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Article

Feasibility of using reverse osmosis brines for crop cultivation of *Salicornia bigelovii* under arid conditions

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Abstract: The increased use of desalination technologies has generated significant volumes of brine; the improper management poses an environmental risk. The reuse of this byproduct for irrigating halophytic species emerges as a sustainable alternative, helping to reduce ecological impacts and promote agricultural production in areas affected by salinity. Therefore, the objective of this study was to evaluate the feasibility of using brine from reverse osmosis processes in the cultivation of *Salicornia bigelovii* by analyzing its effects on soil salinization, plant growth, biomass production, and plant protein content. The study evaluated the morphometric response of *Salicornia bigelovii* to different irrigation salinity concentrations (34,000–50,000 mg L^{-1} salinity). Comparing the concentration of 42,000 mg L^{-1} with the others treatments, it was found that this concentration promoted plant growth, as evidenced by greater height, number of branches, other treatments, it was found that this concentration promoted plant growth, as evidenced by greater height, number of branches, and fresh and dry weight. In addition, it maintained a high protein content (9.16%) compared to the control of 34,000 mg L^{-1} (10.16%). However, at 50,000 mg L^{-1} salinity, a significant reduction was observed in all evaluated parameters, indicating that the plant tolerance threshold was exceeded due to effects such as ionic toxicity and osmotic stress. Furthermore, physicochemical analyses of the substrate revealed that salinity induces conditions similar to those found in Solonchak, a type of coastal saline soil characterized by high electrical conductivity and high sodium content. These findings support the use of brine as a viable irrigation alternative, provided that plants salt tolerance limits are respected, establishing *Salicornia bigelovii* as a promising option for cultivation in coastal and desert areas.

Keywords: desalination; halophytes; salinity; sustainability; water scarcity

1. Introduction

The increasing scarcity of freshwater, especially in arid and semiarid regions, has driven the development of technologies that make it possible to harness unconventional water sources, among these, desalination has established as a viable strategy for ensuring the supply of water for human, agricultural, and industrial uses, as it allows for the production of water free of salts and contaminants from saline sources, such as seawater or brackish water, without relying on the hydrological cycle [1–3]. However, this process generates large volumes of brine as a byproduct, especially in reverse osmosis systems, a technology used in approximately 65% of desalination plants worldwide due to its high performance and low production costs at scale [4–6]. The resulting brine is characterized by high concentrations of salts, organic matter, and other compounds that, when discharged, can cause osmotic imbalances in marine ecosystems and degrade soil quality in terrestrial ecosystems [7,8].

To minimize the environmental impact of brine generation, various strategies have been proposed to ensure proper disposal and recovery. Among the most relevant alternatives are the production of sodium hydroxide (NaOH), evaporation ponds for sodium chloride (NaCl) recovery, the extraction of metals of interest such as lithium (Li) and magnesium (Mg) through electrodialysis and electrolysis processes, and, finally, its use in agriculture as irrigation water for the cultivation of halophytic species [9].

Halophytic species exhibit physiological adaptations that enable them to grow in highly saline soils, thanks to their ability to regulate ion uptake and maintain cellular osmotic balance. This approach not only mitigates the negative effects of brine disposal but also offers new opportunities for agricultural development on marginal lands affected by salinization [10], because soil salinity in agricultural lands is a global problem affecting approximately 77 million hectares. This has created a need to explore alternative crops that can tolerate saline environments without compromising freshwater use [11].

In this context, *Salicornia bigelovii*, a halophyte with high salt tolerance, is considered one of the most promising species within the Salicornia genus, due to its high biomass production and the significant protein and oil content in its seeds, which give it high nutritional and agro-industrial value [12]. Various studies have shown that the biomass of *Salicornia bigelovii*, irrigated with seawater, can be efficiently incorporated into the feed of livestock such as lambs, goats, and camels in proportions ranging from 25% and 50%, reinforcing its potential as a sustainable alternative in livestock systems [13].

In terms of food security, this species represents a viable option for mitigating malnutrition, as it provides a high protein food source that can be consumed in the form of flour, salads, and green salt, all byproducts of *Salicornia bigelovii* [12,14,15]. Furthermore, in coastal environments and highly saline soils, it can serve as a means of subsistence for vulnerable communities by enabling the use of land where conventional crops do not thrive due to soil degradation [16]. Therefore, this approach seeks to minimize environmental impact, create jobs, produce food through sustainable agriculture, and promote economic development in the region through projects that improve living conditions [17].

From an environmental perspective, *Salicornia bigelovii* ability to grow using seawater or desalination brine as an irrigation source represents a significant advantage, as it helps reduce pressure on freshwater resources [18]. For example, Robertson et al. [19] analyzed the financial viability of utilizing reject brine generated at a reverse osmosis plant and reported that using this brine as irrigation water for *Salicornia bigelovii* cultivation yielded positive economic returns. In this context, the use of brine, whose disposal cost ranges from \$0.32 to \$0.66 per cubic meter, accounting for between 5% and 33% of the total operating cost of desalination plants, can be transformed into an opportunity to recover value from this waste, reducing its environmental impact and promoting its integration into production systems based on halophyte crops [20,21]. On the other hand, Al-Tamimi et al. [22] reported that they used reverse osmosis brine from the desalination unit at concentrations of 25,641 mg L^{-1} of salts, obtaining yields of 16 kg m^{-2} *Salicornia bigelovii* biomass. Its market value, estimated at approximately $4.73 per kilogram, reinforces its economic viability as an alternative crop [20].

The study will provide experimental evidence on the effects of different brine concentrations on the crops agronomic performance and will also help identify the salt tolerance threshold of *Salicornia bigelovii.* This aspect constitutes a significant contribution and novelty, given that the existing literature reports the use of specific salt concentrations but lacks precise information on the maximum optimal salinity level that the plant can tolerate without significantly affecting its growth, biomass production, and vegetable protein content, as well as the possible synergy derived from the use of brine from a desalination plant. This approach not only generates more precise quantitative evidence but also enhances the practical applicability of using brine as a resource in agricultural systems. Furthermore, the study contributes to consolidating a sustainable strategy based on circular economy principles by transforming a desalination byproduct into a productive input, thereby expanding opportunities for agricultural development in areas affected by water scarcity and soil salinization. Furthermore, the research gap in bibliometric studies on Elsevier's Science Direct platform indicate that scientific output on the combination of brine, reverse osmosis, and *Salicornia bigelovii* remains limited, as only two articles addressing these topics together have been identified, one published in 2019 and the other in 2023. This scarcity of information highlights the importance of continuing research aimed at adapting halophytic species through the use of brine as irrigation water, as well as evaluating its effects on different phenological stages and determining the salinity tolerance thresholds that maximize yield and its potential utilization [14].

Therefore, the objective of this study was to evaluate the optimal salinity concentration of brines from reverse osmosis processes for the cultivation of *Salicornia bigelovii* by analyzing their effects on soil salinization, plant growth, biomass production, and plant protein content.

2. Materials and methods

2.1. Collection and transplantation of *Salicornia bigelovii*

Salicornia bigelovii seedlings were collected from their natural habitat on Huivulai Island, Sonora, Mexico, at the following coordinates: 27° 03′ 51″ N, 109° 58′ 55″ W, during the month of March 2025 (**Figure 1a**). They were then individually transplanted into pots filled with peat moss substrate and transferred to Instituto Tecnológico de Sonora. They were kept in a greenhouse where they were randomly positioned. To control environmental variability (temperature and relative humidity), the area was maintained under automated climate control at 25°C ± 2°C and 35% relative humidity for 60 days. Each pot was treated with 250 mL of gibberellic acid (100 mg L^{-1}) to facilitate the seedlings adaptation to the new environment and reduce transplant related stress [23].

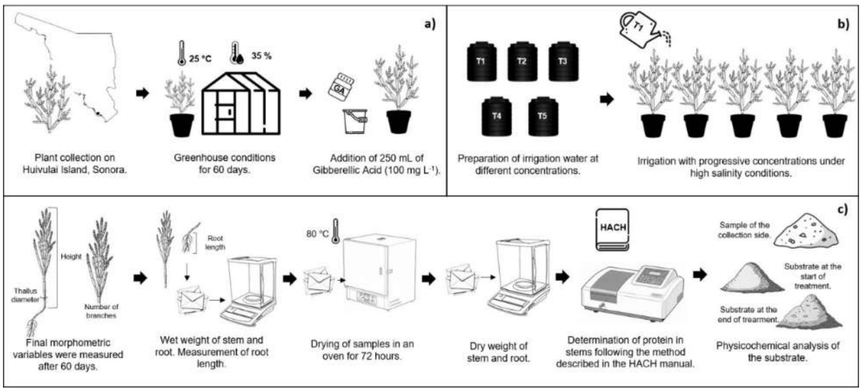


Figure 1. Diagram of the experimental process, ranging from the collection of *Salicornia bigelovii* to the measurement of the variables under study. **(a)** Collection and transplantation of *Salicornia bigelovii* under greenhouse conditions; **(b)** Irrigation application with different salt concentrations; **(c)** Measurement of morphometric parameters.

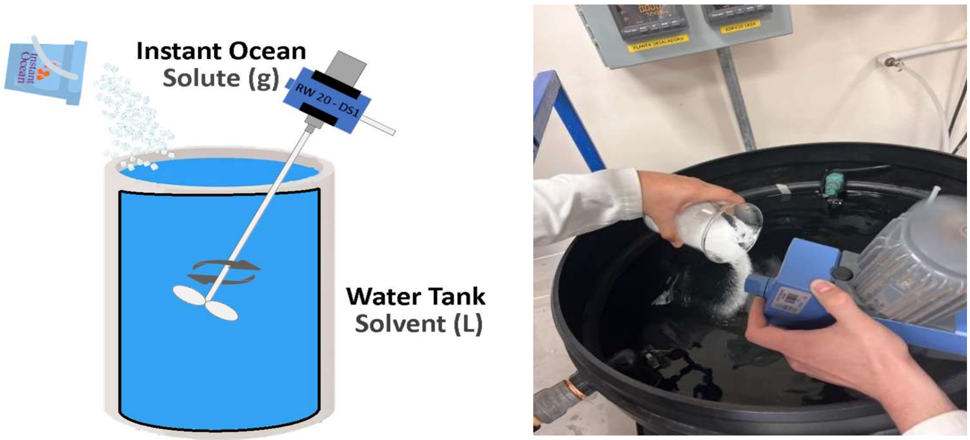
2.2. Irrigation application

A completely randomized design was used, with 5 treatments corresponding to different saline concentrations (34,000; 38,000; 42,000; 46,000 and 50,000 mg L^{-1}) and 9 replicates per treatment (**Figure 1b**). To prevent osmotic shock and promote the gradual adaptation of *Salicornia bigelovii* to high salinity conditions, a three stages irrigation regimen with gradual increases in salinity concentration was established [24]. This regimen was applied over a total period of 60 days, divided into three applications (**Table 1**). In the first application, all treatments began with a uniform salinity concentration of 12,000 mg L^{-1} for 15 days, Ohori et al. [25] identified this concentration as the minimum required for the growth of *Salicornia bigelovii*. In the second application, salinity was progressively increased according to the treatment for another 15 days. Finally, in the third application, the final concentration established for each treatment was reached and maintained at a constant level for 30 days. The control treatment corresponded to a salinity of 34,000 mg L^{-1}, equivalent to seawater (the natural habitat of *Salicornia bigelovii*), and served as a reference for comparing the effect of higher salinity levels.

Table 1. Application of different saline concentrations of irrigation water in the cultivation of *Salicornia bigelovii* and total volume used per treatment.

Treatment	Saline concentration final (mg L^{-1})	Application 1 period 15 day		Application 2 period 15 day		Application 3 period 30 day	
		Concentration (mg L^{-1})	Volume (L)	Concentration (mg L^{-1})	Volume (L)	Concentration (mg L^{-1})	Volume (L)
1	34,000	12,000	6	22,000	6	34,000	12
2	38,000	12,000	6	26,000	6	38,000	12
3	42,000	12,000	6	30,000	6	42,000	12
4	46,000	12,000	6	34,000	6	46,000	12
5	50,000	12,000	6	38,000	6	50,000	12

Different saline concentrations (Treatment 1, 2, 3, 4 and 5) were prepared. A total of 120 liters was prepared (**Figure 2**). In application 1, 30 liters were used over a 15 day period; in application 2, 30 liters were used over a 15 day period; and in application 3, 60 liters were used over a 30 day period. To achieve the appropriate concentration, distilled water was mixed with Instant Ocean synthetic salt (St. Blacksburg, VA, USA) which contains the ions listed in **Table 2** [26].



(a) **(b)**

Figure 2. General outline for the preparation of different irrigation water salinity concentrations. **(a)** Schematic diagram of salt dissolution in the water tank ; **(b)** Preparation and mixing of the saline solution under laboratory conditions.

Table 2. Ion composition of Instant Ocean synthetic salt [26].

Ion	Salt composition (% total weight)	Sal composition (mg L^{-1})
Chloride (Cl^-)	47.470	18,740
Sodium (Na^+)	26.280	10,454
Sulfate (SO_4^{2-})	6.600	2631
Magnesium (Mg^{2+})	3.230	1256
Calcium (Ca^{2+})	1.013	400
Potassium (K^+)	1.015	401
Bicarbonate (CO_3^{2-}/HCO_3^-)	0.491	194
Boron (B^{3+})	0.015	6
Strontium (Sr^{2+})	0.001	7.5
Solids Total	86.11 %	34,090
Water	13.88	-
Total	99.99 %	-

The mixture was homogenized using a Model RW 20DS1 digital mixer (Wilmington, NC, USA). To achieve the corresponding concentration in each treatment, the following formula was used Equation (1):

$$C_1V_1 = C_2V_2 \quad (1)$$

Where:

C_1, C_2 = Solution concentration 1, 2 (mg L^{-1}), as solute.

V_1, V_2 = Solution Volume 1, 2 (L), as solvent.

2.3. Morphometric variables

Morphometric variables were assessed to quantify seedling growth and development at the end of the treatment period. Characteristics of the aboveground and root systems were analyzed, including final height (cm), stem diameter (cm), number of branches (u), root length (cm), and fresh and dry weight (g) of the root and stem (**Figure 1c**).

2.3.1. Plant height, stem diameter, and branching

To determine the final height of the seedlings, a millimeter ruler was used to measure from the base of the stem (substrate level) to the apex of the main shoot. Measurements were taken in centimeters (cm), taking care to keep the stem vertical to ensure accuracy. Stem diameter was measured with a Vernier caliper (Truper Vernier Model Caldi-6MP, Jilotepec, State of Mexico, Mexico) to a precision of 0.01 mm. The measurement was taken at a standard height of 2 cm above the substrate surface, avoiding nodes or thickened areas. To quantify the number of branches, all secondary shoots emerging from the main stem were counted manually. The observation was carried out directly on each seedling [9,27,28].

2.3.2. Dry weight, fresh weight, and root length

The fresh weight of the root was determined after separating the seedling from the base of the stem. The root was then weighed using an analytical balance (Azcel Model CY 224C, Mumbai, Maharashtra, India). The final root length was measured before the drying process using a Vernier caliper (Truper Vernier Model Caldi-6MP, Jilotepec, State of Mexico, Mexico). To determine dry weight, the roots were placed in a drying oven (Yamato Scientific America Inc. Model DX402C, Santa Clara, CA, USA) at 80 °C for 72 h. Once drying was complete, the samples were weighed again on an analytical balance [9,27].

2.3.3. Dry and fresh weight of the stem

The fresh weight of the stem was determined after separating it from the root, ensuring no root tissue remained attached, and was measured using an analytical balance (Azcel Model CY 224C, Mumbai, Maharashtra, India). Subsequently, to obtain the dry weight, the samples were placed in a drying oven (Yamato Scientific America Inc. Model DX402C, Santa Clara, CA, USA) at a constant temperature of 80 °C for 72 h. Once drying was complete, the samples were weighed again on the analytical balance [9,29].

2.4. Protein determination

Protein content was determined indirectly from total nitrogen. Plant tissue samples were oven dried (Yamato Scientific America Inc. Model DX402C, Santa Clara, CA, USA) at 80 °C for 72 h and pulverized in a mortar. A 0.25 g sample was then weighed and subjected to acid digestion with 4 mL of sulfuric acid. The digested sample was placed in a preheated HACH digester at 440 °C for 1 minute, then 7 mL of 50% hydrogen peroxide was added and heated for 4 minutes. After digestion, the extracts were diluted in 100 mL of distilled water, and nitrogen was determined using

HACH colorimetric kits with a spectrophotometer (HACH Company DR3900, Loveland, Colorado, USA). The resulting total nitrogen concentration was converted to crude protein using a conversion factor of 6.25. All analyses were performed in triplicate [30–33].

2.5. Physicochemical analyses of peat moss substrate and solonchak coastal soil

Physicochemical parameters of the peat moss substrate were determined prior to transplanting as an initial condition and at the end of the *Salicornia bigelovii* crop harvest to evaluate the effects of saline treatments on substrate properties. Additionally, a sample of coastal soil representative of the species natural habitat was analyzed and used as a comparative reference. The analyses included measurements of electrical conductivity (dS m^{-1}), pH, sodium content (kg ha^{-1}), and Exchangeable Sodium Percentage (%), following the procedures established in Mexican Official Standard NOM-021-RECNAT-2000 for the physicochemical characterization of soils.

2.6. Statistical analysis

A one-way analysis of variance (ANOVA) was performed to assess the differences between the means of the five treatments. Subsequently, Fisher multiple range test was applied with a significance level of $p = 0.05$. The statistical analysis was conducted using Minitab 17 software, version 21.1.0.

3. Results and discussion

3.1. Morphometric variables

The results obtained show that the morphological response of *Salicornia bigelovii* was significantly influenced by the salinity concentration of the irrigation water (**Figure 3**). In general terms, treatments with 34,000 mg L^{-1} (control) and 42,000 mg L^{-1} salinity favored the plants vegetative development, as reflected in higher values for height, number of branches, stem diameter, and fresh and dry biomass, compared to treatments exposed to higher salinity levels (**Table 3**).

In particular, treatment with a salinity of 42,000 mg L^{-1} presented the highest values for fresh and dry weight of stems and roots, as well as for root length, stem diameter, branching, and height, suggesting that this concentration may represent a level close to the optimal salt tolerance for the growth of this halophyte. Recent studies have documented that Salicornia possesses physiological, biochemical, and molecular mechanisms that allow it to maintain growth under saline conditions. However, when its tolerance threshold is exceeded, salt stress causes a significant reduction in vegetative development [34].

Furthermore, at a salinity concentration of 50,000 mg L^{-1}, a significant decrease was observed in all the morphometric parameters evaluated, indicating that the plants salt tolerance threshold had been exceeded. This negative effect can be attributed to ionic toxicity and the induction of physiological drought, factors that interfere with water uptake, cell division, and the plants general metabolism [15]. These results are consistent with previous studies reporting that *Salicornia bigelovii* is highly tolerant to salinity, but excessive salt concentrations can induce osmotic stress, compromising essential physiological functions [9,35].

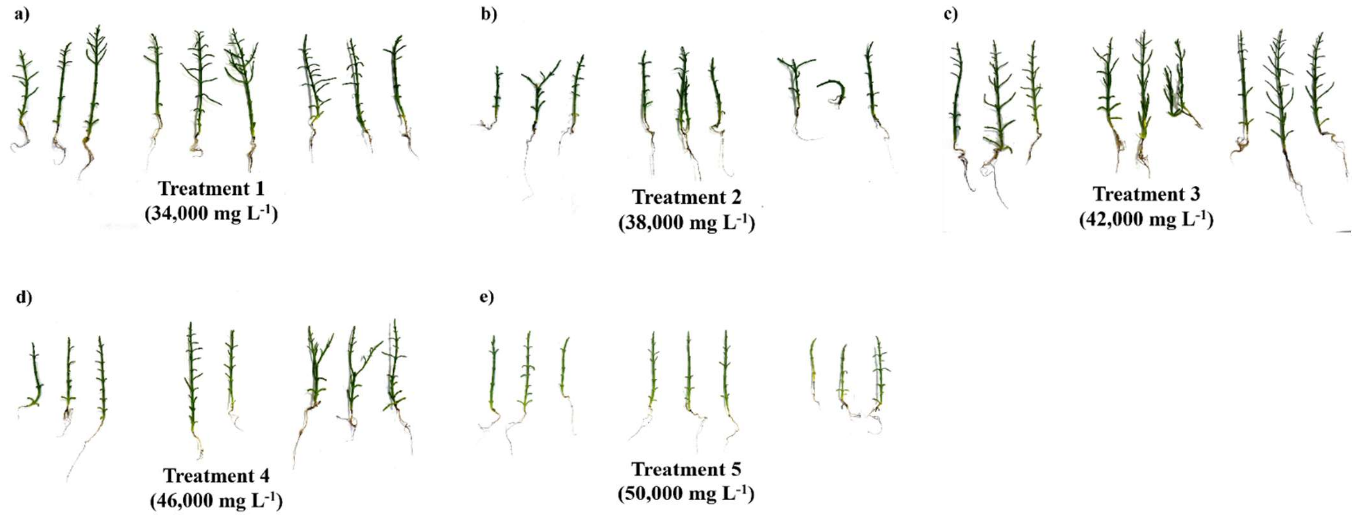


Figure 3. Morphophysiological development of *Salicornia bigelovii* under different salinity treatments in irrigation water. **(a)** Treatment 1 (34,000 mg L^{-1}), showing greater stem elongation and branching; **(b)** Treatment 2 (38,000 mg L^{-1}), showing moderate vegetative development; **(c)** Treatment 3 (42,000 mg L^{-1}), showing a response similar to Treatment 1 in terms of growth and branching; **(d)** Treatment 4 (46,000 mg L^{-1}), showing reduced plant growth under conditions of higher salinity; **(e)** Treatment 5 (50,000 mg L^{-1}), showing the lowest vegetative development and reduced branching due to high salinity stress.

Table 3. Morphometric parameters of *Salicornia bigelovii* under different irrigation water salinity concentrations.

Treatment	Saline concentration (mg L^{-1})	Plant height (cm)	Branches (u)	Stem diameter (cm)	Root length (cm)	Fresh weight (stem) (g)	Fresh weight (root) (g)	Dry weight (stem) (g)	Dry weight (root) (g)
1	34,000	10.31±0.63 a	13.00±1.12 a	0.50±0.01 a	8.16±0.47 b	2.15±0.22 b	0.07±0.008 b	0.21±0.01 b	0.02±0.001 b
2	38,000	6.95±0.51 b	6.00±0.83 c	0.46±0.01 bc	9.78±1.16 ab	1.17±0.10 cd	0.06±0.005 b	0.12±0.01 c	0.02±0.001 b
3	42,000	10.74±0.72 a	13.00±1.08 a	0.50±0.01 a	10.93±0.99 a	2.62±0.20 a	0.17±0.022 a	0.30±0.02 a	0.05±0.006 a
4	46,000	7.68±0.40 b	9.67±1.55 b	0.47±0.00 ab	9.03±0.76 ab	1.47±0.17 c	0.07±0.014 b	0.17±0.02 bc	0.02±0.003 b
5	50,000	5.98±0.67 b	9.33±1.03 b	0.43±0.01 c	9.01±0.59 ab	0.89±0.08 d	0.04±0.003 b	0.11±0.01 d	0.01±0.001 b

Mean ± standard error (n=9). Different letters indicate a significant difference ($P \leq 0.05$) according to Fisher test.

Among the main tolerance mechanisms described in Salicornia in response to high Na^+ concentrations are the accumulation of water in parenchyma tissues, which allows for the dilution of intracellular salts, the maintenance of cell turgor, and the preservation of tissue function [15]. Additionally, this species activates various adaptive responses, including osmoregulation, ion compartmentalization, synthesis of osmolytes and antioxidant compounds, and modulation of phytohormones and enzymes related to salt stress. These physiological characteristics explain its ability to develop in hypersaline environments and support its growing interest as a strategic crop in arid regions [16].

In this context, the results obtained demonstrate the potential use of brine from desalination plants for irrigating *Salicornia bigelovii* during its seedling stage, which would help optimize the use of this resource, reduce the environmental impacts associated with its disposal, and promote a circular economy approach [36]. It is also noted that is necessary to analyze crop yield throughout complete growth cycles, including reproductive phases, seed production, and total biomass yield under brine irrigation conditions, as well as to assess the stress experienced by the plant upon each exposure to salinity levels higher than seawater concentration.

3.2. Protein determination

In general, protein content decreased as salinity increased. The highest protein value was 34,000 mg L^{-1}, and the lowest was 50,000 mg L^{-1} (**Figure 4**) The treatments: control (34,000 mg L^{-1}) and 42,000 mg L^{-1} showed significantly higher protein levels ($p \leqslant 0.05$) than the remaining treatments. Across the evaluated range (34,000–50,000 mg L^{-1}), protein content declined by 2.41 percentage points, corresponding to approximately a 23.7% reduction relative to the control. This decline suggests that elevated salinity may negatively affect protein accumulation in *Salicornia bigelovii*, likely due to osmotic stress and ionic toxicity, which could limit protein biosynthesis and overall nitrogen metabolism [15,35,36].

Despite this general trend, protein content did not decrease linearly with salinity. The pronounced reduction observed at 38,000 mg L^{-1}, followed by a partial recovery at 42,000 mg L^{-1}, is consistent with a threshold dependent physiological response. One plausible hypothesis is that moderate salinity initially disrupts metabolic balance, reducing protein synthesis and increasing protein turnover. However, once specific tolerance mechanisms are activated, partial metabolic stabilization may occur. This transient response may reflect the energetic cost of osmotic adjustment. Under intermediate stress, plants likely allocate ATP toward the synthesis of compatible osmolytes (e.g., proline, glycine betaine, and soluble sugars) and the active sequestration of ions into vacuoles via H^+-ATPases. These processes are essential for maintaining cellular turgor, but they may temporarily limit protein accumulation [37]. At 42,000 mg L^{-1}, the partial recovery in protein content may suggest the activation of adaptive mechanisms such as improved ionic regulation, osmolyte balance, and protein stabilization, as described by Rozema and Schat [38]. However, direct measurements of osmolytes, ATPase activity, or ion compartmentalization are recommended to corroborate these hypotheses.

The protein content values obtained are consistent with those reported in previous studies. Christiansen et al. [32] reported an average protein content of 8.12% in *Salicornia bigelovii* grown with reverse osmosis brine (24,000 mg L^{-1} salinity) in Dubai. Similarly, López-Corona et al. [27] reported a content of 7.4% in the stems of plants grown under field conditions in the coastal region of Hermosillo, Sonora.

The high protein levels obtained in the treatments with salinity levels of 34,000 (control) and 42,000 mg L^{-1} emphasize the potential of *Salicornia bigelovii* as a viable alternative for forage and feed production in arid and semi-arid coastal areas. This interest has promoted various initiatives to encourage its cultivation under sustainable production models in Mexico [27,36]. Based on these analyses, it is recommended to study a concentration range of 42,000 ‒ 46,000 mg L^{-1} to more precisely define the optimal physiological threshold for maximizing the growth and nutritional quality of *Salicornia bigelovii.*

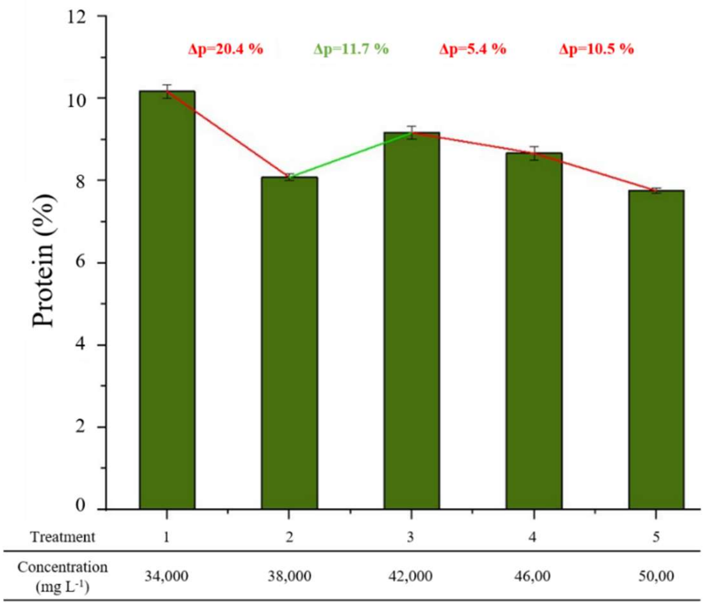


Figure 4. Protein content under different irrigation water salinity concentrations.

3.3. Physicochemical analysis of the substrate and Solonchak coastal soil

Physicochemical analyses show that the peat moss substrate under salt treatments establishes relevant comparisons with conditions observed in coastal soils classified as Solonchak. The electrical conductivity of the substrate increased from 0.59 dS m^{-1} in the 34,000 mg L^{-1} (control) to 63.10 dS m^{-1} in the 50,000 mg L^{-1} salinity treatment (**Table 4**), reflecting an accumulation of soluble salts similar to that observed in Solonchak coastal soils. Solonchak soils are saline, characterized by electrical conductivity greater than 15 dS m^{-1} in the top 125 centimeters; however, values as high as 150 dS m^{-1} have also been reported [39,40].

Table 4. Physicochemical properties of the substrate, solonchak soil, and applied treatments.

Source/treatment	Concentration (mg L^{-1})	CE (dS m^{-1})	pH	Na (kg ha^{-1})	ESP (%)
Source					
Peat moss substrate		0.59	4.30	3024	6.68
Treatment					
1	34,000	46.60	4.53	16,272	20.33
2	38,000	51.40	4.66	16,128	23.24
3	42,000	51.50	4.44	19,440	26.08
4	46,000	52.50	4.61	20,880	25.87
5	50,000	63.10	4.45	24,840	29.27
Soil natural habitat		85.10	7.34	17,280	32.24

EC: Electrical conductivity, ESP: Exchangeable Sodium Percentage.

Electrical conductivity is a direct indicator of the concentration of soluble salts in the soil, therefore, an increase in conductivity reflects higher salinity. This increase in salinity raises soil osmotic pressure, limiting water uptake by the roots and disrupting various physiological processes in the plant. Excessive salt accumulation in the root zone alters the soils osmotic potential and limits plant growth significantly, particularly in arid and semi arid regions where salinization represents a growing problem associated with inadequate agricultural management and climate change [41].

On the other hand, the sodium (Na) content increased significantly with salinity, reaching maximum values of 24,840 kg ha^{-1} in the most saline treatment (50,000 mg L^{-1}). The increase in soil sodium concentration is one of the main factors associated with soil degradation. Sodium accumulation leads to surface sealing, reduces porosity, and decreases hydraulic conductivity, restricting water movement as well as gas exchange in the soil. The high sodium concentrations observed in the applied treatments are comparable to those reported in Solonchak type coastal soils, which are characterized by high salinity. This condition is reflected in their high electrical conductivity values, indicative of a high concentration of soluble salts, among which sodium predominates [39,41,42].

The treatments applied increased the electrical conductivity of the peat moss substrate, from 0.59 dS m^{-1} to 63.10 dS m^{-1} in the treatment with the highest salinity, accompanied by an increase in sodium content from 3024 to 24,840 kg ha^{-1}. However, the substrate pH remained relatively stable within an acidic range of 4.30–4.66. This behavior contrasts somewhat with that observed in many coastal soils, which typically have a neutral or slightly alkaline pH due to salt accumulation. This difference can be attributed to the acidic nature of the peat moss substrate [39,43].

The results suggest that the salinization observed was predominantly of the neutral type from an acid base perspective, likely due to the chemical composition of the applied salts (85.64% NaCl); therefore, it is recommended to monitor changes in the soil through plant and soil nutrient balances following the continuous and cumulative use of desalination brines to determine potential impacts.

This type of salt increases the electrical conductivity of the medium without inducing the formation of hydroxyl groups that could raise the pH. This effect is explained by the fact that sodium adsorbs at the exchange sites of the substrate, increasing exchangeable sodium and promoting the displacement of hydrogen ions (H^+) into the soil solution [44].

Furthermore, in substrates rich in organic matter, such as peat moss, the organic matrix contains abundant acidic functional groups, primarily carboxyl (-COOH) and phenolic (-OH) groups, which confer a high buffering capacity. This characteristic helps stabilize H^+ activity and limit significant changes in pH even under considerable increases in salinity. This behavior is consistent with previous reports indicating that media with high organic matter content tend to buffer pH variations even when salinity increases, which coincides with the pH results of this study [39,43,45].

In this context, soil salinization is currently one of the main constraints on agricultural production worldwide and poses a significant challenge to food security, given that it is estimated that more than 900 million hectares are affected by this process [42]. Projections indicate that the salinization of agricultural lands will intensify by 2050, exacerbating the degradation of arable soils. This problem is further exacerbated by population growth, which will require a 35–56% increase in food production by 2050. Given this scenario, various strategies have been proposed to minimize the impact associated with brine generation and promote its recovery, including the production of sodium hydroxide, NaCl recovery, metal extraction, and, finally, its use in agriculture as irrigation water for the cultivation of halophytic species [9]. The use of brine in agriculture is emerging as a sustainable alternative, integrating principles of the circular economy and efficient water resource management. In this context, the present study specifically proposes the use of brines generated in reverse osmosis processes for the irrigation of *Salicornia bigelovii* as a viable strategy for the valorization of these effluents [34].

4. Conclusion

Salicornia bigelovii exhibits a high capacity to adapt to saline conditions, showing optimal morphometric development and protein content in treatments with irrigation water at 34,000 mg L^{-1} (control) and 42,000 mg L^{-1} salinity. In particular, the treatment with 42,000 mg L^{-1} salinity showed morphometric results that were statistically similar to the control treatment ($p = 0.05$). Furthermore, the 42,000 mg L^{-1} salinity treatment achieved a protein content significantly higher than that of other treatments with higher salinity. In contrast, the treatment with 50,000 mg L^{-1} salinity showed a drastic reduction in all evaluated parameters, indicating that this concentration exceeds the physiological tolerance threshold of *Salicornia bigelovii*. With regard to the substrate, electrical conductivity increased progressively with salinity, reaching 63.10 dS m^{-1} of electrical conductivity and 24,840 kg ha^{-1} of sodium in the most saline treatment (50,000 mg L^{-1} salinity). In general terms, an adequate simulation of the Solonchak soils typical of arid and semi-arid regions with halophytic vegetation was obtained. Together, the results demonstrate the viability of crop cultivation under saline conditions, with a salinity concentration of 42,000 mg L^{-1} identified as the most favorable, as it promotes superior morphological growth and higher protein content. These findings confirm that brine water from desalination processes can be used as an alternative source of irrigation, provided it remains within the crop's optimal salinity ranges (35,000–42,000 mg L^{-1} salinity). This approach promotes the circular economy model by reusing brine and cultivating *Salicornia bigelovii*, with the aim of minimizing environmental impact, creating jobs, producing food through sustainable agriculture, and encouraging community participation in projects that improve their living conditions. In this way, *Salicornia bigelovii* emerges as a viable and sustainable agricultural option in regions affected by water scarcity and salinity.

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