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USE OF DESALINATION BRINES IN THE CULTIVATION OF HALOPHYTES: A VISION OF CIRCULAR ECONOMY

Arlett Leticia **Ibarra-Villarreal**[1], Germán Eduardo **Dévora-Isiordia**[1*], Rosario **Montoya-Pizeno**[1], Edgar Omar **Rueda-Puente**[2], Rafael Enrique **Cabanillas-López**[3], Marco Antonio **Gutiérrez-Coronado**[4]

[1]Instituto Tecnológico de Sonora. Departamento de Ciencias del Agua y Medio Ambiente. Calle 5 de Febrero 818 Sur, Ciudad Obregón, Sonora, Mexico. C. P. 85000.
[2]Universidad de Sonora. Departamento de Agricultura y Ganadería. Boulevard Luis Encinas y Rosales S/N, Colonia Centro, Hermosillo, Sonora, Mexico. C. P. 83000.
[3]Universidad de Sonora. Departamento de Ingeniería Química. Boulevard Luis Encinas y Rosales S/N, Colonia Centro, Hermosillo, Sonora, Mexico. C. P. 83000.
[4]Instituto Tecnológico de Sonora. Departamento de Biotecnología y Ciencias Ambientales. Calle 5 de Febrero 818 Sur, Ciudad Obregón, Sonora, Mexico. C. P. 85000.
* Author for correspondence: german.devora@itson.edu.mx

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ABSTRACT

Water scarcity and distribution constitute a problem driven by population growth and industrial overexploitation. To secure water supply, desalination technologies for seawater and brackish water have been adopted, becoming critically important. Reverse osmosis is the highest-rated technology for this process and generates two output streams: permeate water and brine, the latter characterized by a high concentration of total dissolved solids (TDS). When untreated, brine is discharged into water bodies and soils, causing ecological damage. To mitigate this impact, the circular economy proposes reusing part of the brine in agriculture through halophyte plants, which offer the advantage of growing under high salt concentrations. The objective of the research was to document the salinity tolerance of halophyte species and the potential use of water rejected from the desalination process as irrigation water, with a circular economy approach. Brine reuse represents an opportunity to reduce waste and generate environmental, social, and economic benefits. Among the main halophyte species capable of tolerating brine above 30 000 mg L^{-1} are *Suaeda salsa* (L.) Pall., *Salicornia bigelovii* Torr., *Rhizophora mangle* L., and *Chenopodium quinoa* Willd. *Salicornia europaea* L. is classified as a halophyte species with medium tolerance (10 000–30 000 mg L^{-1}). Species with low salinity tolerance (5000–10 000 mg L^{-1} TDS) include *Atriplex nummularia* Lindl., *Zoysia japonica* Steud., and *Crithmum maritimum* L. These plants also possess significant nutritional and pharmaceutical properties and can be used as livestock feed, human food, for oil extraction, soil remediation, and other applications.

Keywords: Reverse osmosis, *Rhizophora mangle* L., *Salicornia bigelovii* Torr., salinity tolerance, *Suaeda salsa* (L.) Pall.

INTRODUCTION

Rapid population growth and industrialization have increased demand on water resources, making it difficult to meet basic human needs such as drinking water, food production, and electricity. Although most of the planet is covered by water, only about 2.5 % is available as fresh water, and three-quarters of this volume is frozen in glaciers and ice caps, making it practically inaccessible in the short term (Ríos-Arriola *et al*., 2022; Dévora-Isiordia *et al*., 2023). Currently, about 2.2 billion people lack access to safe drinking water (Salehi, 2022). Climate change is expected to worsen this situation and threaten sustainable development, highlighting the urgent need to preserve existing water sources and develop new ones (Dévora-Isiordia *et al*., 2021).

The development and implementation of desalination technologies has increased. Desalination removes salts, contaminants, and minerals from seawater or brackish water to produce fresh water for human, agricultural, or industrial use. Its main advantage is that it provides water independently of the hydrological cycle. However, the process generates two output streams: desalinated water and reject water or brine (Musie and Gonfa, 2023; Saleem *et al*., 2023). Brine is characterized by causing environmental problems due to its high concentration of salts, organic matter, and other substances, disrupting the osmotic balance of marine species and causing dehydration and mortality (Valdés *et al*., 2021).

Research by Gil-Trujillo and Sadhwani Alonso (2023) showed that optimization of diffusers can improve dilution performance in seawater. Soil contamination is also a concern, as salinity degrades physical, chemical, and microbiological soil properties, reducing crop yield (Chi *et al*., 2025). To prevent soil damage, several disposal methods for brine have been proposed, such as discharge into surface waters or sewers, deep-well injection, evaporation ponds, soil application, zero-liquid discharge, and aquaculture farms (Dévora-Isiordia *et al*., 2017). The Yaoba oasis in China is an example of this problem, where the accumulation of salts from irrigation water quality has limited agricultural development and deteriorated groundwater quality (Lu *et al*., 2025).

Because soil salinity causes yield losses, halophyte crops have been selected for irrigation with brine, reducing the negative effects of disposal and applying reuse techniques under circular economy principles (Al-Tamimi *et al*., 2023). Gómez-Bellot *et al*. (2021) evaluated brine from reverse osmosis for irrigating two forage halophyte species, *Crithmum maritimum* L. and *Atriplex halimus* Lindl., observing no negative effects and considering brine a viable option for revegetation or soil conservation. Oron *et al*. (2023) proposed a zero-discharge replacement system using brine sequentially in duckweed and fish ponds to produce nutrient-rich wastewater for halophyte irrigation, demonstrating efficient food production and reduced environmental impact.

Further applications show promising results. Robertson *et al*. (2019) evaluated *Salicornia bigelovii* Torr. production for fresh tips using brine enriched with nutrients through aquaculture systems, tripling yield to 23.7 Mg ha^{-1} and increasing economic return despite higher per-hectare costs. Li *et al*. (2019) reported that *Suaeda salsa* (L.) Pall. and *Suaeda glauca* Bunge retain ions in their roots, while Li *et al*. (2023) found

that *S. glauca* and *Limonium aureum* (L.) Hill accumulate heavy metals and NaCl in their tissues, regulating soil salinity. Al-Tamimi *et al*. (2023) also evaluated *Salicornia* at different concentrations and nutrient contents using three irrigation types, obtaining yields of 16 kg m^{-2} with brine at 25 641 mg L^{-1}. Higher forage production (2–2.8 kg m^{-3}) occurred with pressure-compensated drip irrigation and subsurface irrigation. The economic water productivity analysis showed that brine from aquaculture tanks combined with pressure drip irrigation costs USD 5.8–6.2 m^{-3}, higher than desalination costs (USD 1.5 m^{-3}), but they concluded that the greatest economic benefits come from pass-through aquaculture irrigation and drip or subsurface systems.

The scientific contribution of this work lies in the synergy between brine reuse from desalination processes and the cultivation of halophyte plants of potential commercial value within a circular economy framework. This approach reduces environmental impacts from brine discharge, promotes waste valorization, and presents a sustainable management proposal for desalination brine. This review aims to raise awareness of sustainable brine disposal and emphasizes the potential of halophyte cultivation for this purpose. Therefore, the objective was to document the salinity tolerance of halophyte species and evaluate the potential use of reject water from desalination as irrigation water under a circular economy approach. To achieve this objective, the following research questions were established: What is the most widely used desalination system? Which crops can be irrigated with brine water? What is the salt tolerance of these crops? What is their industrial potential? Is it possible to apply the circular economy to the synergy between saline waste from desalination plants and the cultivation of halophytic plants?

MATERIALS AND METHODS

To ensure a focused and current foundation for the study, a systematic search strategy was implemented. Literature selection was restricted to research articles published within the last 10 years up to 2025. The search for relevant literature was carried out using the SCOPUS database, one of the most comprehensive digital sources of peer-reviewed scientific articles and widely used in bibliometric analysis (Sweileh, 2021). The process began with general concepts related to brines from desalination processes and subsequently incorporated more specific terms to focus the search on reverse osmosis, circular economy, and halophytes, applying the Boolean operators “AND” and “OR” (Maçaira *et al*., 2018).

The *h*-index and number of citations were used to assess the productivity and impact of researchers through their publications. An acceptable minimum average *h*-index of ≥ 10 and an average of 1000 citations were considered for all authors. The *h*-index measures research impact by combining productivity and influence: articles were ranked from highest to lowest number of citations, and the *h*-index corresponds to the number of publications that have received at least that same number of citations.

RESULTS AND DISCUSSION

Bibliometric analysis

This systematic review with statistical data analysis examines the current status of the use of brine from desalination processes as irrigation water for the cultivation of halophyte plants. According to Boolean search engines in SCOPUS, the combination circular economy "AND" "OR" reverse osmosis brine yielded 1032 articles; halophyte "AND" "OR" circular economy yielded 14 articles; and halophyte "AND" "OR" reverse osmosis brine yielded eight articles published between 2015 and 2025.

Individual productivity and global interdisciplinary collaboration are essential for developing, researching, and identifying halophyte species capable of tolerating brine residues from desalination systems. This study, based on the establishment of keywords, resulted in 1054 articles that contributed to answering the research questions. The three most cited authors were Cárdenas-Pérez, Araus, and Oron, with 22 824, 10 400, and 4105 citations and *h*-indexes of 71, 53, and 36, respectively. Of the 70 research articles used for this study, the average number of citations was 1379, with an average *h*-index of 11.79. Israel and Spain were the countries with the highest number of publications (57).

It is essential to continue researching and obtaining information from additional databases, as global scientific output is constantly changing. The results of the last two search combinations show that research in the field of halophytes, reverse osmosis brines, and their synergistic use within a circular economy framework remains low. This highlights the importance of continuing research and establishing the current state of the art, which was a key motivation for this work. More publications are needed to understand the adaptation of halophytes under irrigation schemes using brine, including evaluations of yields, phenology, and related parameters.

Desalination systems and reverse osmosis

Several systems have been developed for seawater desalination, including reverse osmosis, electrodialysis, and distillation (Table 1). Each method has different characteristics in terms of energy requirements, membrane use, and operating pressure, with the objective to reduce the salt content of seawater or brackish water to obtain water suitable for human, agricultural, and industrial use. Each method presents specific advantages and disadvantages, and the choice depends on factors such as energy consumption, operating costs, and environmental impact (Ashraf *et al*., 2022).

Currently, reverse osmosis is the most widely used desalination technology worldwide due to its high production capacity, low energy consumption, high permeate quality, and lower cost compared with thermal desalination systems (Feria-Díaz *et al*., 2021; Montoya-Pizeno *et al*., 2023). Ongoing advances in low-pressure membrane materials and energy-recovery systems have further reduced reverse osmosis costs, reaching USD 0.4–0.8 m^{-3} with specific energy consumption of 2.2–3 kWh m^{-3} for seawater

Table 1. Classification of desalination processes by separation mechanism (Feria-Díaz *et al*., 2021; Ashraf *et al*., 2022).

	Process	Technique	System
Separation of salts in water	Membrane	Pressure	Reverse osmosis
	Resin	Chemical attraction	Ionic exchange
	Membrane selective	Electric charge	Electrodialysis
Separation of water from salts	Evaporation	Steam	Thermal vapor compression Mechanical vapor compression Multi-effect vertical tube distillation Multi-effect distillation of horizontal tubes Solar distillation Simple flash distillation Submerged tube distillation Multistage flash distillation
	Crystallization	Cold	Freezing Hydrate formation

(Armendáriz-Ontiveros *et al*., 2022; Feo-García *et al*., 2024). In contrast, thermal technologies, although more robust under high salinity, maintain significantly higher energy demands (6–10 kWh m^{-3}) and total costs of USD 1.2–2 m^{-3}, limiting their application mainly to regions with residual thermal sources or abundant solar energy (Ríos-Arriola *et al*., 2022; Benahmed *et al*., 2025)..

The reverse osmosis process (Figure 1) begins with physicochemical pretreatment tailored to the characteristics of the feedwater to remove undissolved solids, organic matter, and microorganisms, preventing membrane fouling (Ahmed *et al*., 2023). After

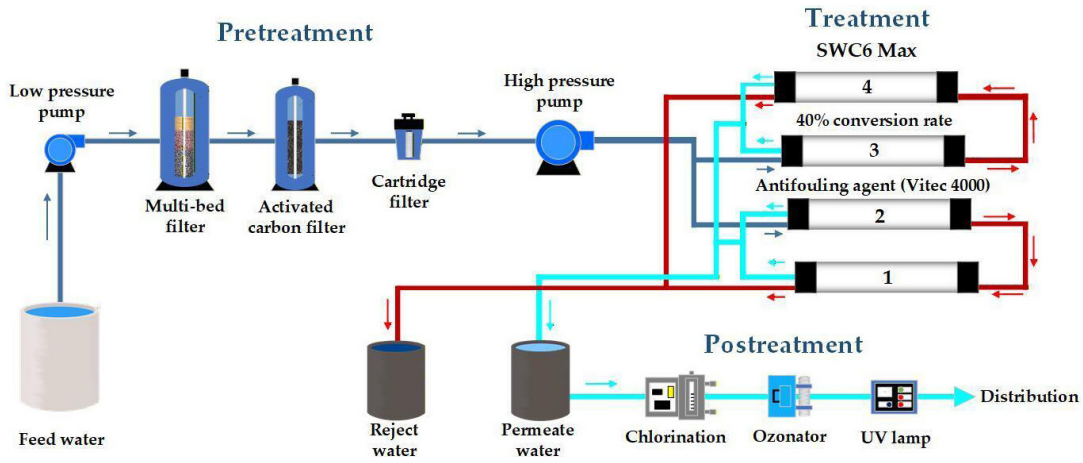

Figure 1. Reverse osmosis process flow diagram.

pretreatment, brackish or seawater is pressurized and passed through a semipermeable membrane that separates unwanted particles to obtain water that meets established quality standards (Feria-Díaz *et al*., 2021). At the end of the process, permeate water and brine are obtained. Because the osmotic pressure of seawater is 2.68 MPa, the system requires a high-pressure pump applying at least twice that value (5.51 MPa). The permeate exits at 0.3 MPa, sufficient for distribution, while the reject stream exits at 5.24 MPa and is reutilized through energy-recovery devices, which contributes to the higher energy efficiency of reverse osmosis compared with thermal methods.

The semipermeable membrane used consists of three polymer layers: a thin polyamide film (0.2 μm), polysulfone (40 μm), and polyester (120 μm) (Álvarez-Sánchez *et al*., 2025). The permeate contains low salt concentrations and undergoes post-treatment (remineralization and disinfection using chlorination, ultraviolet treatment, or ozone) to meet quality requirements for use and consumption (Valdés *et al*., 2021). The brine retains impurities and process chemicals such as anti-scalants (polyphosphates), biocides (chlorine), and pH-adjusting agents (HCl or NaOH) and is characterized by a high concentration of total dissolved solids (TDS) (Gómez-Bellot *et al*., 2021; Shokry *et al*., 2025).

The brine problem

The reject water, also known as brine, has specific characteristics depending on the source and quality of the feed water, the pretreatment applied, the desalination process, and the percentage of recovered water. In some cases, TDS exceeds 55 000 mg L^{-1}; this increase, known as the concentration factor, establishes the number of times salts and contaminants are concentrated in the reject stream compared to the feed water. It is calculated based on conversion and is a key indicator, since higher conversion results in a higher concentration factor (Gil-Trujillo and Sadhwani-Alonso, 2023).

Brine contains ions such as Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-} , HCO^{3-} and PO_4^{3-}. In theory, all ions in seawater and brine should concentrate proportionally according to the concentration factor, but in practice they do not, due to physicochemical processes within the reverse osmosis membrane, solubility and precipitate formation (concentration polarization), and the electrochemical properties of the ions (Zolghadr-Asli *et al*., 2023; Myung *et al*., 2025). This type of water is generally discharged directly into the sea, generating negative environmental impacts on aquatic flora and fauna. High salinity, temperature, and metal content can cause eutrophication, reduced dissolved oxygen, and species extinction, especially in sensitive ecosystems such as coral reefs (Gómez-Bellot *et al*., 2021; Cornejo-Ponce *et al*., 2022).

In 2022, 20 956 desalination plants worldwide produced more than 115.62 million m^3 d^{-1} of brine (Ríos-Arriola *et al*., 2022). The main sources were Saudi Arabia, the United Arab Emirates, Kuwait, and Qatar (Jones *et al*., 2019; Lee *et al*., 2024). In China, 30 160 million Mg of brine wastewater with concentrations of 1000–20 000 mg L^{-1} were treated in 2022; 26.4 % originated from the coal and petrochemical industry, 20.7 % from the chemical industry, and 2.3 % from desalination technologies.

In reverse osmosis processes, brine production is directly related to the recovery percentage. For example, a seawater feed of 35 000 mg L^{-1} and a flow rate of 103 600 m^3 d^{-1} at 41.6 % recovery produces 60 000 m^3 d^{-1} of reject water at 60 000 mg L^{-1} (Liu *et al*., 2024). In this study, the focus was on saline waste from reverse osmosis desalination plants; therefore, the concentration of reject water depends on the characteristics of the feed water (concentration, flow rate, and conversion). Brines also differ in concentration according to their origin: brackish water (1000–10 000 mg L^{-1}) yields reject water at about 20 000 mg L^{-1}, while seawater at 35 000 mg L^{-1} results in a reject concentration of 60 000 mg L^{-1}.

Case studies and economic viability

The appropriate management of brine is critical to minimize its environmental and financial impact, as the cost of brine disposal ranges from 5 to 33 % of the total cost of a desalination plant (Cornejo-Ponce *et al*., 2022). Because of this, its reuse is implemented in different areas. In China, 1508 million m^3 are reused annually for the irrigation of crops tolerant to saline concentrations, such as *S. bigelovii*. Its production cost is estimated at USD 878.30 ha^{-1}, while its selling price is USD 4.73 kg^{-1}. Cárdenas-Pérez *et al*. (2021) report that the biomass yield of *S. bigelovii* is 35 Mg ha^{-1}. Financial analyses indicate that, under optimal conditions, its cultivation can generate a profit of USD 76 000 ha^{-1}, which is higher than other halophytes such as *Distichlis spicata* (L.) Greene and *Sporobolus virginicus* (L.) Kunth (Rotter *et al*., 2025).

Another example of reuse is the production of salt blocks obtained from the crystallization of salts (Figure 2). These blocks are used as livestock feed due to their nutritional value. Their monthly production is around 544 000 blocks of 10–25 kg,

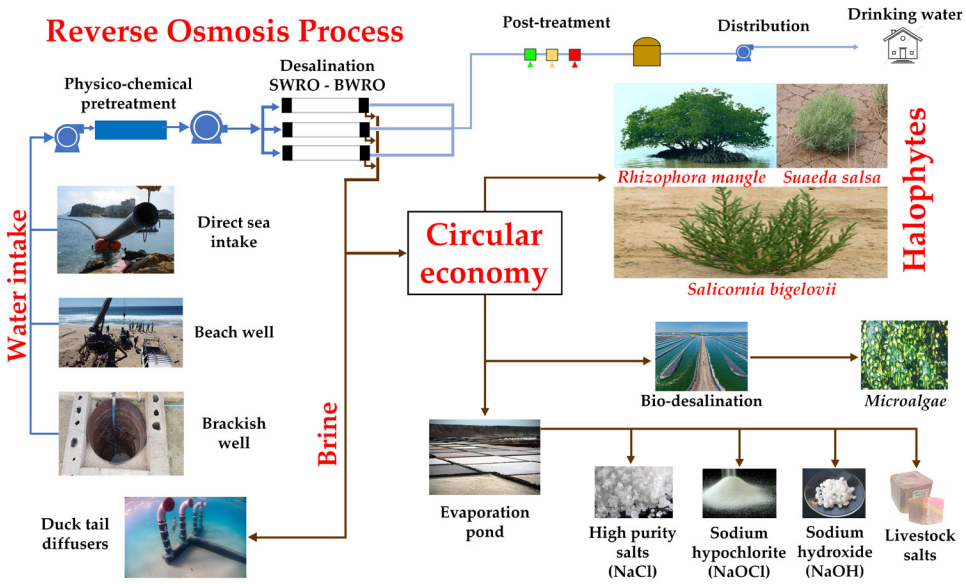

Figure 2. Conceptual transition from linear to circular economy models (Mallick, 2022).

with 108 988 Mg of salt derived from a brine source of 60 000 mg L^{-1}. This reduces the release of brine into the environment and generates an economic benefit through commercialization, with regional selling prices ranging from USD 25 to 45. Similarly, sodium chloride, sodium sulfate, and acid and alkaline solutions are obtained from salt crystallization processes by evaporation (Liu *et al*., 2024).

Even so, the most commonly used alternatives for brine disposal include ocean discharge, evaporation ponds, canal disposal, and deep well injection. Although ocean discharge is the most widely used method, it can negatively affect marine flora and fauna (Lee *et al*., 2024). An example is *Posidonia oceanica* (L.) Delile, which is sensitive to changes in salinity in the Mediterranean Sea and is affected by brine spills and is therefore used as an indicator of environmental impact (Blanco-Murillo *et al*., 2023).

Petersen *et al*. (2018) also report significant impacts on the reef-building coral species *Stylophora pistillata* Esper, *Acropora tenuisy* Dana, and *Pocillopora verrucosa* Ellis due to a 10 % increase in salinity combined with antifoulants (0.2 mg L^{-1}) in the Gulf of Aqaba in the Red Sea. The presence of amphipods and species tolerant to hypersaline spills, such as marine worms and polychaetes, has also been compromised along the coasts of Spain near brine discharges (Grammatiki *et al*., 2025). In another study, de Serio *et al*. (2025) define a tolerance threshold of 5000 mg L^{-1} and exposure of less than 48 h to avoid physiological stress in benthic communities. Key species like crustaceans and mollusks, crucial to the nutrient cycle and the stability of the food web, would suffer otherwise.

The circular economy solution

The brine produced during the reverse osmosis process is typically discarded due to its high salt concentration, leading to significant environmental impacts and elevated disposal costs (Gómez-Bellot *et al*., 2021). However, this resource can now be managed under circular economy principles, transforming it into a valuable input. The circular economy is an advanced model compared to the linear economy (Figure 3). Its objective is sustainable development, seeking to optimize waste management through reuse by

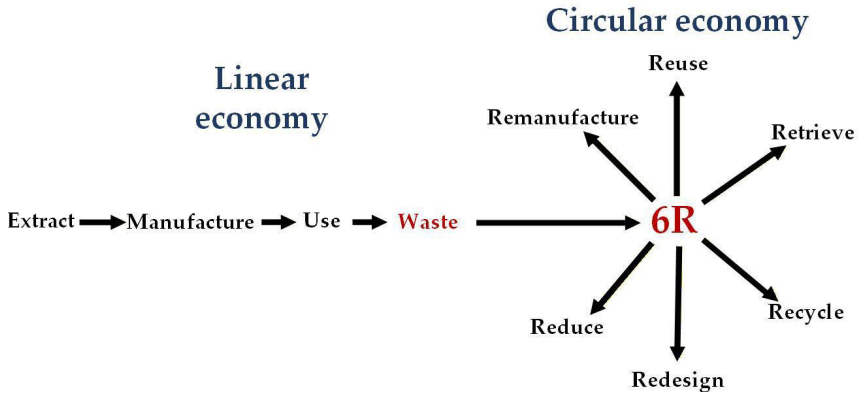

Figure 3. Transition from linear economy to circular economy (Mallick, 2022).

applying principles that include preserving and enhancing natural capital, optimizing resource use, and promoting system efficiency (Espinoza, 2023; Raudales-García *et al*., 2024).

This approach emphasizes reducing environmental impacts throughout the product life cycle by implementing the 6Rs: reduce, reuse, recycle, recover, remanufacture, and redesign (Mallick, 2022). The circular economy provides economic, environmental, and social benefits by promoting business competitiveness and pollution reduction (Espinoza, 2023). The potential use of brine as irrigation water for halophyte cultivation aligns with these principles through resource reuse and proper management (Cornejo-Ponce *et al*., 2022; Mallick, 2022; Raudales-García *et al*., 2024). In this context, waste from one process becomes an input for another sector, such as agriculture (Gómez-Bellot *et al*., 2021; Mallick, 2022).

Use of brine for the cultivation of halophyte plants

Circular economy is a relevant model for arid regions where water is a scarce resource (Cornejo-Ponce *et al*., 2022). These regions face severe water scarcity and salinity problems that generate abiotic stress and put agricultural production at risk. Agriculture consumes 70 % of available water, making it the activity with the highest demand due to low irrigation efficiency and the high water requirements of crops. In this context, it is necessary to explore strategies to use non-conventional water resources and marginal lands (Araus *et al*., 2021).

The reuse of brine in agriculture is an option that contributes to water conservation through sustainable practices (Oron *et al*., 2023). Plants differ in their tolerance to salinity; the most tolerant are halophyte plants, which withstand electrical conductivity (EC) values over 30 dS m^{-1}. Above this threshold, most crops cannot survive, and only crops with thresholds above 4–8 dS m^{-1} are classified as very tolerant. Therefore, the volume of brine that can be applied depends on plant type and brine properties (Lee *et al*., 2024).

The low salinity tolerance of many crops limits the use of saline water for irrigation, making it essential to select flora that naturally grow in saline soils. A soil is classified as saline when its EC exceeds 4 dS m^{-1}, with an exchangeable sodium percentage below 15 and a sodium adsorption ratio below 13. These soils, also known as white alkaline soils or Solonchaks, generally reduce germination and development in most crops. Therefore, it is necessary to consider crop alternatives adapted to adverse conditions, such as halophyte plants (Biswas and Naher, 2019; Gómez-Bellot *et al*., 2021; Sparks *et al*., 2024).

Halophyte plants constitute a small group representing about 1 % of global flora, encompassing around 2500 genera that include shrubs, bushes, mangroves, and grasses capable of growing in environments with high salt concentrations (Sánchez and Matos, 2018; Lee *et al*., 2024). These plants have evolved to tolerate high salinity and require salt exposure for optimal growth, completing their life cycle in salinities of 200 mM NaCl or higher. However, a precise threshold cannot be defined due to their

taxonomic and ecological complexity (Behera and Ramachandran, 2021; Cárdenas-Pérez *et al*., 2021; Teotia and Chaudhary, 2024).

Based on their degree of salinity tolerance, halophyte plants are divided into obligate halophytes and facultative halophytes. Obligate halophytes grow and develop in highly saline environments, while facultative halophytes can develop in habitats with low or no salinity. Their classification remains ambiguous because different authors use diverse criteria such as anatomy, tolerance mechanisms, and salt tolerance intensity (Rahman *et al*., 2021).

From a physiological perspective, considering salinity tolerance and ion accumulation and transport, they can be classified into three types: recritohalophytes, which secrete salt through external salt glands; euhalophytes, which accumulate salt in the vacuoles of green succulent tissues of leaves and stems, reducing the ionic content in the cytoplasm; and salt-exclusion halophytes, which accumulate large amounts of salt in tissue vacuoles (Lu *et al*., 2021; Rahman *et al*., 2021).

In functional terms, halophyte plants have developed specialized mechanisms to tolerate salt stress and maintain cellular osmotic balance. These include sequestration of Cl^- and Na^+ ions in vacuoles, accumulation of osmoprotectants to reduce osmotic potential, selective membrane transporters to regulate salt adsorption and exclusion, and the production of defense metabolites such as superoxide and glutathione reductase to neutralize reactive oxygen species (Mzoughi and Majdoub, 2021; Rahman *et al*., 2021).

There is a wide range of salt concentrations in different types of water, from ultrapure water to seawater (Table 2). This classification is important when assessing the salinity tolerance of halophyte plants, as each species has a specific threshold for salt exposure. Ultrapure and pure water have extremely low TDS concentrations and are therefore unsuitable for irrigating halophytes, especially non-facultative species that require saline conditions for optimal growth. In contrast, brackish, saline, and seawater contain TDS levels consistent with the conditions tolerated by halophytes, enabling the use of saline discharges from desalination plants for irrigating species adapted to high salinity.

Table 2. Electrical conductivity (EC) and total dissolved solids (TDS) across different water types (Sarathe *et al*., 2022).

Water	EC (dS m^{-1})	TDS (mg L^{-1})
Ultrapure	0–0.00004	0–0.03
Pure	0.00004–0.00046	0.03–0.30
Deionized	0.00046–0.00465	0.30–3.00
Potable	0.00465–1.55270	3.00–1000
Brackish	1.5527–15.5279	1000–10 000
Saline	15.5279–46.5838	10 000–30 000
Sea water	46.5838–77.6397	30 000–50 000

Salinity tolerance of halophyte plants

Salinity tolerance is a key criterion for selecting halophyte species suitable for reusing brine from desalination processes, thereby reducing environmental impact and supporting circular economy strategies. Halophyte species exhibit varying tolerance levels (high, medium, and low) depending on their physiological adaptations (Table 3).

Table 3. Salinity tolerance classification of halophyte crops based on electrical conductivity (EC) and total dissolved solids (TDS) values.

Crop	Salinity tolerance		Tolerance level TDS (mg L^{-1})	Reference
	EC (dS m^{-1})	TDS (mg L^{-1})		
Suaeda salsa (L.) Pall.	62.11	40 000	High >30 000	Wang *et al*. (2023)
Salicornia bigelovii Torr.	55	35 420		Cárdenas-Pérez *et al*. (2021), García-Galindo *et al*. (2021)
Rhizophora mangle L.	54.34	35 000		Lopes *et al*. (2023)
Chenopodium quinoa Willd.	54	34 776		Sánchez and Matos (2018)
Salicornia europaea L.	40	25 760	Medium 10 000–30 000	Araus *et al*. (2021)
Paspalum vaginatum Sw.	15	9960	Low 5000–10 000	Chavarria *et al*. (2021)
Puccinellia spp.	13.6	8766		Vaziriyeganeh *et al*. (2022)
Stenotaphrum secundatum (Walter) Kuntze	10	6440		Ascencios *et al*. (2019)
Zoysa japonica Steud.	10	6440		Hooks *et al*. (2022)
Atriplex nummularia Lindl.	9.07	5844		Christiansen *et al*. (2022)
Atriplex halimus L.	7.9	5087		Gómez-Bellot *et al*. (2021)
Crithmum maritimun L.	7.9	5087		Gómez-Bellot *et al*. (2021)

Cultivation of halophyte plants with different salinity tolerance

Highly tolerant species such as *Suaeda salsa* (L.) Pall. (Figure 4A), *Salicornia bigelovii* Torr. (Figure 4B), *Rhizophora mangle* L. (Figure 4C), and *Chenopodium quinoa* Willd. (Figure 4D) are ideal crops for areas with high salinity levels (Table 3). These halophyte species are adapted to extreme salinity and can be cultivated in arid or coastal zones where saline or brackish water predominates (Sánchez and Matos, 2018). For example, *S. salsa* tolerates salinity up to 40 000 mg L^{-1}, making it suitable for saline soils irrigated with brackish water and useful as forage in arid regions (Wang *et al*., 2023).

Species such as *Salicornia europaea* L. (Figure 4E) are suitable for coastal areas with moderate salinity (Table 3). This crop shows better growth when irrigated with water at 40 dS m^{-1} and can be used for forage, biodiesel, and applications in the pharmaceutical and cosmetic industries (Araus *et al*., 2021). In contrast, species with lower salinity tolerance (Figure 4F–L) perform better in slightly saline soils (Table 3). *Crithmum maritimum* L. (Figure 4F) and *Atriplex halimus* L. (Figure 4G) can be irrigated with reverse osmosis brine at 4.7–7.9 dS m^{-1} without adverse effects on growth,

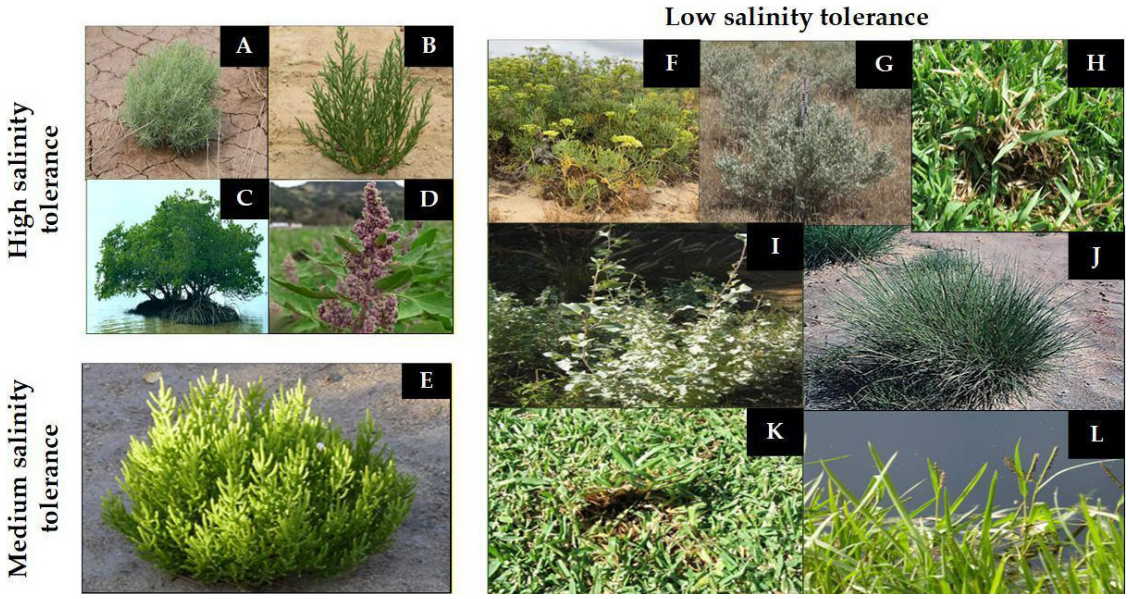

Figure 4. Representative halophyte species with different levels of salt tolerance. A: *Suaeda salsa* (L.) Pall. (Gao *et al*., 2022); B: *Salicornia bigelovii* Torr. (García-Galindo *et al*., 2021); C: *Rhizophora mangle* L. (Lopes *et al*., 2023); D: *Chenopodium quinoa* Willd. (Pizo-Ossa *et al*., 2024); E: *Salicornia europaea* L. (Araus *et al*., 2021); F: *Crithmum maritimum* L. (Roxo *et al*., 2023); G: *Atriplex halimus* L. (Gómez-Bellot *et al*., 2021); H: *Stenotaphrum secundatum* (Walter) Kuntze (Ascencios *et al*., 2019); I: *Atriplex nummularia* Lindl. (Christiansen *et al*., 2022); J: *Puccinellia ciliata* Bor (Çınar and Ünay, 2024); K: *Zoysia japonica* Steud. (Hooks *et al*., 2022); L: *Paspalum vaginatum* Sw. (Chavarria *et al*., 2021).

supporting the use of brine for halophyte irrigation across salinity levels ranging from brackish water to seawater (Gómez-Bellot *et al*., 2021). Likewise, *Atriplex nummularia* Lindl. (Figure 4I) maintains good bromatological quality, particularly in crude protein (14.36 %), organic matter (69.91 %), mineral matter (30.09 %), and dry matter (22.43 %), when irrigated with desalination brine (Christiansen *et al*., 2022). Species of *Atriplex* have been widely studied for their tolerance to saline effluents from brackish water desalination (Sánchez and Matos, 2018).

These crops have significant potential for agriculture and the rehabilitation of saline-affected areas. Using brine from desalination processes represents an alternative irrigation source that reduces discharge volumes and provides added value. However, factors such as brine properties, the irrigation method, volume and frequency, and soil characteristics, including texture, moisture, and ion concentrations, must be considered to assess economic feasibility and prevent environmental risks (Lee *et al*., 2024).

Halophyte species with agroindustrial potential

The production potential of halophytes varies according to species and the environmental conditions. Species with the greatest agroindustrial relevance are

characterized by high salinity tolerance and high biomass production. Some halophyte crops can reach yields of 10–20 Mg of dry biomass per hectare when irrigated with seawater (Table 4). These traits position them as valuable resources for multiple industries (Lee *et al*., 2024).

In the food industry, *Salicornia bigelovii* and *Suaeda salsa* stand out for their high protein content (16–18 %), essential oils (up to 30 %), and carbohydrates, making them valuable for various industrial applications. The oil extracted from *S. bigelovii* is rich in polyunsaturated fatty acids, making it an ideal input for the production of edible oils and nutritional supplements. In addition, *S. bigelovii* and *S. europaea* have been described as potential substitutes for common salt, as consuming salt derived from these plants, with equivalent sodium levels, has little effect on blood pressure. In countries such as Korea and Japan, *Salicornia* is marketed as a gourmet product (Cárdenas-Pérez *et al*., 2021; Wang *et al*., 2023). *Chenopodium quinoa* has a high protein content of 14.1 %, surpassing crops such as rice (8.1 %), wheat (7.2 %), and corn (9.9 %). Its seeds contain essential amino acids, vitamins (A, B2, and E), and minerals such as calcium, magnesium, iron, copper, zinc, and lithium (Yousfi *et al*., 2025), allowing its use in bread, desserts, and other dishes prepared from its grains and leaves (Tourajzadeh *et al*., 2024).

Halophyte species also play an important role in livestock nutrition due to their ability to produce high-quality biomass under saline conditions. Several halophyte species,

Table 4. Advantages and disadvantages of halophyte species of agricultural interest (Hameed *et al*., 2024).

	Advantages	Disadvantages	References
Suaeda salsa (L.) Pall. *Suaeda fruticosa* (L.) Forssk.	Provide cardioprotective foods, support cultivation of salt-tolerant plants, act as nitrogen adsorbents in saline agriculture, and accumulate heavy metals for soil remediation.		Li *et al*. (2023)
Atriplex nummularia Lindl. *Atriplex halimus* L.	Useful for livestock feed, human food, oil extraction, and soil remediation; adaptable to saline conditions and suitable for commercial-scale crops.	Vulnerable to habitat loss, climate change, and invasive species; limited knowledge on mechanisms, optimal conditions, and economic value; barriers to consumer acceptance and commercial expansion.	Navarro-Torre *et al*. (2023)
Chenopodium quinoa Willd. *Crithmum maritimum* L.	Highly salt-tolerant; grow adequately in arid and coastal areas with saline or brackish water; *C. quinoa* provides grains and leaves widely used in food products.		Navarro-Torre *et al*. (2023) Sánchez and Matos (2018) Tourajzadeh *et al*. (2024)
Salicornia bigelovii Torr. *Salicornia europaea* L.	Reduce soil salinity by absorbing sodium; valuable in food and nutraceutical industries as salt substitutes; suitable for commercial cultivation under saline irrigation.		Cárdenas-Pérez *et al*. (2021) Jiang *et al*. (2025) Navarro-Torre *et al*. (2023)

such as *A. nummularia*, *S. salsa*, and *S. bigelovii,* are valuable in animal feed because of their high protein and fiber content (Cárdenas-Pérez *et al*., 2021), while *S. europaea* has also been recognized as a nutritious fodder for livestock (Araus *et al*., 2021). In the energy sector, *Salicornia* seeds are used in biodiesel production due to their oil content (26–33 %), which exceeds that of cotton (15–24 %) and soybeans (17–21 %). Their oil yield can reach 11 442 kg ha^{-1}, surpassing conventional crops and offering a sustainable biofuel option. Species of the genus *Atriplex* have also shown potential for bioethanol production (Cárdenas-Pérez *et al*., 2021). For the pharmaceutical and cosmetics industry, *S. bigelovii*, *S. europaea*, and *S. salsa* contain flavonoids, antioxidants, and phenolic compounds with anti-inflammatory and antibacterial properties, enabling their use in health and skincare products (Araus *et al*., 2021; Wang *et al*., 2023).

From an environmental perspective, genera such as *Suaeda* and *Atriplex* are effective in phytoremediation, as they absorb nitrogen and phosphorus from the soil. Species such as *A. halimus*, *S. bigelovii*, and *S. europaea* can accumulate heavy metals including cadmium, zinc, copper, selenium, nickel, and lead, while *C. quinoa* can accumulate chromium in its tissues (Cárdenas-Pérez *et al*., 2021). Regarding soil salinity mitigation, plants such as *S. fruticosa*, *S. salsa*, and *Sesuvium portulacastrum* L. reduce salinity and alkalinity by absorbing sodium ions and storing salts in their tissues (Jiang *et al*., 2025).

CONCLUSIONS

Water scarcity continues to drive the expansion of desalination technologies, making the sustainable management of resulting brine increasingly important. Utilizing brine as an input for halophyte cultivation offers a circular-economy pathway that can diversify agricultural production and create new economic and food opportunities. However, scientific output on the combined topics of halophytes, reverse osmosis brine, and circular-economy applications remains low. Future research should focus on identifying halophytes with high nutritional and economic value, determining their tolerance thresholds to maximize biomass yield, and assessing viable economic activities that justify cultivation costs. Exploring plant-microorganism interactions that enhance early germination and establishment will be essential to improve halophyte production systems.

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