

Development of Decision-Making Models for Optimizing the Production Technology of Natural Salt Substitutes Based on *Salicornia perennans* in Kazakhstan

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ABSTRACT

This study presents the development of decision-making models to optimize production technology for natural salt substitutes based on *Salicornia perennans*, a halophyte well-suited to Kazakhstan's extensive saline soils. Given its unique adaptations—such as succulence, ion compartmentalization, and antioxidant production—*Salicornia perennans* emerges as a promising sustainable salt alternative, particularly for regions where traditional crops struggle. Through controlled laboratory trials, we analyzed the impact of saline conditions on nutrient composition and plant resilience. Key findings suggest that *Salicornia* cultivated under 50-100 mM NaCl conditions produces biomass with optimal sodium and micronutrient levels, ideal for salt substitution with desirable sensory properties. Multi-criteria decision-making (MCDM) models were then employed to assess variables such as nutrient retention, moisture stability, and cost-effectiveness. This systematic approach allows for the optimal selection of growth conditions, balancing ecological sustainability and production efficiency. Economic-mathematical modeling demonstrated the cost-benefit advantages of *Salicornia* cultivation on saline soils compared to traditional salt imports, especially given its low input requirements. Life Cycle Assessment (LCA) confirmed a reduced environmental footprint, highlighting *Salicornia perennans* as a sustainable agricultural resource. Additionally, risk assessment frameworks were developed to address variability in soil characteristics and climate conditions, ensuring the robustness of production strategies. In conclusion, *Salicornia perennans* represents a viable, scalable solution for natural salt substitutes in Kazakhstan. By leveraging decision-making models to optimize production, this study offers a pathway to sustainable food technology that aligns with regional agricultural goals.

KEYWORDS: *Salicornia perennans*, natural salt substitutes, decision-making models, sustainable agriculture, saline soil optimization.

1. Introduction

Halophytes account for approximately 1% of global flora, holding a distinctive place within plant biodiversity [1]. The global halophyte gene pool encompasses around 2,000–2,500 species, with over 700 species found in Central Asia. These species belong to 34 families and 214 genera, of which approximately 30% are endemic to 19 botanical families [2]. These species and ecotypes constitute a unique genotypic resource for food, forage, oil, and pharmacological plants, given their ability to colonize ecosystems with elevated salinity—conditions unsuitable for conventional agricultural crops—underscoring their potential significance for agro-biodiversity [3,4,5].

Halophytes demonstrate resilience in environments where salt concentrations exceed 200 mM NaCl (~20 dS/m), with productivity often increasing alongside rising salt levels, frequently surpassing growth rates achieved under freshwater conditions [6,7,8]. Evolutionarily, halophytes have developed specific morphological, anatomical, and physiological adaptations, including ion compartmentalization, osmoregulation, succulence, selective ion transport, absorption mechanisms, and enhanced antioxidant systems. These traits contribute to maintaining redox homeostasis under salt stress [9]. At the cellular level, halophytes accumulate NaCl in vacuoles and retain organic salts within the cytoplasm, actively reducing ionic toxicity and minimizing the effects of salt stress [10,11].

Due to their high adaptive capacity, halophytes inhabit various saline zones, including coastal and mangrove soils, wetlands, and arid and semi-arid regions. These plants can be successfully cultivated on saline soils and even in seawater, providing an alternative to conventional agricultural crops and serving as sources of food, essential oils, medicinal substances, fiber, and fodder [12,13,14].

According to FAO-UNESCO data, saline lands span approximately 950 million hectares worldwide, with up to 10 million hectares annually exiting agricultural use due to soil salinization and alkalization [15]. In Kazakhstan, saline lands cover 93.7 million hectares, representing 36% of agricultural territory subject to halophytization, with a trend toward the expansion of halophyte meadows in areas adjacent to the receding Aral Sea. Over-irrigation of agricultural fields for cotton and rice exacerbates soil salinization and waterlogging [16,17]. Extensive halophyte meadows are spreading further inland as water inflow to the Aral Sea declines, driven by high evaporation rates and decreased water availability. Plants inhabiting these regions have demonstrated the active development of adaptive mechanisms in response to environmental changes, exhibiting physiological plasticity and increased salt tolerance through significant NaCl accumulation in plant tissues [18].

The genus *Salicornia*, a promising halophyte, comprises annual herbaceous plants in the Amaranthaceae family and grows on saline coastal soils, salt lake shores, and ravines. In Kazakhstan, *Salicornia* is widespread across all regions except mountainous areas. Antioxidants produced by *Salicornia* species provide a detoxification strategy against reactive oxygen species [19]. Beyond their essential role in protecting plants from oxidative stress, these bioactive molecules exhibit notable health benefits, including antioxidant, antimicrobial, and anti-inflammatory properties, offering significant interest to various industries [20].

2. Materials and Methods

Plant Material Collection and Identification

Salicornia perennans samples were collected from two regions with saline soil in Kazakhstan: the Karmakchinsky district of the Kyzylorda region and the Moynkum district of the Zhambyl region. Identification of plant species was confirmed by morphological assessment based on taxonomic keys due to phenotypic plasticity within the Salicornia genus, ensuring the accuracy of plant selection for experimentation.

Laboratory Cultivation Conditions

To simulate optimal growth environments, plants were cultivated under controlled laboratory conditions. Temperature was maintained at 25-30°C, with relative humidity at 55-75%, and light intensity at 200-300 kW over a 14-16 hour photoperiod. Weekly irrigation was conducted with nutrient solutions at two NaCl concentrations: 50 mM and 100 mM, replicating varying saline soil conditions.

Physicochemical properties, including moisture content and water activity, were measured using standard protocols:

- **Moisture Content:** Determined with a Radwag MA analyzer according to GOST 13496.4-2019 for accurate assessment of moisture levels essential for storage stability.

- **Water Activity (aw):** Measured with an Aqualab 4TE device following the protocol by Roa and Daza, helping understand microbial stability for food application.

The primary nutritional and mineral contents, such as sodium, potassium, magnesium, and essential trace elements (e.g., iron, zinc), were analyzed using protocols from GOST standards:

- **Sodium, Potassium, and Other Minerals:** Quantified by spectrophotometric methods (GOST 32343-2013), focusing on their role in determining salt substitutive quality.

Heavy Metals: Levels of cadmium, lead, mercury, and arsenic were measured to ensure safety, using GOST 30178-96 guidelines to confirm compliance with food safety standards.

Multi-criteria decision-making (MCDM) models were applied to optimize factors impacting production. Variables considered included:

Moisture Stability and Shelf Life: Calculated based on water activity and moisture content, contributing to extended shelf life.

Cost-Effectiveness: Modeled using economic-mathematical frameworks to evaluate production costs in saline soils relative to traditional salt sources.

A Life Cycle Assessment (LCA) was conducted to evaluate the environmental footprint of cultivating Salicornia perennans. Input metrics included water, energy, and nutrient use across various growth stages, with the LCA results supporting the

sustainability of the salt substitute in comparison to conventional sources.

Risk assessment frameworks addressed the variability in soil and climate conditions across the selected regions. This involved analyzing the resilience of *Salicornia* to fluctuating salinity levels, temperature, and moisture conditions, ensuring the robustness of production under diverse environmental scenarios.

3. Results and Discussion

Salicornia perennans is a unique representative of halophytic flora, thriving in the extreme conditions of saline soils where most other plants are unable to survive due to high salt concentrations. This resilience is attributed to a suite of morphophysiological adaptations, including leaf succulence, which allows efficient moisture retention, and exceptional salt tolerance. As illustrated in Figure 1, *Salicornia perennans* proliferates in the Karmakchinsky district of the Kyzylorda region, where soil salinity reaches elevated levels, creating natural conditions conducive to its growth.



Figure 1 – *Salicornia perennans* from the Karmakchinsky district, Kyzylorda region

Water requirements are significantly lower than those of other halophytes; in its natural habitat, limited rainfall is sufficient, and during experiments, irrigation with sodium chloride solution is conducted weekly. For further studies, *Salicornia perennans* samples were collected in the Karmakchinsky district of the Kyzylorda region (Figure 2).



Figure 2 – *Salicornia perennans* Sample Collection Process

To study the morphophysiological parameters and biological properties of the plants, *Salicornia perennans* samples were cultivated under laboratory conditions (Figure 3). The growth conditions included an average temperature of 25-30°C, humidity levels of 55-75%, and light efficiency of 200-300 kW. Weekly irrigation was conducted with varying NaCl concentrations (50 mM and 100 mM) to optimize growth.

The studied plants displayed similar morphology, yet additional identification was required. Taxonomic uncertainty within the *Salicornia* genus arises from two main factors: firstly, high phenotypic plasticity has led to identical genotypes being assigned different names; secondly, this is further complicated by morphological parallelism and subtle morphological distinctions.



Figure 3 – *Salicornia perennans* Samples Cultivated Under Laboratory Conditions at S. Seifullin Kazakh Agro Technical University

To study the physicochemical properties, young shoots were transplanted into substrates for subsequent analysis. This research facilitates the assessment of fresh biomass utilization in various fields, such as the food industry and agriculture, due to the high nutritional value of *Salicornia*.

During the study, *Salicornia* was cultivated to harvest size, with optimal growth conditions determined for its use as a vegetable crop. The experiment utilized various nutrient media, salinity levels, and *Salicornia* varieties, conducted under laboratory conditions with a 14-16 hour photoperiod. The trial began with planting shoots treated with Hoagland's solution containing 50 mM NaCl for two months. Rooting and seedling growth to harvest size were carried out using different *Salicornia* samples (Figures 4 and 5).



Figure 4 – Transplanted *Salicornia perennans* Shoots on Day 7 After Planting



Figure 5 – Transplanted *Salicornia perennans* Shoots on Day 12 After Planting

The experiment demonstrated that the survival and germination rates were optimal at a salinity of 50-100 mM and temperatures of 20/8-10°C (day/night). Biomass yield was higher in the hydroponic system than in the sand-based system. However, nutrient concentration needs further optimization, as plants grown hydroponically exhibited signs of stress.

Analysis of fresh and dry biomass allows for assessment of nutrient and salt content and a comparison of moisture levels, which is crucial for understanding the accumulation of beneficial compounds in *Salicornia perennans* under varying cultivation conditions (Figure 6).



Figure 7 – Fresh and Dry Biomass of *Salicornia perennans* for Physicochemical Analysis

The fresh samples exhibit a rich green color, indicating a high chlorophyll concentration, while the dry samples display a duller shade, resulting from the drying process and moisture removal. The next phase of the research involved examining the physicochemical properties of the plant material.

Table 1 – Physical Properties of *Salicornia perennans* from Different Regions of Kazakhstan

Indicators	<i>Salicornia perennans</i> (Karmakchinsky district, Kyzylorda region)	<i>Salicornia perennans</i> (Moynkum district, Zhambyl region)
Moisture, %	83,6 ± 0,5	90,8 ± 0,5
Water Activity (aw), c.u.	0,18 ± 0,02	0,29 ± 0,02

The moisture content of the Karmakchinsky sample is 83.6%, which is 8% lower than that of the Moynkum district sample, where this indicator reaches 90.8%. This reduction in moisture is crucial for enhancing product stability, as a lower moisture level slows down microbial decomposition, thereby extending shelf life. Additionally, the water activity of the Karmakchinsky sample is 0.18, which is 37.9% lower than that of the Moynkum sample (0.29). This parameter, directly impacting water availability for microbes and molds, provides the Karmakchinsky sample with high spoilage resistance, maintaining its suitability for long-term storage. Reduced water activity also improves organoleptic properties: the product becomes less watery and denser in texture, making it desirable for use in various food products as a stabilizing and salt-replacing component. Furthermore, the moisture and water activity values indicate that the Karmakchinsky sample is less dependent on storage conditions and requires minimal preservatives. These quantitative differences suggest that *Salicornia perennans* from the Karmakchinsky district is a more promising candidate for use as a high-quality natural salt substitute with enhanced storage and textural characteristics.

Table 2 – Chemical Properties of *Salicornia perennans* from Different Regions of Kazakhstan

Indicators	<i>Salicornia perennans</i> (Karmakchinsky district, Kyzylorda region)	<i>Salicornia perennans</i> (Moynkum district, Zhambyl region)
Nitrogen %	0,77 ± 0,012	1,30 ± 0,019
Phosphorus %	0,04 ± 0,001	0,07 ± 0,001
Potassium %	0,8 ± 0,009	0,51 ± 0,008
Calcium %	0,81 ± 0,015	3,1 ± 0,005

Magnesium %	6,57 ± 0,12	0,23 ± 0,004
Sodium %	1,32 ± 0,018	1,2 ± 0,017
Iron mg/kg	253 ± 3,29	64 ± 0,96
Zinc mg/kg	104 ± 1,14	20,4 ± 0,33
Na/K	1,65	2,35

As shown in Table 1, the chemical composition of *Salicornia perennans* from the Karmakchinsky district of the Kyzylorda region indicates its superiority as a natural salt substitute. The sodium content is 1.32%, which is 10% higher than in the Moynkum district sample (1.2%), providing optimal salinity for the product. Notably, the magnesium level reaches 6.57%, which is 28.6 times higher than that of the other sample (0.23%), significantly enhancing biological value and supporting electrolyte balance. The iron concentration in the Karmakchinsky sample is 253 mg/kg, 3.95 times higher than in the Moynkum sample (64 mg/kg), contributing substantially to meeting daily dietary requirements for this micronutrient. Zinc levels are 104 mg/kg, 5.1 times higher than in the Moynkum sample (20.4 mg/kg), boosting the immunomodulatory properties of the final product.

The potassium content in the Karmakchinsky sample is 0.8%, 56% higher than in the Moynkum sample (0.51%), yet this level does not negatively impact the product's taste characteristics. Calcium concentration is 0.81%, 3.8 times lower than in the Moynkum sample (3.1%), avoiding potential adverse effects on organoleptic properties and texture. The nitrogen level is 0.77%, 40.8% lower than in the other sample (1.3%), reducing the risk of forming undesirable nitrogen compounds during processing. Phosphorus content is 0.04%, compared to 0.07% in the Moynkum sample, contributing to an optimal mineral balance. In the Karmakchinsky sample, the Na/K ratio is 1.65, meaning sodium content is 65% higher than potassium, providing moderate sodium dominance, sufficient salinity, and minimal bitterness that could arise with higher potassium levels.

Meanwhile, the Na/K ratio in the Moynkum sample reaches 2.35, indicating nearly 2.4 times more sodium than potassium. This higher Na/K ratio further enhances salinity but reduces the balance of the mineral composition.

Thus, *Salicornia perennans* from the Karmakchinsky district, with its elevated sodium, magnesium, and key micronutrient content, along with optimized levels of other minerals, is more suitable for use as a natural salt substitute. This composition ensures not only the necessary salinity but also enriches the product with essential nutrients, enhancing its nutritional value and functional properties.

An analysis of heavy metal content in *Salicornia perennans* samples from the Karmakchinsky and Moynkum districts demonstrates their compliance with strict safety standards, allowing the raw material from these regions to be considered safe for use in the food industry (Table 2).

Table 2 – Heavy Metal Content

Indicators	<i>Salicornia perennans</i> (Karmakchinsky district, Kyzylorda region)	<i>Salicornia perennans</i> (Moynkum district, Zhambyl region)
Cadmium mg/kg	0,1 ± 0,002	0,1 ± 0,002
Lead mg/kg	0,1 ± 0,002	0,2 ± 0,004
Mercury mg/kg	0,02 ± 0,00003	0,03 ± 0,0005
Arsenic mg/kg	0,1 ± 0,001	0,1 ± 0,001

The concentrations of cadmium, lead, mercury, and arsenic in both samples are below permissible limits: cadmium is less than 0.1 mg/kg, lead is less than 0.1 mg/kg for the Karmakchinsky district and less than 0.2 mg/kg for the Moiynkum district, mercury is less than 0.02 mg/kg and less than 0.03 mg/kg, respectively, and arsenic is less than 0.1 mg/kg in both cases. This level of chemical purity is particularly important when using *Salicornia perennans* as a salt substitute, as low heavy metal content not only enhances product safety but also ensures compliance with food safety standards.

The multi-criteria decision-making (MCDM) models identified optimal strategies for the sustainable production of *Salicornia perennans* as a natural salt substitute by assessing and prioritizing key variables.

Nutrient Retention: The model highlighted the effectiveness of cultivating *Salicornia* at 50-100 mM NaCl levels, which provided balanced sodium content without compromising essential micronutrients such as potassium, magnesium, and iron. The nutrient retention was optimal in samples with a 50-100 mM NaCl concentration, which is recommended for maximizing the health benefits of *Salicornia*-based products. This solution ensures the production of a salt substitute rich in essential nutrients, meeting both quality and health standards.

Moisture Stability and Shelf Life: Samples from the Karmakchinsky district, with moisture content at 83.6% and water activity at 0.18, demonstrated superior stability and extended shelf life, attributed to reduced microbial activity. The study recommends targeting similar moisture and water activity levels in production to enhance product stability. Lowering water activity to this level minimizes the need for preservatives, offering a cleaner label and appealing to consumers seeking natural, additive-free products.

Cost-Effectiveness: By integrating economic-mathematical modeling, the production cost for *Salicornia* was found to be significantly lower than traditional salt imports, mainly due to the minimal input requirements. Given Kazakhstan's extensive saline soils, this cultivation approach is economically advantageous. We recommend prioritizing *Salicornia* cultivation in these regions as a cost-effective and sustainable alternative to conventional salt sources. The model's solutions suggest a shift toward utilizing marginal lands, which not only reduces costs but also aligns with Kazakhstan's goals for sustainable agriculture.

The Life Cycle Assessment (LCA) results underscore the environmental advantages of *Salicornia* cultivation. Due to its low water and nutrient needs, *Salicornia* achieves a reduced environmental footprint compared to traditional crops. Based on these findings, the study suggests incorporating *Salicornia* into crop rotation systems on saline soils as a long-term strategy for reducing greenhouse gas emissions and conserving resources. Furthermore, *Salicornia*'s ability to thrive on non-arable saline soils addresses the increasing demand for sustainable land use, presenting a viable option for agricultural expansion without compromising arable land.

In conclusion, LCA confirmed that *Salicornia perennans* is an environmentally sustainable crop with considerable potential for integration into Kazakhstan's

agricultural system. This crop contributes to a circular economy by turning underutilized saline soils into productive land, aligning with national objectives for sustainable development.

The risk assessment emphasized *Salicornia*'s resilience under fluctuating salinity levels and varying environmental conditions, particularly its ability to maintain stable growth at 50-100 mM NaCl concentrations. Given Kazakhstan's diverse climate and soil conditions, *Salicornia* is an ideal crop for large-scale cultivation on saline soils across the country.

Specific solutions include implementing monitoring systems for soil salinity and moisture levels to ensure conditions are maintained within optimal ranges, thus safeguarding productivity under different regional conditions. In areas prone to extreme climatic variations, irrigation practices should incorporate saline water as an effective solution for maintaining soil salinity levels conducive to *Salicornia* growth.

4. Conclusions

The conducted studies have shown that the unique morphophysiological characteristics of this plant, adapted to the extreme conditions of saline soils, provide it with high salt tolerance and the ability to accumulate sodium at optimal concentrations. The sodium content in the samples reached 1.32%, which is 10% higher than that of plants from other regions, ensuring sufficient salinity for the final product. An additional advantage of the Karmakchinsky sample lies in its elevated levels of magnesium (6.57%), iron (253 mg/kg), and zinc (104 mg/kg), enhancing its biological value. The moisture level and water activity (83.6% and 0.18, respectively) confer resistance to microbial spoilage and extend the product's shelf life, which is essential for its application in the food industry. Safety analysis of *Salicornia perennans* confirmed compliance with stringent heavy metal standards for cadmium, lead, mercury, and arsenic, ensuring product safety for consumption. The balanced Na/K ratio (1.65) also helps minimize bitterness, making *Salicornia* from the Karmakchinsky district an ideal basis for producing a natural salt substitute with high nutritional value. Thus, the study results confirm that *Salicornia perennans* from the Karmakchinsky district is a promising raw material for developing natural salt substitutes that enrich food products with essential nutrients. The low resource requirements of *Salicornia perennans* make it an environmentally sustainable crop. The study recommends integrating *Salicornia* into Kazakhstan's agricultural framework to contribute to reduced greenhouse gas emissions, optimized resource use, and preservation of arable land. Monitoring and adjusting salinity and moisture levels in response to climatic variability ensure reliable *Salicornia* yields across different regions in Kazakhstan, supporting its consistent use as a natural salt substitute.

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