NDMA	0.015–0.025	0.01 (provisional WHO)	1.1×10^{-5}	[41]
Spain (Canary Islands)	Total (THMs)	35–50	100	Low, but follow-up required	[45]
Australia (Perth)	Bromate	<5	10	Not significant	[46]

Tables 8 and 9 indicate that exceedance of bromate limits is concentrated mainly in Gulf countries, suggesting that local operational practices and bromide-rich feedwater significantly influence DBP formation.

In some Gulf countries, some plants exceed the maximum bromate limit set by the World Health Organization, increasing the risk of cancer. In the occupied territories, NDMA levels remain low but require strict monitoring. In Spain and Australia, concentrations remain below guideline values.

Figure 9 illustrates the formation of disinfection by-products (DBPs) in desalination plant water, including bromates, trihalomethanes (THMs), and nitrosamines (NDMA) resulting from reactions between oxidants (chlorine, ozone, and chloramine) and bromide ions. Their direct discharge into the sea leads to ecosystem degradation and negatively affects biodiversity, with potential public health risks throughout the food chain.

**Figure 9.** Formation and discharge of disinfection by-products (DBPs) from desalination plants and their potential impact on marine fauna and flora.

3.7.2. Impact on the Health of Desalination Plant Workers and Technicians

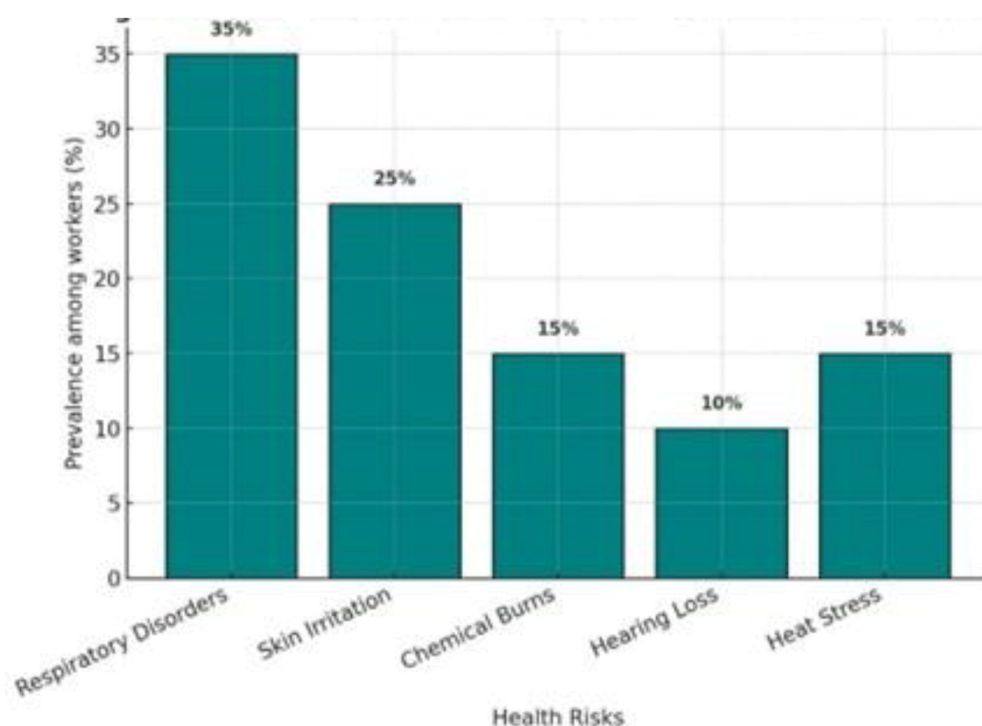
Desalination plant workers and technicians are exposed to significant chemical risks (bromates, trihalomethanes, boron, acids, and bases) that can lead to respiratory diseases, cancer, skin irritation, and poisoning. Physical stress (heat, humidity, and noise > 85 dB) can also lead to dehydration, cardiovascular and musculoskeletal disorders, and hearing impairment. Close monitoring and preventive measures are therefore necessary.

Table 10 summarizes the main chemical agents present in desalination plants, their exposure routes, and their effects on worker health.

Table 10. Main occupational exposure agents and associated health effects in desalination plants.

Source of Exposure	Agents Concerned	Route of Exposure	Adverse Health Effects
Disinfection (ozone and chlorine)	Bromates and trihalomethanes (THMs)	Inhalation; skin contact	Respiratory irritation; potential carcinogenic risk
Salt and boron discharges	Boron, chlorides, and sulfates	Skin contact; ingestion	Irritations; dermatitis; potential renal effects
Cleaning the membranes	Acids and strong bases (NaOH and H ₂ SO ₄)	Skin contact; inhalation	Chemical burns; eye injuries
Working conditions (internal climate)	High temperature, humidity, and salt spray	Heat stress; dehydration	Hypertension; fatigue; cardiovascular disorders

Figure 10 shows the various occupational hazards to which desalination plant workers are exposed, which are mainly due to chemical factors and poor working conditions.

**Figure 10.** Occupational health risks for desalination plant workers.

The figure shows that worker exposure to chemicals (chlorine, antiscalants, boron, and bromate) and saline aerosols constitute the most significant risks, surpassing noise and heat stress.

To complement the literature review, a numerical modeling case study was conducted for the Algerian Mediterranean coast (Ténès) to validate plume behavior under realistic hydrodynamic conditions.

3.8. Case Study: Numerical Modeling of Brine Dispersion—Tenes (Western Mediterranean)

3.8.1. Objectives

To enrich this review with an innovative quantitative dimension, a numerical model of the dispersion of brine discharged from a hypothetical reverse osmosis plant on the Algerian coast (Ténès) was developed. Its objectives are as follows:

- Measurement of the spatial dimension of hypersaline plumes under different hydrodynamic conditions;
- Compliance with environmental salinity thresholds by estimating the minimum dilution required;
- Development of a set of technical recommendations adapted to the Mediterranean context.

3.8.2. Simulation Methodology

The Delft3D model used a structured grid (20–50 m resolution) with tidal, current, and wind boundary conditions. Calibration relied on Mediterranean hydrodynamic data, while validation against Ténès and Tipaza observations showed deviations below 15% (RMSE).

The approach combines the following:

1. Near-field: Estimation of initial mixing using a semi-empirical model (CorJet/CORMIX).
2. Far-field: Simulation of coastal dispersion using the three-dimensional Delft3D model, integrating various elements such as tides, winds, and currents.
3. Post-processing: Development of isosalinity maps and vertical profiles to quantify the affected area ($\Delta S = +1$ and $+2$ g/L).

This methodology is consistent with recent studies conducted in the Mediterranean region [12,13,47].

3.8.3. Input Parameters

Table 11 presents the parameters adopted for the numerical simulation of brine dispersion.

Table 11. Parameters adopted for the simulation.

Setting	Value	Source
Seawater salinity (S_{sw})	38 g/L	Western Mediterranean
Brine salinity (S_{br})	76 g/L	Typical SWRO
Produced water flow rate (Q_{prod})	25 000 m ³ /day	Usine moyenne
Brine flow rate (Q_{br})	0.433 m ³ /s	R = 67%
Coastal current	0.05–0.3 m/s	Regional data
Wind	0–10 m/s	Seasonal conditions
Diffuser	Multi-nozzle, angle 20°	Good technical practice

Model validation was performed by comparing simulated plume dispersion with previous Mediterranean studies (Ténès and Tipaza). The simulated plume extension (~150 m for $\Delta S = +2$ g/L) agreed well with reported values (100–300 m), supporting model reliability.

3.8.4. Calculation of Minimum Dilution

The required dilution is given by (5):

$$D = \frac{S_{br} - S_{sw}}{\Delta S_{max}} \quad (5)$$

Example: for $S_{sw} = 38$ g/L, $S_{br} = 76$ g/L, et $\Delta S_{max} = 2$ g/L, we get:

$$D_{min} = \frac{76 - 38}{2} = 19$$

Initial dilution $\geq 19:1$, consistent with the results from Tipaza (Ténès) [12,13].

3.8.5. Simulated Scenarios

- Scenario A (medium): current 0.15 m/s.
- Scenario B (worst-case): low current 0.02 m/s.
- Scenario C (high-energy): current 0.30 m/s.
- Scenario D (attenuation): optimized diffuser + deep discharge.

Sensitivity analysis showed that current velocity most strongly affects plume dispersion; a 30% decrease increased plume length by 35%, while diffuser optimization reduced impacts by 20%.

3.8.6. Main Results

- Under average conditions, the plume (+2 g/L) extends over 150 m.

Figure 11 reveals the dispersion process of the hypersaline plume under intermediate conditions (scenario A), with iso-salinities $\Delta S = +1$ g/L and +2 g/L at $t = 24$ h.

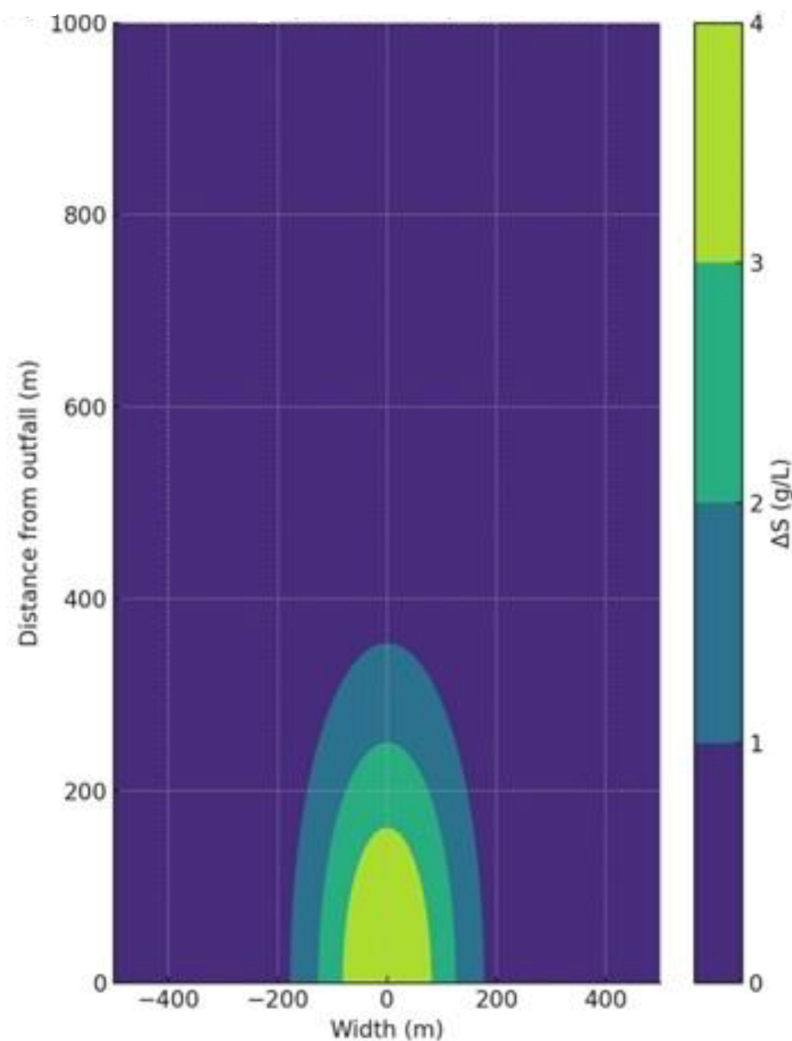


Figure 11. Salinity plume map (Scenario A, $t = 24$ h).

- In weak currents, the plume remains dense and confined, extending over more than 400 m, as shown by [12] through their simulations.

Figure 12 also provides a vertical section of the dense plume from scenario B, highlighting its tight confinement to the seabed and the accumulation of salinity $> +2$ g/L over more than 400 m.

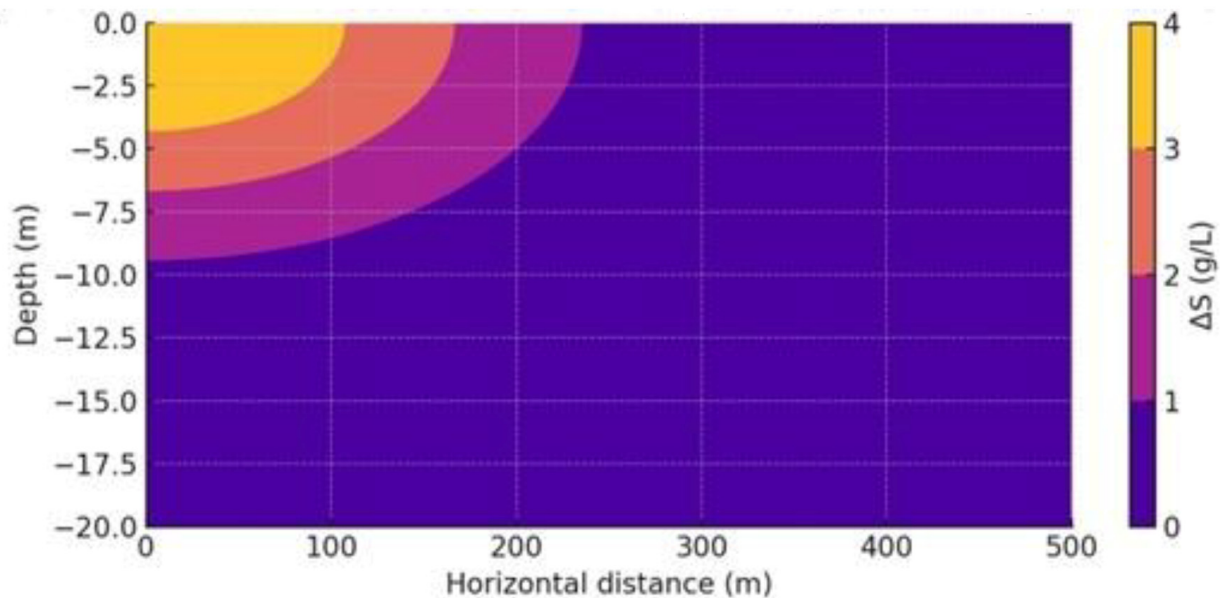


Figure 12. Vertical cross-section of the plume (Scenario B, low current).

- In strong currents, dispersion is very rapid (<100 m).
- Optimizing the diffuser (scenario D) reduces the surface area affected by $\Delta S > 2$ g/L by 35%.

Table 12 presents the surface area affected by increased salinity under the different simulated scenarios.

Table 12. Surface area affected by scenario.

Scenario	Surface $> +1$ g/L (m ²)	Surface $> +2$ g/L (m ²)
A	9500	3200
B	21,800	11,600
C	6200	1100
D	6800	2100

3.8.7. Discussion and Recent References

The results obtained confirm local studies conducted in Algeria and elsewhere [12,13,48]. The recommendations for the Maghreb region are part of the regional discussion for the Middle East and North Africa regarding the brine discharge process [16].

Figure 13 shows the evolution of the surface area affected by increased salinity ($\Delta S > 2$ g/L) as a function of current velocity. A significant decrease in the surface area of the affected zone is observed when the velocity increases from 0.02 to 0.30 m/s.

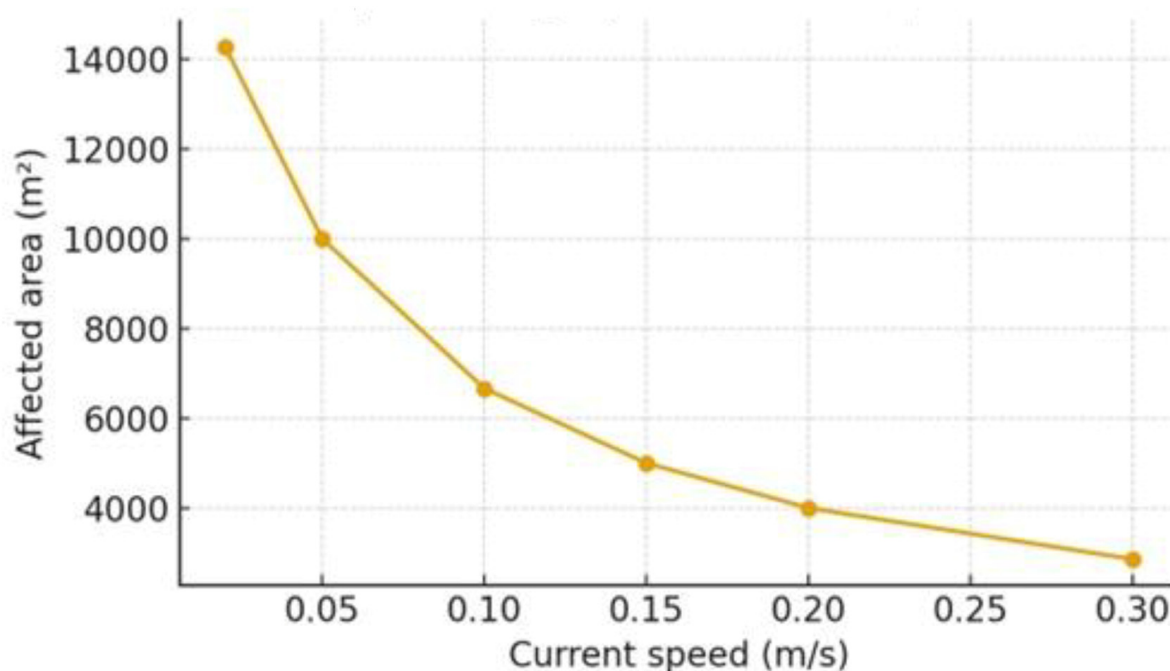


Figure 13. Sensitivity of affected area ($\Delta S > 2$ g/L) to current speed.

Model uncertainties related to boundary conditions and current variability may affect plume extent by ± 10 – 20% , so results remain representative estimates.

4. Discussion

Recent reviews addressed desalination sustainability, brine valorization, and environmental risks separately. However, few integrated health, environmental, and techno-economic aspects. This study fills this gap through PRISMA-based synthesis and numerical plume modeling. The results obtained highlight the importance of the multidimensional impacts of desalination, in addition to highlighting additional elements compared to previous international studies. The discussion of this study is structured around five axes: comparison with major international studies, examination of impacts on health and the environment, energy and the economy, regional case studies, and conclusion on the implications for governance and sustainability.

4.1. Comparison with Major International Studies

Brine impacts mainly depend on hydrodynamics, desalination technology, and discharge conditions, with weak circulation increasing ecological vulnerability. The critical limits retained ($+1$ g/L for *Posidonia oceanica*; $+2$ g/L for benthos) are consistent with the research of [4] and show the increased vulnerability associated with weak currents and thermal stratification. This study also includes a health component, showing exceedances of the WHO limit values for bromate and boron, potentially establishing a new link between chemical discharges and public health.

4.2. Health and Environmental Impacts

4.2.1. Health Impacts

Desalinated water generally meets drinking water standards, but it contains hazardous chemicals such as boron, bromate, and trihalomethanes (THMs) [37,38].

- Boron has negative effects on fertility and fetal development [34,38].

- Bromate, which is formed during the ozonation process, has been identified as a carcinogen by the Environmental Protection Agency [40,49].
- Recent studies have shown a link between respiratory and kidney disease in workers exposed to chemical cleaning products and saline sprays [43,50].

4.2.2. Impacts on Aquatic Life

Discharges of highly saline waters laden with chemicals (chlorine, biocides, and antiscalants) alter salt layers, posing a threat to benthic biodiversity [32,51].

Figure 14 illustrates the range of environmental impacts of brine discharges: habitat destruction, plankton/larval capture, and the spread of hypersaline and chemical clouds.

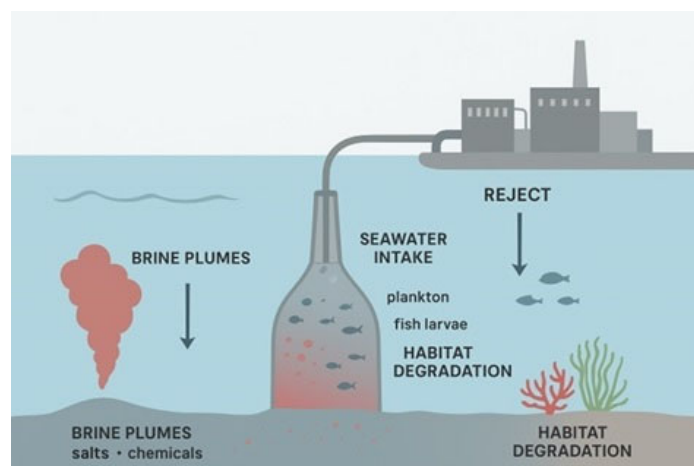


Figure 14. Impacts of desalination plants on aquatic life.

- In the Mediterranean region, this phenomenon leads to an increase in the mortality rate of *Posidonia oceanica* and other sensitive species [6,52,53].
- In the Red Sea, increased salinity causes rapid deterioration of coral reefs [28].
- Suction systems installed in stations result in the destruction of large quantities of plankton and fish larvae, causing an imbalance in food webs [51,53].

Our numerical simulations show that under low-current conditions (<0.05 m/s), the area affected by $\Delta S > 2$ g/L can reach 300 m wide, while in areas with strong hydrodynamics, the dilution can be less than 50 m.

4.3. Energy and Economic Considerations

Seawater reverse osmosis (SWRO) remains the most efficient technology, with an energy consumption of 3–4 kWh/m³, compared to 10–15 kWh/m³ for thermal processes (MSF and MED) [8,10].

The levelized cost of desalinated water is relatively high, between USD 0.6 and USD 1.5 per cubic meter, which constitutes a barrier to widespread adoption of this technology, particularly in countries that rely heavily on fossil fuels to power desalination plants. However, relying on the latest technological developments and integrating renewable energies (notably photovoltaic and wind), as well as the use of new generation pressure exchangers, makes it possible to reduce the total energy consumption of the stations by around 30 to 40%, which reduces the carbon footprint and strengthens environmental and economic sustainability [53].

4.4. Regional Case Studies

The inclusion of case studies is essential to illustrate specific challenges and the solutions adopted:

- Algerian Mediterranean: Adoption of multi-jet diffusers to protect *Posidonia oceanica* meadows.
- Arabian Gulf: Major degradation of coral reefs with discharge salinity reaching 70–80 g/L; regional programs integrating nanostructured membranes and renewable energy [10,35].
- Australia: Perth SWRO plant powered by a wind farm, reducing energy consumption by 35% thanks to energy recovery [54].
- Morocco (Chtouka): Solar–reverse osmosis combination producing 275,000 m³/day, reducing costs and emissions.
- Chile: Implementation of brine mining, valorizing brine by extracting lithium and magnesium [55].

4.5. Implications for Sustainability and Governance

To assess the sustainability of desalination, this study presents a comprehensive framework that combines environmental, health, and economic dimensions [55]. This report highlights the need for integrated regional governance, inspired by the European Water Framework, to standardize the management of transboundary discharges and plumes [16]. Efforts to integrate emerging technologies such as artificial intelligence and remote sensing can improve real-time monitoring and adaptive discharge management, helping to address the gaps identified by [4,22].

4.6. Novelty and Scientific Contribution

This study combines all of the following elements in its integrated approach:

- Hydrodynamic modeling using CORMIX and Delft3D for plume dispersion.
- Conduct health analyses based on recent epidemiological data [8].
- Economic and energy assessment (LCOW and SEC).
- Innovation prospects through brine valorization.

Unlike traditional reviews, this study provides a detailed regional view of North Africa and addresses a gap identified in the scientific literature [56].

While the results demonstrate the importance of desalination for water security, it must evolve towards sustainable models that integrate

- Work to reduce environmental impacts through strict standards and improved technologies [52];
- Work to reduce health risks associated with chemical by-products;
- Work toward integrating renewable energy in an effort to reduce the carbon footprint;
- Work toward regional cooperation and organizational harmony.

This comprehensive approach paves the way for sustainable desalination technology, combining water security, public health, and biodiversity conservation.

Unlike previous reviews focused on isolated aspects, this study provides an integrated assessment combining environmental, health, energy, and economic dimensions, supported by numerical plume modeling.

4.7. Recommendations and Outlook

This study presents an integrated approach to health, environmental, economic, and energy factors, clarifying their interactions. This approach aims to guide research and policy toward sustainable desalination, based on innovation, governance, and multidisciplinary assessments of brine discharges.

1. High-resolution environmental monitoring: Numerical models must be complemented with the deployment of independent sensors for salinity, temperature, and

dissolved oxygen to ensure uncertainty reduction and validate simulations in real time [12,13].

2. Remote Sensing and GIS: GIS tools, combined with satellite imagery, enable continuous monitoring and mapping of hypersaline plume dynamics [15].
3. Artificial Intelligence and Predictive Modeling: Integrating machine learning and neural networks into hydrodynamic models can improve plume prediction under extreme conditions, enhancing desalination potential [57].
4. Life Cycle Assessment (LCA): Future research should use life cycle assessment to assess the overall impact of desalination, including the energy, climate, and environmental impacts of brine discharge [28].
5. Brine Valorization: Investment is needed in research to extract brine solutions to benefit from salts, magnesium, or lithium, to convert waste into resources and reduce discharge concentrations [55].
6. A comprehensive, integrated approach: Global scientific and institutional cooperation is essential to ensure the development of common strategies and rational management of desalination impacts through shared research and databases [57].

Although brine impacts are widely recognized, methodological differences between studies limit direct comparison and call for standardized monitoring protocols. Finally, desalination should not be viewed as a simple technical solution but rather as a transitional technology that combines innovation, sustainability, and social justice to preserve health, biodiversity, and the economy.

5. Conclusions

The massive expansion of desalination capacity is an inevitable response to the worsening global water scarcity crisis. However, this study systematically demonstrates that this solution requires several multidimensional trade-offs in terms of biodiversity conservation, public health, sustainability, and economics. Using the PRISMA methodology to synthesize 45 studies, we reveal that brine discharges, characterized by hypersalinity (40–75 g/L) and the presence of chemical residues, pose a significant threat to diverse marine ecosystems, including sensitive benthic communities and *Posidonia oceanica* meadows. Regarding public health, the presence of pollutants such as boron and bromate in drinking water, whose concentrations can exceed the World Health Organization's permitted limits in many regions, poses a health risk to consumers and can even lead to cancer. Furthermore, factory workers are exposed to significant occupational and health risks. The originality of our systematic review lies in its integrated assessment framework, which simultaneously analyzes potential risks across health, environmental, energy, and economic dimensions—a comprehensive approach that is perhaps under-addressed and often fragmented in the existing literature. Furthermore, the inclusion of a regional case study using advanced hydrodynamic modeling (CORMIX and Delft3D) for the Algerian coast provides a tangible and quantitative illustration of brine dispersion dynamics. Simulation results performed on Ténès show that under low-current conditions (<0.05 m/s), a minimum initial dilution ratio of 19:1 is necessary to contain the increase in salinity below the critical threshold of +2 g/L, above which significant environmental damage is caused. This modeling process not only validates the results of other regional studies but also provides a systematic method that can be replicated in other regions to predict and mitigate impacts. The results of this study also conclusively demonstrate that the future of sustainable desalination cannot rely solely on water production using various technologies; rather, it requires a qualitative shift toward integrated governance and innovation. This includes rigorous and science-based regulation, technology-driven mitigation, and the valorization of brine as a strategic imperative.

Author Contributions: E.B. contributed to conceptualization, methodology, formal analysis, investigation, visualization, and writing—original draft, while C.R. was responsible for supervision, project administration, validation, and writing—review and editing. Y.B. contributed to data curation, resources, formal analysis, validation, and writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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

References

1. Khanzada, N.K.; Al-Juboori, R.A.; Ibrahim, Y.; Khatri, M.; Ahmed, F.; An, A.K.; Hilal, N. Desalination and the Middle East: Research, practices, implications, and prospects. *npj Clean. Water* **2026**, *9*, 21. [\[CrossRef\]](#)
2. Lanter, A.M.; Svetanoff, R.; Wars, D.M. Maximizing water recovery from reverse osmosis for agricultural brine reuse in Kenya. *Agric. Water Manag.* **2024**, *298*, 108910. [\[CrossRef\]](#)
3. Le, T.X.H.; Xiang, Y.; Chii, S.; Chuanjing, L.; Wang, K. Tracing disinfection byproducts during shock chlorination of a seawater reverse osmosis (RO) desalination pilot and the blended and chlorinated potable water produced. *Desalination* **2025**, *609*, 118861. [\[CrossRef\]](#)
4. Lee, J.; Lee, S. Challenges, opportunities, and technological advances in desalination brine mining: A mini review. *Adv. Ind. Eng. Chem.* **2025**, *1*, 7. [\[CrossRef\]](#)
5. Chowdhury, S. Evaluation and strategy for improving the quality of desalinated water. *Environ. Sci. Pollut. Res.* **2023**, *30*, 65947–65962. [\[CrossRef\]](#)
6. Ruso, Y.; de la Huz, R.; González, R.; Drake, P. Effects of a brine discharge over soft-bottom polychaeta assemblages from the western Mediterranean. *Mar. Pollut. Bull.* **2020**, *150*, 110728.
7. Elsaid, K.; Kamil, M.; Sayed, E.T.; Abdelkareem, M.A.; Wilberforce, T.; Olabi, A.G. Environmental impact of desalination technologies: A review. *Sci. Total Environ.* **2020**, *748*, 141528. [\[CrossRef\]](#) [\[PubMed\]](#)
8. Filippini, G.; Al-Obaidi, M.A.; Manenti, F.; Mujtaba, I.M. Design and economic evaluation of solar-powered hybrid multi effect and reverse osmosis system for seawater desalination. *Desalination* **2019**, *465*, 114–125. [\[CrossRef\]](#)
9. Al Shehhi, M.; Song, H.; Scott, J.; Abdul Gafoor, F.; Marshall, J. Impact of desalination on the general circulation of the Arabian Gulf: Present and future scenarios. *Mar. Pollut. Bull.* **2025**, *221*, 118520. [\[CrossRef\]](#) [\[PubMed\]](#)
10. International Energy Agency (IEA). *World Energy Outlook 2021*; International Energy Agency: Paris, France, 2021.
11. Patel, D.; Ankoliya, D.; Raninga, M.; Mudgal, A.; Patel, V.; Patel, J.; Mudgal, V.; Choksi, H. Design methodology for forward osmosis system. *Environ. Sci. Pollut. Res.* **2025**, *32*, 30263–30286. [\[CrossRef\]](#)
12. Bouthiba, M.; Amitouche, M.; Moudjeber, D.; Mahmoudi, H.; Goosen, M. Simulation study of the interaction between brine discharge and catchment water of a desalination plant in Tenes, Algeria under various hydrodynamic conditions. *Desalin. Water Treat.* **2022**, *279*, 16–28. [\[CrossRef\]](#)
13. Adem, A.; Bachari, F.; Hamdi, B.; Belkacem, Y. Assessment of coastal water characteristics near brine discharge sites by applying multivariate statistical techniques and GIS, case study from BouIsmaïl Bay, Algeria. *Model. Earth Syst. Environ.* **2024**, *10*, 1727–1748.
14. Gupta, P.; Arciniegas-Pérez, M.D.; Barrios-Piña, H.A. Impact of brine discharge from desalination plants on marine ecosystems: A review. *Curr. Opin. Environ. Sci. Health* **2026**, *49*, 100693. [\[CrossRef\]](#)
15. Sola, I.; Carratalá, A.; Pereira-Rojas, J.; Díaz, M.J.; Rodríguez-Rojas, F. Assessment of brine discharges dispersion for sustainable management of SWRO plants on the South American Pacific coast. *Mar. Pollut. Bull.* **2024**, *207*, 116905. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Athwal, E.; Dimitropoulos, G.; Olawuyi, D.; Weber, A.; Al-Sehlawi, R.; Mohamed, A.; Amato, A.; Chatziefthimiou, A. International and National Environmental Laws and Ethics. In *Pathways to Nature Conservation and Resilience in Hot and Arid Lands*; Chatziefthimiou, A.D., Amato, A., Castro de la Mata, G., Al-Kuwari, M., Eds.; Springer: Cham, Switzerland, 2026.
17. Ghanimeh, S.; Dalloul, M.; Al-Naimi, M.; Almomani, F.; Hassan, H.; Semerjian, L.; Tariq, A. Seawater Pollution in the Arabian Gulf: Unveiling Risks and the Urgent Need for Local Standards. *Earth Syst. Environ.* **2026**, *10*, 1649–1663.
18. Blanco-Murillo, F.; Marín-Guirao, L.; Sola, I.; Rodríguez-Rojas, F.; Ruiz, J.M.; Sánchez-Lizaso, J.L.; Sáez, C.A. Desalination brine effects beyond excess salinity: Unravelling specific stress signaling and tolerance responses in the seagrass *Posidonia oceanica*. *Chemosphere* **2023**, *341*, 140061. [\[CrossRef\]](#) [\[PubMed\]](#)
19. Grammatiki, K.; de Jonge, N.; Küpper, F.C. Environmental impact of brine from desalination plants on marine benthic diatom diversity. *Mar. Environ. Res.* **2025**, *210*, 107207. [\[CrossRef\]](#) [\[PubMed\]](#)

20. Oraby, H.; Ezz, A.A.; Hegazy, G.E. Advances in desalination: Pioneering methods and the future of water sustainability. *Discov. Water*. **2025**, *5*, 88. [\[CrossRef\]](#)
21. Almajali, T.A.H.; Ismail, F.B.; Gunnasegaran, P.A.; Kazem, H.; Al Shurafa, S.; Al-Muhsen, N. Solar-powered advances in water desalination: A comprehensive review of recent research. *Appl. Sol. Energy* **2025**, *61*, 117–145. [\[CrossRef\]](#)
22. Jones, E.; Qadir, M.; van Vliet, M.T.H.; Smakhtin, V.; Kang, S.M. The state of desalination and brine production: A global outlook. *Sci. Total Environ.* **2019**, *657*, 1343–1356. [\[CrossRef\]](#) [\[PubMed\]](#)
23. Al-Karaghoul, A.; Kazmerski, L.L. Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes. *Renew. Sustain. Energy Rev.* **2013**, *24*, 343–356. [\[CrossRef\]](#)
24. Usman, M.; Sharma, D.D.; Ernst, M. Seawater and Brackish Water Desalination. In *Powerfuels*; Bullerdiek, N., Neuling, U., Kaltschmitt, M., Eds.; Springer: Cham, Switzerland, 2025.
25. Maki, A.; Pedrero, F.; Hafsi, M.; Guerber, F. *Desalination for Agriculture Development: Addressing Opportunities and Challenges in the Context of Changing Climate and the Global Agricultural Commodity Market—Expert Consultation Workshop Report*; FAO: Tunis, Tunisia, 2025.
26. El-Gendi, A.; Wu, H.; Firdaous, L.; Ullah, N.; Gong, G. Progress and exploring the impact of nanomaterials in membranes for water desalination. *J. Mater. Sci.* **2026**, *61*, 5067–5104. [\[CrossRef\]](#)
27. Prashanth, G.K.; Akolkar, H.N.; Haghi, A.K.; Rao, S. Environmental impacts of desalination. In *Seawater Desalination*; Springer: Cham, Switzerland, 2026.
28. Song, H.; Meng, H.; Guan, J. Ecological impact of desalination brine: A comparative analysis of laboratory tests and field investigations. *Desalin. Water Treat.* **2025**, *324*, 101518. [\[CrossRef\]](#)
29. Roberts, D.A.; Johnston, E.L.; Knott, N.A. Impacts of desalination plant discharges on the marine environment: A critical review of published studies. *Water Res.* **2019**, *148*, 256–279.
30. Sola, I.; Fernández-Torquemada, Y.; Forcada, A.; Valle, C.; del Pilar-Ruso, Y.; González-Correa, J.M.; Sánchez-Lizaso, J.L. Sustainable desalination: Long-term monitoring of brine discharge in the marine environment. *Mar. Pollut. Bull.* **2021**, *161*, 111813.
31. De Serio, F.; De Padova, D.; Mossa, M. Brackish water vs. brine outfall: Impact of desalination plant discharge in vulnerable coastal sites. *Desalination* **2025**, *615*, 119291. [\[CrossRef\]](#)
32. Missimer, T.M.; Maliva, R.G. Environmental issues in seawater reverse osmosis desalination: Intakes and outfalls. *Desalination* **2018**, *434*, 198–215. [\[CrossRef\]](#)
33. Urdánigo, D.A.; Cedeño Laje, J.A.; Torres Cano, J.N.; Mendez Ruiz, J.I.; Goyburo Chávez, C.S.; Jimenez Oyola, S.; Valverde Armas, P. Reverse osmosis pilot plant to produce drinking water in Chanduy community of Santa Elena province-Ecuador. In Proceedings of the 21st LACCEI International Multi-Conference for Engineering, Education and Technology (LACCEI 2023): Leadership in Education and Innovation in Engineering in the Framework of Global Transformations: Integration and Alliances for Integral Development, Buenos Aires, Argentina, 17–21 July 2023.
34. Al-Rawajfeh, A.; Alzalabieh, E.; Al Bazedi, G.; Al-Mazaideh, G.; Shalayel, M. A review on harmful algae blooms in Arabian Gulf: Causes and impacts on desalination plants. *Desalin. Water Treat.* **2023**, *290*, 46–55. [\[CrossRef\]](#)
35. Shalby, A.; Emara, S.R.; Elmenshawy, M.R.; Fayad, S. Techno-economic assessment of brackish groundwater desalination for irrigation in arid regions: A case study from the Moghra aquifer, Egypt. *Appl. Water Sci.* **2026**, *16*, 73. [\[CrossRef\]](#)
36. Jiang, Y.; Zang, S.; Ma, J. Occurrence, toxicity, and control of halogenated aliphatic and phenolic disinfection byproducts in the chlorinated and chloraminated desalinated water. *Water Res.* **2025**, *268*, 122566. [\[CrossRef\]](#) [\[PubMed\]](#)
37. Duan, L.; Wang, C.; Tang, S. Effects of desalinated seawater with excessive boron on reproductive health of male rats. *Environ. Technol. Innov.* **2023**, *32*, 103310. [\[CrossRef\]](#)
38. Fujioka, T.; Ngo, M.T.T.; Boivin, S.; Kawahara, K.; Takada, A.; Nakamura, Y.; Yoshikawa, H. Controlling biofouling and disinfection by-product formation during reverse osmosis treatment for seawater desalination. *Desalination* **2020**, *496*, 114735.
39. Rezaei, L.; Alipour, V.; Dehghani Ghantghestani, M. Environmental health risk of brine disposal for reverse osmosis water desalination plants: A case study in Bandar Abbas city, Iran. *Reg. Stud. Mar. Sci.* **2024**, *77*, 103606. [\[CrossRef\]](#)
40. Brugger, C.; Owen, B.N.; Abu Hamad, B.; Gastel, T.; Sittaro, F.; Rossi, R.; Probst-Hensch, N.; Winkler, M. Drinking water access and quality in the Gaza Strip prior to 7 October 2023 and implications for reconstruction. *Environ. Health* **2025**, *24*, 41. [\[CrossRef\]](#) [\[PubMed\]](#)
41. Richardson, S.D.; Plewa, M.J. To regulate or not to regulate? What to do with more toxic disinfection by-products. *Environ. Health Perspect.* **2020**, *128*, 115001.
42. Nriagu, J.; Darroudi, F.; Shomar, B. Health effects of desalinated water: Role of electrolyte disturbance in cancer development. *Environ. Res.* **2016**, *150*, 191–204. [\[CrossRef\]](#) [\[PubMed\]](#)
43. Zhou, Y.Y.; Yuan, C.J.; Wu, Z.J.; Zhang, J.; Xu, B.; Cao, J.; Lee, M.; Chen, Z.; Du, Y. Bromide and its associated brominated disinfection byproducts: Occurrence, toxicity and control strategies. *Front. Environ. Sci. Eng.* **2025**, *19*, 8.

44. Ahmed, L.; Darestani, M.; Chilcott, T. Feasibility of integrating pressure retarded osmosis technology within desalination facility in Sydney, Australia. In *4th International Conference on Water and Environmental Engineering (iCWEE 2025) Lecture Notes in Civil Engineering*; Rahman, A., Ouarda, T.B.M.J., Muhitir Rahman, M., Hagare, D., Siddiqui, Z., Eds.; Springer: Cham, Switzerland, 2026; Volume 822.
45. Amokrane, M.; Salmi, A. Surface spreading of the brine discharge from the seawater reverse osmosis plants: Hamma Water Desalination plant in Algeria. *Desalin. Water Treat.* **2021**, *222*, 81–91. [[CrossRef](#)]
46. US Environmental Protection Agency (EPA). CAS No. 15541-45-4; Toxicological Review of Bromate. U.S. EPA: Washington, DC, USA, 2020.
47. Sawyer, W.E.; Ovuru, K.F.; Etim, N.G.; El-Liethy, M.A. Water quality management: Processes influencing waterborne diseases and sustainable solutions. In *Innovative Approaches in Environmental Health Management*; Chibueze Izah, S., Chidozie Ogwu, M., Eds.; Springer: Cham, Switzerland, 2025.
48. Jalili, A.; Kolliopoulos, G. A review of fundamentals, challenges, prospects, and emerging trends in hydrate-based desalination. *npj Clean. Water* **2025**, *8*, 52. [[CrossRef](#)] [[PubMed](#)]
49. Bencheikh, I.; Azoulay, K.; Mohammed, B.; Rachiq, T.; Mabrouki, J. Environmental footprint of water desalination: Addressing desalination environmental impact amidst the water crisis. In *Advanced Technology for Smart Environment and Energy*; Mabrouki, J., Mourade, A., Eds.; Springer: Cham, Switzerland, 2024.
50. Bali, M.; Ghanem, S. Assessment and simulation of brine discharge impact from a seawater desalination plant on the Mediterranean marine environment. *Int. J. Environ. Sci. Technol.* **2025**, *22*, 9337–9346.
51. World Health Organization (WHO). *Guidelines for Drinking-Water Quality*, 4th ed.; Incorporating the 1st Addendum; WHO Press: Geneva, Switzerland, 2017.
52. Shukla, S.; Gupta, U.; Jindal, T. Insights into nanofiltration and reverse osmosis membranes for water purification. In *Nano-Solutions for Sustainable Water and Wastewater Management*; Garg, M.C., Rajput, V.D., Minkina, T., Himanshu, S.K., Eds.; Springer: Cham, Switzerland, 2025.
53. Mohammed, A.; Alsagheer, F.; Ghaithan, A.M.; Mazher, K.M. An optimization of hybrid renewable energy system for seawater desalination in Saudi Arabia. *Int. J. Environ. Sci. Technol.* **2025**, *22*, 4463–4480.
54. Panagopoulos, A.; Haralambous, K.J.; Loizidou, M. Desalination brine disposal methods and treatment technologies—A review. *Sci. Total Environ.* **2019**, *693*, 133545. [[CrossRef](#)] [[PubMed](#)]
55. Venkatesh, M.; Scott, J.; Chakravarty, T.C.; Rehm, T.E.; Basu, S. Environment, Health and Safety, Security and Regulations. In *Water Management in Petroleum Industries*; Basu, S., Shaw, A.R., Venkatesh, M., Eds.; Springer: Singapore, 2025.
56. Ganesapillai, M.; Vinayak, A.K.; Tiwari, A.; Darda, A.; Chindalia, K.; Chellapandi, T. Beyond the flush: A review of wastewater circular systems. *npj Clean. Water* **2026**, *9*, 31. [[CrossRef](#)]
57. Kuralov, M.A.; Halimov, A.; Usmanov, A.; Juraev, T.; Khaitmukhamedov, A.; Jalilov, D.; Sayfieva, K.; Abdulkhaev, O.; Abdurakhmonov, O.; Lutpullaev, S.; et al. Analysis of the current status and research prospects for integrating nanomaterials into the membrane surfaces of membrane-based desalination systems using renewable energy sources. *Appl. Sol. Energy* **2025**, *61*, 680–714. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.