EFFECT OF EDAPHIC CONDITIONS AND SALINE OF IRRIGATION WATER ON THE EMERGENCE AND INITIAL DEVELOPMENT OF *Salicornia bigelovii* CULTIVATION: A PERSPECTIVE FOR AGRICULTURE IN COASTAL AREAS †

[EFECTO DE LAS CONDICIONES EDÁFICAS Y LA SALINIDAD DEL AGUA DE RIEGO EN LA EMERGENCIA Y DESARROLLO INICIAL DEL CULTIVO DE *Salicornia bigelovii*: UNA PERSPECTIVA PARA LA AGRICULTURA EN ZONAS COSTERAS]

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SUMMARY

Background. The desalination process is key to addressing water scarcity; however, it faces challenges such as the environmental impact of brine. Several strategies minimize this impact, including the use of halophytes. *Salicornia bigelovii* is a halophyte with multiple benefits. The phenological stages of germination and seedling are the most susceptible for establishment. In arid areas, agriculture depends on salinity-resistant plants to mitigate problems of soil degradation and water scarcity. **Objective.** To evaluate the impact of edaphic conditions and irrigation salt concentrations on the emergence and initial development of *Salicornia bigelovii*. **Methodology.** Part 1. Sowing was carried out in germination trays with three types of substrate and irrigated with fresh water for 50 days. Part 2. Sowing was carried out in peat moss substrate, four saline irrigation water treatments were applied: 0 M, 0.05 M, 0.10 M and 0.15 M. The variables evaluated were the percentage of emergence, plant height, root length, number of root hairs, fresh weight and plant dry weight. **Results.** The emergence percentage was affected by the physicochemical characteristics of the substrates and the salts present in the irrigation water, with no emergence observed at higher saline concentrations. In the morphometric parameters, it was observed that as the saline concentration in the irrigation water increased, there was a decrease and even complete inhibition of emergence at concentrations of 0.10 M and 0.15 M. **Implications.** By identifying the appropriate substrate for the cultivation of salicornia, it will be possible to select areas with greater potential for cultivation and, in addition, the sustainable use of brine as irrigation water will be promoted. **Conclusion**. Substrates with high salinity values and high saline concentrations in the irrigation water show a decrease in crop emergence and in the morphometric variables evaluated, demonstrating the adverse effect of increased salinity and therefore certainty in the establishment of a Salicornia-based crop.
Key words: brine; desalination; halophytes; water scarcity**.**

RESUMEN

Antecedentes. El proceso de desalinización es clave para enfrentar la escasez de agua, sin embargo, enfrenta desafíos como el impacto ambiental de la salmuera. Diversas estrategias minimizan este impacto, incluyendo el uso de halófitas como *Salicornia bigelovii*, la cual es una halófita con múltiples beneficios. Las etapas fenológicas de germinación y plántula son las más susceptibles para un establecimiento. En áreas áridas, la agricultura depende de plantas resistentes a la salinidad para mitigar problemas de degradación de suelo y escasez de agua. **Objetivo.** Evaluar el impacto de las condiciones edáficas y concentraciones salinas del riego en la emergencia y desarrollo inicial de *Salicornia bigelovii*. **Metodología.** Parte 1. La siembra se realizó en charolas de germinación con tres tipos de sustrato y fueron regadas con agua dulce durante 50 días. Parte 2. La siembra se realizó en sustrato peat moss, se aplicaron cuatro tratamientos salinos de agua de riego: 0 M, 0.05 M, 0.10 M y 0.15 M. Las variables evaluadas fueron las de porcentaje de

† *Submitted September 5, 2024 – Accepted December 4, 2024. http://doi.org/10.56369/tsaes.5839*

ISSN: 1870-0462.
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emergencia, altura de planta, longitud de raíz, número de pelos radiculares, peso fresco y peso seco planta. **Resultados.** El porcentaje de emergencia se vio afectado por las características fisicoquímicas de los sustratos y por las sales presentes en el agua de riego, observándose nula emergencia a las mayores concentraciones salinas. Se observó que a medida que aumenta la concentración salina en el agua de riego se presenta una disminución en parámetros morfológicos, incluso una inhibición completa de la emergencia en las concentraciones de 0.10 M y 0.15 M. **Implicaciones.** Al identificar el sustrato adecuado para el cultivo de salicornia se podrá seleccionar áreas con mayor potencial para el cultivo y, además, se promoverá el uso sustentable de salmueras como agua de riego. **Conclusión.** Los sustratos con altos valores de salinidad y las altas concentraciones salinas en el agua de riego muestran una disminución en la emergencia del cultivo y en las variables morfométricas evaluadas, demostrándose el efecto adverso del incremento de la salinidad y por lo tanto certidumbre en el establecimiento de un cultivo a base de Salicornia.
Palabras claves: desalinización; escasez de agua; halófitas; salmuera.

INTRODUCTION

Water scarcity is a problem that affects all socioeconomic activities worldwide, as a consequence of accelerated population growth and economic development that exert great pressure on water resources (Araus *et al.*, 2021; Dévora-Isiordia *et al.*, 2022). In response to this problem, desalination has become an important tool for sustainable water management, especially in coastal areas with limited freshwater. Desalination refers to the process of removing salts, colloids, and minerals from salt water and converting it into fresh water (Dévora-Isiordia *et al.*, 2022). However, this process presents challenges, such as the high construction and operating costs of desalination plants, and the environmental impact of disposing of the brine produced during the process. This waste, known as concentrate or brine, is a major ecological problem, as its direct release into the environment can have serious consequences for aquatic flora and fauna (Dévora-Isiordia *et al.*, 2017; Gómez-Bellot *et al.*, 2021). To minimize the environmental impact, several alternatives have been developed for the disposal and valorization of this waste. Among the most prominent are the production of sodium hydroxide, the creation of evaporation ponds for NaCl extraction, the extraction of metals such as lithium and magnesium by electrodialysis and electrolysis, and finally, its use for agricultural purposes as irrigation water in salinity-tolerant crops (Dévora-Isiordia *et al.*, 2017; Sánchez and Matos, 2018).

Currently, conventional agricultural activity in the world is developed in arid desert environments, producing 65 to 75% of the world's food. However, over time, these arid and desert areas have presented aspects that undermine the productivity of crops. One of them is the unavailability of water resources and another is soil degradation due to salinity and finally saline intrusion, factors that have led to the use of plants resistant to soil salinity and irrigation water (Cárdenas-Pérez *et al.*, 2021; Wang *et al.*, 2023).

Plant growth is directly affected by the amount of salts present in the soil and/or irrigation water. Saline soils are characteristic of areas with arid and semi-arid climates, due to low precipitation and high evaporation. Halophyte species are an agricultural alternative for these areas. Halophytes constitute 1% of the flora worldwide and there are more than 2500 genera (Mzoughi and Majdoub, 2021; Wang *et al.*, 2023). One species in particular, *Salicornia bigelovii*, commonly known as “sea asparagus” is the most important halophyte worldwide due to its tolerance to highly saline conditions (Cárdenas-Pérez *et al.*, 2021). In Mexico, the genus Salicornia is found along the Pacific coast being widely distributed in the coastal areas of the states of Sonora and Baja California, being considered native to the state of Sonora (Beltrán-Burboa *et al.*, 2017; López-Corona *et al.*, 2020; Zapata-Sifuentes *et al.*, 2021). *Salicornia bigelovii* has attracted increasing interest in agriculture and research due to its ability to thrive in highly saline environments (Rueda-Puente *et al.*, 2011), the interest lies in the capacity for production of oils, food for human and animal consumption, uses in cosmetology, biofuels and medicine, among others (Rueda Puente *et al.*, 2017; Gómez-Bellot *et al.*, 2021; Zapata-Sifuentes *et al.*, 2021).

Several studies with Salicornia have been generated worldwide. However, it is important to expand the knowledge on adaptability considering other ways to reproduce it (Morales-Santos *et al.*, 2017; Mazón-Suástegui *et al.*, 2020), and the use of brine residue from desalination processes (Dévora-Isiordia *et al.*, 2017), as well as considering the chemical and physical conditions of the soil, which have a direct relationship with plant germination, emergence and growth (Navarro-Bravo *et al.*, 2000).

Salinity has effects on crop growth and productivity, depending on the degree of salinity tolerance and the phenological stage of the crop, with the germination and seedling stages being the most affected by salt stress. The salt present in the soil limits water absorption by the seed and seedling. Halophytic plants, such as *Salicornia bigelovii*, have developed morphological, physiological and biochemical mechanisms that promote the absorption of saline water, leading to the development of studies related to the use of brines or desalination by-products (García-Galindo *et al.*, 2021; Gómez-Bellot *et al.*, 2021). Based on the growing need to find viable alternatives for agriculture in areas affected by soil salinity and water limitations, the objective of this research was to evaluate the impact of edaphic conditions and irrigation salinity concentrations on the emergence and initial development of *Salicornia bigelovii*, in order to know the conditions that favor its potential use in agricultural areas affected by salinity and water scarcity, thus promoting the sustainable use of brines and contributing to the resilience of vulnerable agricultural areas.

MATERIALS AND METHODS

Study site and plant material

The seeds were collected from mature plants of *Salicornia bigelovii*, which develop naturally in Bahía de Kino, Sonora, Mexico (Lat. 28°49′32″N and Long. 111°56′23″W), the collection was carried out in October 2023. Subsequently, for seed selection, the plants were sieved in a 2 mm diameter mesh and those with the largest size, uniform color and without apparent damage were selected. The plants obtained correspond to the Bahía de Kino ecotype. The seeds were immersed in potable water (270 mg L^{-1} of total dissolved solids) for one hour. Those that floated were discarded because they were considered non-viable, due to internal damage caused by pests or diseases, as well as their low density, which is associated with dehydration and loss of nutrients (Flores Barahona *et al.*, 2019). For disinfection, they were placed in 3% sodium hypochlorite for three minutes and then rinsed with sterile distilled water three times to remove excess hypochlorite (Hernández-Perales, Cisneros-Almazán, *et al.*, 2017). Once the *Salicornia bigelovii* seeds were obtained and selected, they were subjected to two evaluations, phase 1: evaluate germination variables in three substrates using fresh water as irrigation water and phase 2: evaluate germination variables in peat moss substrate using saline water.

Phase 1: evaluate germination variables in three substrates using fresh water as irrigation water:

Substrate types

Three types of substrates were used for planting the crop: Substrate 1: peat moss, Substrate 2: alluvial soil from the Yaqui Valley, Sonora, Mexico (Lat. 26°45'27°33' N and Long. 109°30'110°37' W) and Substrate 3: Solonchak soil from the town of paredón colorado, Sonora, Mexico (Lat. 27°04'39" N and Long. 109°55'49" W) (Figure 1). Soil sampling and physicochemical analysis (texture, pH, organic matter (OM), electrical conductivity (EC) and nutrients) were carried out following the methodology described in NOM-021-RECNAT-2000.

Sowing was carried out in germination trays with three different types of substrates with 72 experimental units for each treatment. The trays were placed in a greenhouse at a temperature of 25 °C for 50 days. Irrigation was carried out at saturation with distilled water with a saline concentration of 1.96 mg L^{-1} of total dissolved solids (TDS).

Variables to evaluate

The percentage of emergence was evaluated by quantifying the total emergence of seedlings 50 days after the end of the experiment (García-Galindo *et al.*, 2021). It was quantified using the following equation:

$$emergence\ percentage = \frac{(\text{No. of emerged seeds})*(100)}{(\text{No.of seeds})} \qquad (1)$$

Plant height (cm) and root length (cm) were measured with a truper® vernier model caldi-6mp. Fresh weight (g $plant^{-1}$) and dry weight (g $plant^{-1}$) were also determined using a drying oven at 80 °C for 72 h (Yamato Scientific America Inc. Model DX402C. Santa Clara, CA, USA). Finally, number of root hairs per plant was quantified (Rueda-Puente *et al.*, 2017).

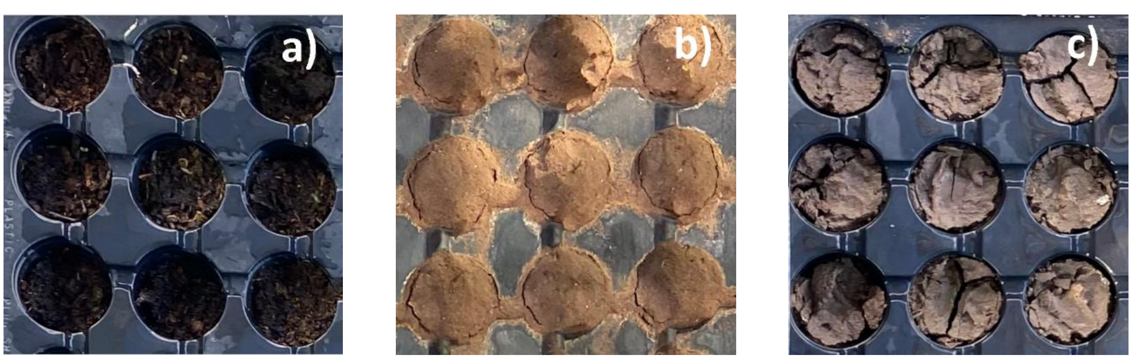

Figure 1. a) Substrate 1: peat moss, b) Substrate 2: alluvial soil y c) Substrate 3: Solonchak soil.

Phase 2: evaluate germination variables in peat moss substrate using saline water:

Selection of irrigation water

In the second phase, planting was carried out in peat moss substrate. Four saline treatments were applied using synthetic "ocean sea salt" with a total of 72 experimental units per treatment (Table 1). The same morphometric variables previously mentioned in phase 1 of the experiment were measured: plant height (cm), root length (cm), number of root hairs per plant, fresh weight (g plant^{-1}) and dry weight (g plant^{-1}).

Table 1. Irrigation water used in the cultivation of *Salicornia bigelovii* in peat moss substrate.

Molarity (Mol L^{-1})	TDS (mg L^{-1})	Iriigation water
0	1.93	Distilled
0.05	18 842	brackish
0.10	33 713.4	sea
0.15	47 572.28	brine

The statistical analyses were carried out with the software statgraphic Centurion 19 version 19.6.03. VA. USA. Using a one-way ANOVA was performed to compare treatment means; Tukey HSD test test ($p \leq 0.05$).

RESULTS AND DISCUSSION

Substrate selection

The quality of soil or substrate is determined by its physicochemical properties; these characteristics can have a significant impact on plant growth, as shown in the case of *Salicornia bigelovii* seedlings, where it can be observed that the highly saline conditions (Table 2) of substrate 3: Solonchak soil with 85.1 dS m^{-1} of EC and 17,280 kg ha^{-1} of Na, had a negative effect on crop emergence (Figure 2). Soils close to seawater present characteristics of high salinity values and low organic matter contents (Bedoya-Justo and Julca-Otiniano, 2021). Salt stress has been reported as a cause of high vegetation mortality in coastal areas, which negatively affects *Salicornia bigelovii* populations. The germination process of salicornia is favored in rainy seasons, because it reduces the concentration of salts in the environment (Rueda-Puente *et al.*, 2017).

Table 2. Physicochemical analysis of different substrates.

Treatment	Texture	EC (dS m^{-1})	pH	OM (%)	N (N-NO$_3$) (kg ha^{-1})	P (P-PO$_4$) (kg ha^{-1})	K (kg ha^{-1})	Na (kg ha^{-1})
Substrate 1	-----------	0.59	5.04	71.77	229.55	39.77	720.00	3024.00
Substrate 2	Silty clay loam	7.57	7.49	0.42	137.20	33.50	2003.00	1440.00
Substrate 3	Clay loam	85.1	7.34	1.30	18.74	52.72	9936.00	17280.00

EC: electrical conductivity, OM: organic matter. Substrate 1: peat moss, substrate 2: alluvial soil. substrate 3: Solonchak soil.

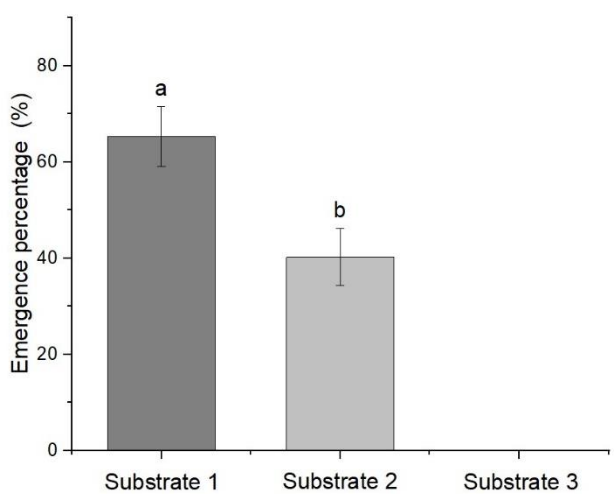

Figure 2. Percentage of emergence of *Salicornia bigelovii* under different soil conditions. Substrate 1: peat moss, Substrate 2: alluvial soil. Substrate 3: Solonchak soil. Vertical lines bars at the top of bars are the error bars percentage (n = 3).

On the other hand, the percentage of emergence (Figure 2), agrees with those variables of root length, plant height (Figure 3), number of root hairs, fresh and dry weight of seedling when presenting the significant results in substrate 1: peat moss (Table 3). This may be directly related to the low salt content and high OM content present in this substrate (Table 2). It should be noted that matter improves the availability and acquisition of nutrients by the plant, influencing root and stem development, thus increasing crop productivity, improving aeration, increasing water retention and reducing erosion (Bedoya-Justo and Julca-Otiniano, 2021; Gerke, 2022). Likewise, it is indicated that the relationship between soil conditions and plant morphometric parameters highlights the importance of maintaining a healthy and well-balanced soil to favor crop growth (Burbano-Orjuela, 2017).

Selection of irrigation water

In relation to the results obtained in the second phase, it was observed that the emergence percentage was affected by the concentration of salts in irrigation water, with no emergence being observed in the treatments with the highest salt concentration (0.10 M and 0.15 M). The values recorded in both treatments are due to the high concentration of salts that increase the osmotic pressure of the medium, causing water stress and inhibiting germination, thus demonstrating that one of the most critical stages in the life cycle of *Salicornia bigelovii* is its germination period (García-Galindo *et al*., 2021; Lyra *et al*., 2022).

On the other hand, the 0 M and 0.05 M concentrations showed 54.99% and 8.05% emergence respectively (Figure 4). Some authors have reported similar results with *Salicornia bigelovii*., where the best results are obtained in distilled water and the higher the salt concentration, the lower the germination percentages (Rueda-Puente *et al.*, 2011; Hernández-Perales *et al.*, 2017; García-Galindo *et al.*, 2021). In the morphometric parameters, it was observed that as the salt concentration in the irrigation water increases, there is a decrease in the parameters measured (Table 4). A comparison of means shows that a relatively low concentration of 0.05 M has a negative effect on the number of root hairs and plant fresh weight, being significantly lower compared to plants irrigated with distilled water (0 M). At 0.10 M and 0.15 M salt concentrations, a complete inhibition of crop emergence was presented. Hernández Perales *et al.*, (2017) reported that 0.5 M and 1 M NaCl salt concentrations effectively affected some morphometric parameters, with the lowest values observed at the 1 M salt concentration. High salinity levels limit plant growth causing water déficit and ionic toxicity (Cárdenas-Pérez *et al.*, 2021).

Table 3. Effect of substrate on *Salicornia bigelovii* seedlings on morphometric parameters.

Treatment	Plant height (cm)	Root lenght (cm)	No. of root hair	Fresh weight (g plant^{-1})	Dry weight (g plant^{-1})
Substrate 1	1.6357 a	1.8571 a	3.7142 a	0.0234 a	0.0020 a
Substrate 2	1.6385 a	0.7857 b	1.4285 b	0.0129 b	0.0013 b
Substrate 3	0.0000 b	0.0000 c	0.0000 c	0.0000 c	0.0000 c
F test	69.3000	28.8100	59.3600	40.6800	80.8300
P value	0.0000	0.0000	0.0000	0.0000	0.0000

Different letters (a b c) within the same column indicate significant differences., Tukey, P≤ 0.05. Substrate 1: peat moss, substrate 2: alluvial soil, substrate 3: Solonchak soil.

Figure 3. Development of *Salicornia bigelovii* a) substrate 1: peat moss, b) substrate 2: alluvial soil.

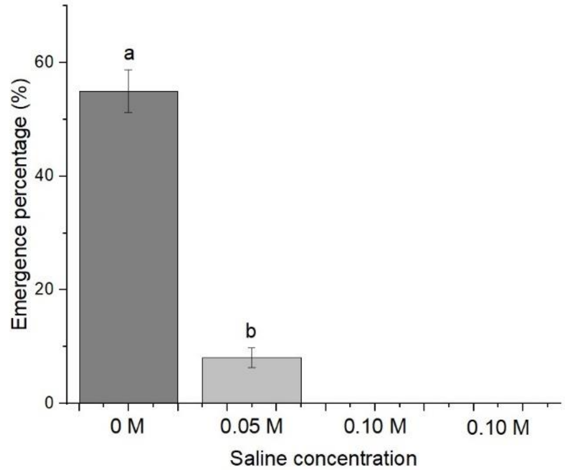

Figure 4. Emergence percentage of *Salicornia bigelovii* with different saline treatments. Vertical lines bars at the top of bars are the error bars percentage (n = 4).

Table 4. Effect of the application of irrigation water with different salt concentrations on *Salicornia bigelovii* seedlings on morphometric parameters.

Molar concentration	Plant height (cm)	Root lenght (cm)	No. of Root hair	Fresh weight (g plant^{-1})	Dry weight (g plant^{-1})
0	1.3111 a	1.1333 a	1.9444 a	0.0088 a	0.0012 a
0.05	1.1166 a	1.4000 a	0.0000 b	0.0043 b	0.0013 a
0.10	0.0000 b	0.0000 b	0.0000 b	0.0000 c	0.0000 b
0.15	0.0000 b	0.0000 b	0.0000 b	0.0000 c	0.0000 b
F test	134.63	40.02	42.94	83.37	82.35
P value	0.0000	0.0000	0.0000	0.0000	0.0000

Different letters (a b c) within the same column indicate significant differences., Tukey, P≤ 0.05.

CONCLUSIONS

The edaphic conditions and the saline concentrations in the irrigation water contribute to broaden the knowledge on the establishment of *Salicornia bigelovii* as an alternative for the coastal zones of the state of Sonora, sites characterized by saline soils and water scarcity. The peat moss substrate showed the best results in the emergence percentage and in the morphometric variables evaluated, suggesting that the low salt content and high organic matter content favor its development.

The emergence of *Salicornia bigelovii* is significantly affected by the salt concentrations evaluated, which negatively impacts the initial establishment of the plants. It is essential to determine the appropriate salinity levels during irrigation to obtain the best results in germination, growth, yield and quality. Based on the results, it is recommended to contribute to the knowledge on the planting of *Salicornia bigelovii* using brine from desalination plants as an adaptive strategy for agriculture and as an opportunity to reduce the environmental impact generated by waste discharged directly into the sea.

Acknowledgments
We thank the Consejo nacional de humanidades ciencias y tecnologías for financial support for the postdoctoral stay of Arlett Leticia Ibarra Villareal and the Seri community of Punta Chueca, Sonora, Mexico for their support in the collection of *Salicornia bigelovii* seed used in the evaluations.

Founding. This research was funded by the Instituto Tecnológico de Sonora through a PROFAPI fund (project CA-2024-006 and 2025-007). This research was also funded by CONAHCyT through the PRONACE Project: Energy, water, and food security native peoples in semiarid coastal regions of northern Mexico. Grant number: 319483.

Conflict of interest. The authors declare that they have no conflicts of interest.

Compliance with ethical standards. This study does not involve human participants.

Data availability. Data is available from Germán Eduardo Dévora Isiordia, email: *german.devora@itson.edu.mx*

Author contribution statement (CRediT). A.L. Ibarra-Villarreal - conceptualization, data curation, formal analisis, writing-original draft, writing-review and editing., **G.E. Dévora-Isiordia-** conceptualization, funding adquisition, validation, visualization, writing-review and editing., **E.O. Rueda-Puente-** conceptualization, supervision, validation, methodology, writing-review and editing.

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