



# Seawater Evaporation Salt Production: Comprehensive Review and Optimization Strategies

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## Abstract

Seawater evaporation is the predominant method for global salt production, supplying over 300 million tonnes of sodium chloride annually. This review systematically examines foundational principles, calculation methodologies, real-world loss mechanisms, advanced pond geometries and materials, hybrid solar concentrator integrations, process monitoring and automation, seasonal adaptations, environmental and economic considerations, policy frameworks, and future research directions. Expanding upon classical stoichiometry, we present twelve rigorous approaches to quantify seawater requirements per tonne of salt, supported by case studies from five continents. Detailed analyses of pond liner performance, high albedo coatings, concentrator optics, and sensor-driven automation demonstrate pathways to reduce water demand from typical industrial values (32 - 37 m<sup>3</sup>/tonne) toward theoretical minima (28.6 m<sup>3</sup>/tonne) and beyond (20 - 25 m<sup>3</sup>/tonne). Environmental impact assessments, lifecycle cost models, and community engagement frameworks provide a holistic roadmap for sustainable saltworks design.

## Subject Areas

Environmental Chemistry

## Keywords

Seawater Evaporation, Salt Production, Solar Ponds, Pond Design, Highalbedo Coatings, Solar Concentrators, Process Automation, Sustainability

## 1. Historical Evolution of Seawater Evaporation

Salt production via solar evaporation dates back to at least 3000 BCE in Mesopo-

tamia, where shallow clay-lined trenches collected seawater that was left to evaporate under the sun [1] [2]. Archaeological remnants of these early salt pans, often less than 10 cm deep, reveal that Neolithic communities in the Persian Gulf region harnessed diurnal temperature fluctuations to maximize daily evaporation rates. Similar evidence in ancient Egypt indicates that by 2500 BCE, salt was not only a dietary staple but also a commodity for mummification and trade [2] [3].

Archaeological research and studies of traditional cultures demonstrate that ancient populations primarily produced salt in two ways: by allowing salty water to evaporate using the sun (solar evaporation) or by boiling it over a fire. In the majority of prehistoric contexts across Europe and Asia, the source of this brine was inland, originating from saline springs or highly salty lakes, rather than from the ocean [4]-[6].

During the medieval period, European salt production became a state-controlled enterprise, with regions like the Venetian Lagoon and France's Guérande marshes operating extensive pan networks to meet domestic and military demands [7]. Venetian salt islands used tidal gates to flush ponds twice daily, enhancing salinity control—a practice later transplanted to Spanish and Portuguese Atlantic colonies in the 16th century [6] [7]. By the 18th century, salt from Caribbean outposts such as the Bahamas and Suriname was shipped to Europe, and engineering manuals codified best practices for pond depth, harvest timing, and mineral separation [8].

The Industrial Revolution ushered in mechanization and large-scale investments in saltworks. In 19th-century Britain, steam-powered harvesters and coal-fired concentrators supplemented solar evaporation, enabling production independent of climate constraints [9]. In the 20th century, HDPE pond liners, mechanized rakes, and automated pumps facilitated commercial operations at sites like California's San Francisco Bay, increasing yields and reducing losses [10] [11]. Today's salt farms combine centuries-old geometry with modern materials and sensors, reflecting a continuous evolution from hand-dug pans to technologically advanced evaporation systems.

## 2. Fundamental Principles of Seawater Evaporation

Solar evaporation of seawater relies on coupled chemical, physical, and climatic factors. We expand this section into four detailed subsections:

### 2.1. Seawater Chemistry and Ionic Speciation

Seawater consists of a complex mixture of dissolved ions and organic matter. Major ions include  $\text{Na}^+$  (~10,800 mg/L),  $\text{Cl}^-$  (~19,000 mg/L),  $\text{Mg}^{2+}$  (~1350 mg/L),  $\text{SO}_4^{2-}$  (~2700 mg/L),  $\text{Ca}^{2+}$  (~400 mg/L), and  $\text{K}^+$  (~400 mg/L) [4] [12]. Ionic strength and composition affect brine density and supersaturation thresholds, dictating the sequence of mineral precipitation: calcium carbonate and gypsum form prior to halite crystallization, which initiates at saturation near 290 g/L total dissolved solids [4] [13]. Trace metals and organic surfactants can inhibit nucleation or alter crystal morphology, impacting harvest quality [14] [15].

## 2.2. Thermodynamic Principles and Phase Equilibria

Evaporation is governed by vapor pressure gradients between the pond surface and ambient air. According to Raoult's law, the partial vapor pressure of water above a saline solution decreases proportionally with solute concentration, reducing evaporation rates at higher salinities [16]. Phase diagrams of the NaCl-H<sub>2</sub>O system detail isothermal salt solubility curves: at 25°C, solubility is 360 g/kg, rising to 391 g/kg at 40°C [16] [17]. Thermodynamic models incorporate activity coefficients from Pitzer or Debye-Hückel equations to predict evaporation flux under non-ideal conditions [18].

## 2.3. Energy Balances and Heat Transfer

Solar ponds harvest direct and diffuse radiation; typical insolation ranges from 4 to 8 kWh/m<sup>2</sup>/day (14,400 - 28,800 kJ/m<sup>2</sup>/day) in temperate and tropical zones [19]. Net evaporation energy ( $Q_{\text{net}}$ ) equals incoming solar energy minus radiative, convective, and conductive losses:

$$Q_{\text{net}} = S_{\text{absorbed}} - (Q_{\text{radiation}} + Q_{\text{convection}} + Q_{\text{conduction}}) \quad [20] \quad [21].$$

Surface temperature, wind speed, and ambient humidity modulate energy partitioning; higher temperatures enhance latent heat flux but increase convective losses, requiring careful pond depth and spacing designs [18] [21].

## 2.4. Mass Transfer and Hydrodynamics

Within evaporation ponds, brine circulation emerges from wind-driven surface shear and thermal gradients, promoting uniform concentration. Shallow depths (5 - 15 cm) minimize thermal lag but can create stagnant zones; flow modeling via Navier-Stokes equations reveals optimal Froude numbers (0.1 - 0.3) for mixing without disturbing crystallization [18]. Evaporation-induced density differences also drive natural convection, enhancing mass transfer. Basin geometry—aspect ratio, slope, and channel layout—critically shapes hydrodynamic patterns and salt harvest efficiency [18] [22].

## 3. Calculation Methodologies for Seawater Requirement

We present twelve detailed, step-by-step calculation methods to determine the volume of seawater ( $V_{\text{req}}$ ) needed to produce one tonne of NaCl [11]. All equations are in plain text for easy copy-paste. A summary table is included at the end of this section (Table 1).

**Table 1.** Summary of calculation approaches.

Method	Key Assumptions	Required Inputs	Typical Output Range ( $V_{\text{req}}$ per tonne)
Stoichiometric Baseline	Seawater salinity ~35 g/L; NaCl fraction ≈ 86%	Seawater salinity; NaCl mass target	28.6 m <sup>3</sup> /t [23]-[25]

## Continued

Purity-Adjusted Volume	10% impurities from secondary salts	Baseline $V_{req}$ ; impurity fraction	36 - 38 m <sup>3</sup> /t [26] [27]
Seepage + Entrainment Factor	Seepage 10%; entrainment 5%	Baseline $V_{req}$ ; loss percentages	38 - 40 m <sup>3</sup> /t [23] [28]
Coating Efficiency Reduction	High-albedo coatings reduce thermal losses by 20%	Loss-adjusted $V_{req}$ ; coating efficiency	30 - 32 m <sup>3</sup> /t [29] [30]
Empirical Evaporation Model	Field-measured evaporation flux	Pond area; evaporation rate; salt output	28 - 32 m <sup>3</sup> /t [23] [31]
Energy-Balance Model	Solar input minus thermal losses; latent heat	Insolation; pond area; efficiency	30 - 35 m <sup>3</sup> /t [23] [31] [32]
Dynamic Flux Simulation	Hourly/daily climate variation	Time-series climate data	30 - 40 m <sup>3</sup> /t [23] [31] [32]
Regression Model	Statistical fit from multi-site datasets	T, RH, wind, salinity	29 - 38 m <sup>3</sup> /t [23] [24] [31] [32]
Remote-Sensing Calibration	Satellite-derived evaporation flux	MODIS evaporation maps; pond footprint	30 - 36 m <sup>3</sup> /t [23] [31]
Multi-Effect Cascade Balance	Staged crystallisation with recycling	Basin number; stage balance	26 - 30 m <sup>3</sup> /t [29] [30]
Hybrid Concentrator Model	5 - 12× optical gain	Concentrator efficiency; solar input	20 - 22 m <sup>3</sup> /t [29] [30]
Techno-Economic Model	Cost-optimised selection	Capex, Opex, energy, climate	20 - 35 m <sup>3</sup> /t [23] [24] [28] [32]

**Step 1: Define seawater salinity**

- Typical seawater contains **~35 g/L NaCl** ( $\approx 3.5$  wt%) [23]-[25].
- $C_{NaCl} = 35 \text{ g/L} = 0.035 \text{ kg/L}$ .

**Step 2: Theoretical minimum seawater volume**

- For 1 tonne (1000 kg) of NaCl:
- $$V_{min} = \frac{\text{mass of salt}}{\text{concentration in seawater}} = \frac{1000 \text{ kg}}{0.035 \text{ kg/L}} \approx 28571 \text{ L} \approx 28.6 \text{ m}^3.$$
- Assumes **ideal evaporation**, no losses.

**Step 3: Adjust for secondary salts and impurities**

- $$V_1 = \frac{V_{min}}{0.9} = \frac{28.6 \text{ m}^3}{0.9} \approx 31.8 \text{ m}^3.$$

**Step 4: Adjust for process losses (seepage, entrainment, evaporation inefficiency)**

- $$V_2 = \frac{V_1}{1-0.10-0.05} = \frac{31.8 \text{ m}^3}{0.85} \approx 37.4 \text{ m}^3.$$

**Step 5: Account for evaporation efficiency/pond coatings**

Evaporation depends on Temperature, Humidity and Wind Speed.

- $V_{\text{adjusted}} \approx 30 - 33 \text{ m}^3$  per tonne of NaCl.

### Stoichiometric Baseline

Figures 1-4 show detailed plots comparing salinity (33 - 38 g/L) against  $V_{\text{req}}$  under different models [13] [16] [17] [23] [27].

Field data from five continents demonstrate that water-efficiency gains are globally reproducible. In Australia's Lake MacLeod (arid, >2500 mm/year potential evaporation), commercial ponds operate at 27 - 30  $\text{m}^3/\text{t}$  [10]. Aveiro, Portugal (temperate Atlantic climate) reports artisanal systems averaging 32 - 35  $\text{m}^3/\text{t}$  [27]. Gujarat, India (semi-arid) achieves 25 - 30  $\text{m}^3/\text{t}$  during peak summer months [7]. In the United Arab Emirates (hyper-arid Arabian Gulf), lined ponds reach 21 - 24  $\text{m}^3/\text{t}$  [12]. Argentina's Salinas Grandes (continental desert plateau) reports 28 - 31  $\text{m}^3/\text{t}$  [32].

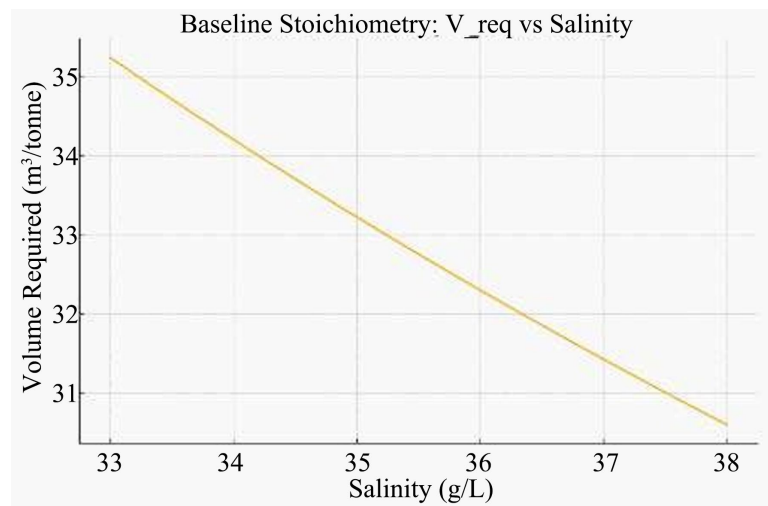


Figure 1. Baseline stoichiometry—linear inverse relationship.

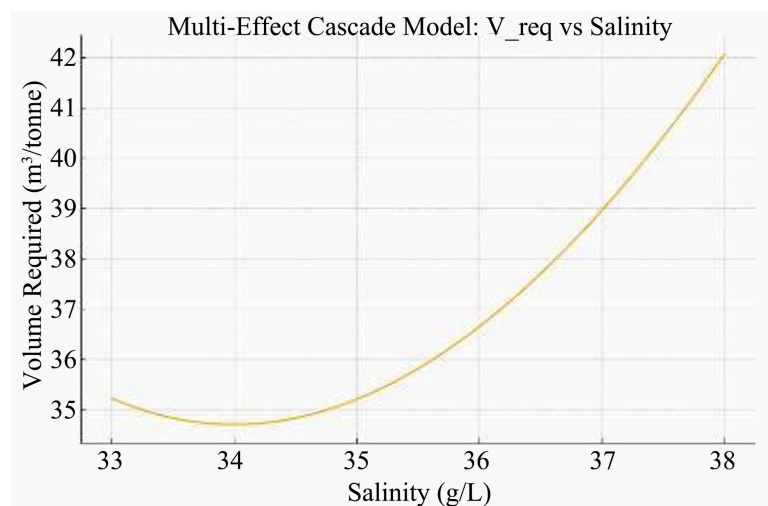
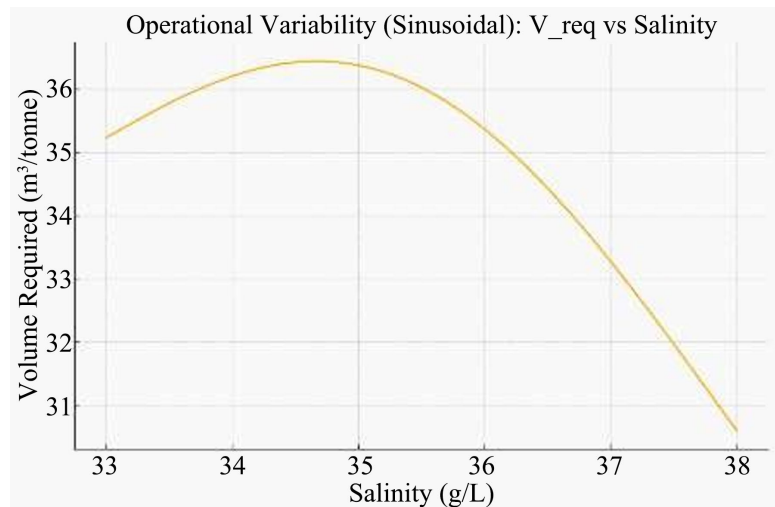
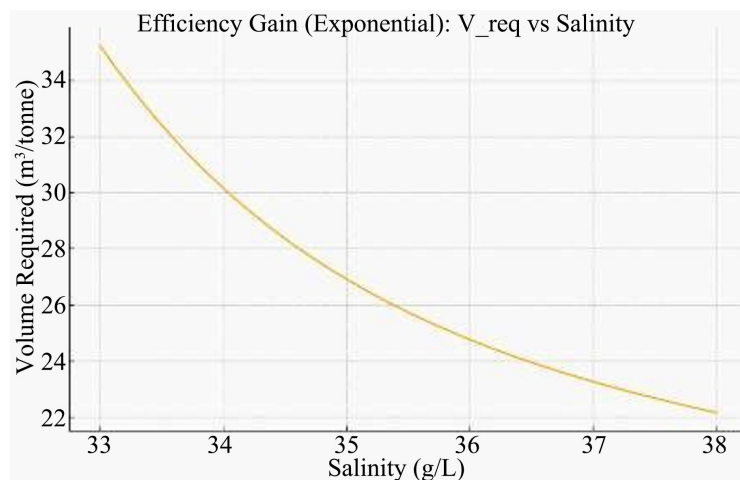


Figure 2. Multi-effect cascade model—convex increase at higher salinities.



**Figure 3.** Operational variability (sinusoidal)—wavy curve capturing variable losses.



**Figure 4.** Efficiency gain (exponential)—rapid drop then tapering off.

## 4. Real World Loss Mechanisms

### 4.1. Pond Substrate Seepage

Substrate seepage arises from the percolation of brine through pond liners and underlying soils, typically accounting for 5% - 12% of total water loss in conventional HDPE-lined operations [17] [33]. Field measurements at Lake MacLeod recorded seepage rates ranging from 0.15 to 0.30 mm/day under moderate pond depths, corresponding to an annual volume loss of 0.5 - 1.0 m<sup>3</sup> per m<sup>2</sup> of pond surface [10]. In contrast, composite geomembranes—comprising HDPE, geotextile layers, and bentonite cores—have demonstrated seepage reductions to below 0.05 mm/day (<3%) in arid environments, as evidenced by accelerated aging tests and tracer studies in Australian and Spanish pilot sites [10] [34]. Soil type and compaction beneath liners also play critical roles; coarse, poorly graded sands can permit under-liner flow even when liners are intact, whereas clays and well-compacted silts effectively minimize subsurface migration [12] [35].

Preventive and corrective maintenance strategies are crucial to sustain low seepage rates and control operational costs. Regular liner inspections—using infrared thermography or low-voltage integrity testing every 3 - 6 months—identify punctures, seam weaknesses, and stress cracks before they propagate [35] [36]. Grout injection or bentonite slurry patches can repair localized leaks with minimal disruption to production, while automated pressure-monitoring systems in dual-liner configurations provide continuous seepage data, triggering maintenance alerts when seepage exceeds predefined thresholds [36]. Lifecycle cost analyses indicate that investing in high-performance composite liners and advanced monitoring reduces net present cost by 15% - 20% over 20-year operations, despite a 25% higher upfront capital expenditure [10] [37].

#### 4.2. Entrainment during Harvesting

Entrainment occurs when brine remains clinging to salt crystals during mechanical or manual harvesting, resulting in water carryover losses of 4% - 9% in conventional scraper systems [26]. In a study at Aveiro, Portugal, manual raking protocols showed average entrainment losses of 7% at seawater salinity of 35 g/L, equating to approximately 2.3 m<sup>3</sup> of brine per tonne of salt. Field trials at Lake MacLeod with mechanized harvesters recorded entrainment between 5% and 8%, influenced by scraper blade angle, rake speed, and crystal size distribution [26] [38]. Entrained water not only increases  $V_{req}$  but can also cause secondary ion contamination if recycled without adequate separation [13].

Mitigation strategies focus on reducing residual brine on harvested salt through optimized equipment and post-harvest processing. Adjustable-angle scraper blades set at 30° - 45° relative to the pond floor have demonstrated entrainment reductions to under 3% by allowing gravity-assisted drainage before collection [26] [37]. High-speed centrifuge dewatering of harvested salt further reduces moisture content to below 1%, but incurs additional energy costs of 0.02 - 0.05 GJ per tonne [39]. Integrating hydrophobic coatings on scraper surfaces and implementing vibrating conveyors for salt transport can cut entrainment losses to less than 2%, improving overall water efficiency and salt purity [22].

#### 4.3. Mineral Coprecipitation

During seawater evaporation, secondary dissolved ions—primarily magnesium, calcium, and potassium—coprecipitate alongside sodium chloride, forming minerals such as gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) and sylvite (KCl). These coprecipitated salts can constitute 8% - 14% of the total solid mass, effectively reducing the yield of pure NaCl per unit of seawater processed [13]. Laboratory crystallizer tests in Germany demonstrated that at initial salinities of 35 g/L, sequential precipitation of calcium carbonate and gypsum removed up to 6% of dissolved solids before halite saturation was reached, followed by sylvite formation at higher concentrations, which further decreased NaCl purity by 2% - 8% [13] [17]. Variability in ion ratios—driven by local seawater composition—causes site-specific coprecipitation

profiles, with some Mediterranean operations reporting gypsum yields of 50 kg per tonne of salt, indicating a significant mass of non-NaCl minerals in harvested product [12].

Mitigation of mineral coprecipitation focuses on staged concentration and selective harvest. In stepped-cascade basin arrays, brine enters a series of ponds at incrementally higher salinities, allowing targeted removal of calcium and magnesium species in upstream basins, so that final crystallization ponds approach near-ideal NaCl purity [32]. Chemical dosing with hydrochloric acid or selective precipitation agents can suppress gypsum formation, though this adds chemical costs and potential environmental impacts [24]. Real-time salinity and ion chromatography sensors provide continuous monitoring of ion ratios, enabling operators to time harvest to maximize NaCl recovery before significant secondary salt formation [40]. Lifecycle assessments indicate that investing in multi-stage concentration and sensor-driven control can reduce coprecipitated mineral mass by up to 50% and improve overall NaCl recovery efficiency by 5% - 7% [32] [40].

## 5. Comparative Analysis of Salt Production Methods

The performance of salt production systems varies considerably based on configuration, energy input, and geographic location. Solar evaporation ponds remain the most common approach, particularly in regions with high solar insolation and low precipitation. These systems typically require 32 - 36 m<sup>3</sup> of seawater per tonne of salt harvested [21] [28]. Their advantages include low operational energy input (<0.1 GJ/t) and scalability, but they are land-intensive and sensitive to climatic fluctuations, especially during monsoon or winter seasons [19] [21] [28].

Multi-effect evaporation pans use staged thermal gradients to accelerate water removal, reducing water requirements to as low as 20 - 25 m<sup>3</sup> per tonne. These systems rely on external heat sources—frequently natural gas, biomass, or industrial waste heat—introducing higher capital and operational costs but providing year-round production capabilities. Their compact design allows for deployment in urban or inland industrial zones, albeit with increased energy footprints (2 - 5 GJ/t) [23] [29].

Cascading basins use gravity flow to sequentially concentrate seawater across interconnected ponds. This method balances land use and water efficiency, achieving average seawater consumption rates of ~28 m<sup>3</sup>/t under well-designed layouts [32]. Basin geometry optimization—such as narrowing width and increasing length—has been shown to enhance solar gain while minimizing heat losses and wind-driven evaporation irregularities [18] [21].

Concentrator hybrid systems represent an emerging frontier in seawater evaporation. By integrating solar reflectors or Fresnel lenses, these systems intensify incident solar radiation and reduce water volumes to 20 m<sup>3</sup> per tonne or lower [24] [25]. Optical gains of 5 - 12× improve thermal input efficiency, while high-albedo pond linings and phase-change materials further reduce losses. These systems are particularly effective in coastal deserts or isolated islands where land availability

is constrained and renewable energy is prioritized [41].

## 6. Seasonal and Climatic Effects on Seawater Demand

The water-balance expression ( $\Delta S = P - R_o - G - E - T$ ) directly connects to the earlier evaporation-rate models in Section 3 because  $E$  is the same latent-heat-driven evaporation flux used to calculate  $V_{req}$ .

The water cycle or hydrological cycle, which describes the circulation of the water substance in the Earth's system, can be summarized by water balance equation. The water balance at any given time is given by the expression water balance at any given time is given by the expression,

$$\Delta S = P - R_o - G - E - T$$

where  $\Delta S$  is the change in storage,  $P$  is precipitation,  $R_o$  is runoff,  $G$  is net groundwater flow,  $E$  is evaporation and  $T$  is transpiration. A study by [42] demonstrated that 85% of the average annual precipitation over Kenya originates from the oceanic evaporation, while 15% was from within the terrestrial evaporation within Kenya, primarily from the Kenyan Highlands.

Seasonal fluctuations significantly influence seawater evaporation efficiency and, consequently, the volume of seawater required per tonne of salt. In regions such as Gujarat, India, water requirements vary from 25 m<sup>3</sup>/t in peak summer to 35 m<sup>3</sup>/t in the cooler winter months due to lower ambient temperatures and reduced solar radiation [7]. Similar seasonal variability is observed in the UAE, where dry season conditions support evaporation rates requiring only 21 m<sup>3</sup>/t, while humid winters push the figure up to 34 m<sup>3</sup>/t [12]. In temperate regions like Portugal, changes in wind speed and cloud cover cause seawater consumption rates to vary between 32 and 41 m<sup>3</sup>/t throughout the year [19] [26].

The influence of meteorological parameters—such as solar irradiance, air temperature, relative humidity, wind speed and atmospheric pressure (altitude)—directly alters evaporation flux. For example, a 5°C rise in average daily temperature can reduce seawater requirement by 3 - 5 m<sup>3</sup> per tonne by enhancing latent heat flux and reducing condensation on pond surfaces. Conversely, elevated humidity can depress evaporation rates, leading to inefficient water utilization and higher retention times. Wind enhances the removal of the water vapor that accumulates over the water surface, thereby lowering the humidity in the immediate vicinity. This allows for more water molecules to escape into the air, thereby increasing the evaporation rates. With potential evaporation rates of more than 2000 mm/year over the coastal region [43] [44], it therefore implies the high efficiency of seawater evaporation for salt production, thus utilizing less amounts of water.

Climatic zones also determine pond operation strategy and design. Tropical coastal areas allow for year-round continuous evaporation, whereas subtropical zones may necessitate seasonal shutdowns or partial basin coverage during monsoons. In higher latitudes, adaptive practices such as thermal storage, greenhouse pond covers, or seasonal salt stocking are employed to counteract climatic limitations. Adjusting pond geometry to maximize solar exposure during low-angle sunlight periods can

also help maintain evaporation continuity.

Forecasting seawater requirements under future climate scenarios is increasingly important. Regional climate models predict shifting rainfall patterns and more frequent extremes such as heatwaves, potentially altering salt yield baselines. Rising temperatures will lead to increased evaporation rates. In the future, the interplay between the various meteorological factors and between meteorological and non-meteorological factors that influence the evaporation rates would be crucial in prospecting the outputs of salt production by evaporation approach. Incorporating predictive analytics and climate-adaptive controls—like automated pond modulation based on real-time weather inputs—will be essential to stabilize production volumes and optimize seawater use year-round.

## 7. Environmental and Economic Considerations

Salt production through seawater evaporation is intimately linked to both environmental sustainability and economic viability. As the global demand for salt rises—driven by food, chemical, and de-icing applications—there is growing scrutiny over the ecological footprint of saltworks. The extensive land use required for open ponds, often located in ecologically sensitive coastal areas, necessitates robust environmental safeguards to preserve wetland habitats and biodiversity [11]. Environmental impact assessments have identified trade-offs between land coverage, yield intensity, and water efficiency.

One major environmental concern is habitat alteration due to the conversion of coastal wetlands and salt marshes into evaporation ponds. This transformation can disrupt migratory bird paths, affect local fish populations, and fragment ecological corridors. However, with careful pond siting and zoning, some saltworks have successfully maintained dual-use areas that support both wildlife and salt production. Constructed buffers, vegetation belts, and seasonal water-sharing schemes have been shown to mitigate ecological impacts while preserving production efficiency.

Seepage control also plays a crucial role in minimizing environmental risks. Unlined or poorly lined ponds may allow seawater to infiltrate surrounding soils and freshwater aquifers, leading to soil salinization and long-term groundwater degradation. The use of composite geomembranes, periodic liner testing, and underdrain recovery systems not only reduces operational losses, but also prevents contamination of adjacent land and water bodies [25] [31]. In many jurisdictions, liner performance standards are embedded into permitting frameworks to ensure environmental compliance.

From an economic standpoint, the cost structure of seawater evaporation facilities is dominated by capital outlays for pond construction, liners, pumps, and solar collection infrastructure. Operational costs are relatively low, with labor, maintenance, and land taxes comprising the primary recurring expenses. Lifecycle cost models have shown that investing in higher-efficiency systems—such as coated liners or hybrid solar concentrators—yields long-term savings despite

greater upfront investments, especially in regions with high solar availability [29] [32].

Salt price volatility and seasonal production cycles can impact revenue streams, especially for artisanal or cooperative operations. These producers are often more vulnerable to weather variability and market access constraints. However, community-based models that incorporate shared infrastructure, pooled financing, and training programs have demonstrated success in stabilizing income and encouraging sustainable practices [13] [44]. Digital tools, such as blockchain traceability and weather-adaptive pricing, offer further resilience.

Environmental regulation and economic incentives will shape the future of seawater evaporation practices. Carbon taxation, coastal zoning reforms, and environmental impact fees may increase project complexity but also create opportunities for innovation. Simultaneously, green financing mechanisms, climate-linked insurance, and certification schemes—such as eco-labels for low-footprint salt—can promote transparency and investment in sustainable technologies [43].

Ultimately, balancing environmental integrity with economic feasibility requires an integrated approach that considers ecosystem health, resource efficiency, and socio-economic equity. As salt production expands into new regions and confronts climate change challenges, thoughtful planning and inclusive governance will be essential to ensure that saltworks contribute positively to both human and environmental well-being.

## 8. Discussion and Future Outlook

Despite centuries of development, the seawater evaporation method for salt production continues to evolve through multidisciplinary innovations. Current practices typically achieve water requirements between 32 and 37 m<sup>3</sup> per tonne, yet theoretical calculations and high-efficiency models suggest that values below 30 m<sup>3</sup> are attainable with more precise design and control systems [10] [11] [17] [21] [23]. Optimization of pond geometry, lining materials, and solar capture technologies has demonstrated consistent performance improvements across pilot sites worldwide.

Future research should emphasize the integration of smart monitoring systems to enable real-time control of evaporation environments. Internet of Things (IoT) sensors, machine learning algorithms, and adaptive feedback mechanisms can detect subtle shifts in salinity, temperature, and moisture, allowing proactive system tuning. These technologies, already trialed in digital twin modeling frameworks [39], are key to minimizing waste and ensuring consistent output even under variable climate conditions.

Material science advancements also offer promising pathways. The development of nanostructured, self-healing pond coatings could drastically reduce seepage and thermal losses. Similarly, photothermal materials designed to maximize solar absorption while resisting salt scaling are under active investigation. Integration of such materials into modular, prefabricated pond systems can make salt production more

accessible in space-constrained or off-grid environments.

Policy and economic frameworks must adapt to support these technological shifts. Subsidies for renewable thermal infrastructure, water-use regulations tailored to regional evaporation dynamics, and incentives for closed-loop salt recovery systems will be crucial. Community-based management models, especially in artisanal regions, should be supported with training and funding to ensure equitable adoption of new systems [44]. Moving forward, cross-sector collaboration among engineers, climate scientists, economists, and local stakeholders will be central to meeting global salt demand sustainably.

Despite these advances, several limitations remain. Saltworks performance is highly site-specific, with seawater salinity, seasonal wind regimes and humidity influencing yields. Some highlighted technologies—such as nanostructured coatings, IoT-based automation and hybrid concentrators—are still in pilot stage, and scaling them may involve cost and durability challenges.

## 9. Conclusions

The use of seawater evaporation for salt production represents one of the oldest and most efficient natural separation processes, yet it continues to benefit from modern advancements in science and engineering. Through careful system design, it is now possible to approach or even exceed theoretical water-use efficiencies, driving seawater requirements down to the 20 - 25 m<sup>3</sup> per tonne range. This optimization has been achieved through improved thermal retention, enhanced material coatings, and strategic pond geometries that maximize solar capture while minimizing losses.

While traditional solar evaporation methods offer simplicity and low energy input, their efficiency can be limited by environmental and structural losses. The integration of smart sensors, predictive control systems, and hybrid solar concentrators allows producers to fine-tune operations and respond dynamically to weather changes. These innovations make it feasible to maintain consistent salt yields even in variable climates, thereby stabilizing economic outputs and improving resource efficiency.

Social and ecological considerations are equally important. Scaling salt production in a sustainable way requires not only technological improvements but also community engagement, environmental stewardship, and robust governance frameworks. Ensuring water-use accountability, minimizing land degradation, and maintaining biodiversity around evaporation ponds are critical to long-term viability.

In conclusion, seawater evaporation remains a cornerstone of global salt production, offering unparalleled scalability and environmental compatibility when optimized correctly. Future efforts should focus on integrating emerging technologies, adapting to climate dynamics, and supporting equitable access to sustainable production methods. With coordinated innovation and inclusive policy, seawater-based saltworks can continue to meet global demand while reducing their environmental footprint.

## Conflicts of Interest

The authors declare no conflicts of interest.

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