Brazilian Journal of Biology®

ISSN 1519-6984 (Print)
ISSN 1678-4375 (Online)

Original Article

# Influence of seasonal factors on the formation of halophytic vegetation under conditions of high salinity on the desiccated bed of the Aral Sea

## Influência de fatores sazonais na formação de vegetação halófita em condições de alta salinidade no leito ressecado do Mar de Aral

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**Abstract**

The desiccation of the Aral Sea led to the formation of the Aralkum Desert, characterized by highly saline substrates and pronounced moisture deficit, which significantly complicates vegetation restoration. This study presents the results of field investigations on the establishment of halophytic shrubs on the desiccated bed of the Aral Sea, taking into account sowing and planting seasonality, soil water regime, and the application of soil amendments. Experimental work was conducted in the spring of 2025 on experimental plots of the dried bed of the Aral Sea. The seeding area was 0.288 hectares, and the planting area was 0.48 hectares. The work was carried out on three plots with a total area of 0.768 hectares, belonging to forest suitability groups II–IV, using zeolite, hydrogel, and hydroseeding technology. Experiments were conducted in spring 2025 at three sites with a total area of 0.48 ha, classified within forest suitability groups II-IV, using zeolite, hydrogel, and hydroseeding techniques. After winter storage, seed viability declined in all studied species, with the most pronounced reductions observed in *Calligonum caput-medusae* (67→30%), *Salsola richteri* (30→10%), and *Nitraria schoberi* (40→17%). The average soil moisture content within the 0-100 cm profile decreased from 61.4% in spring to 47.1% in autumn, while groundwater depth increased from 2.0 to 2.8 m. For *Halostachys caspica*, only spring planting proved effective (up to 14 plants per 100 $m^2$ when zeolite and hydrogel were applied). For *Salsola richteri*, the best results were obtained with autumn sowing combined with zeolite application at sites belonging to forest suitability groups II-III (up to 38 plants per 20 $m^2$), whereas no establishment was recorded at group IV sites. The findings emphasize the need for a differentiated approach to phytomelioration in the Aralkum Desert.

**Keywords:** halophytes, Aral Sea, plant survival, seed germination, soil water regime, arid ecosystems, saline soils.

**Resumo**

A dessecação do Mar de Aral levou à formação do Deserto de Aralkum, caracterizado por substratos altamente salinos e acentuado déficit hídrico, o que dificulta significativamente a restauração da vegetação. Este estudo apresenta os resultados de investigações de campo sobre o estabelecimento de arbustos halófitos no leito seco do Mar de Aral, considerando a sazonalidade da semeadura e do plantio, o regime hídrico do solo e a aplicação de corretivos de solo. O trabalho experimental foi conduzido na primavera de 2025 em parcelas experimentais do leito seco do Mar de Aral. A área de semeadura foi de 0,288 ha e a área de plantio foi de 0,48 ha. O trabalho foi realizado em três parcelas com área total de 0,768 ha, pertencente aos grupos de aptidão florestal II-IV, utilizando as tecnologias de zeólita, hidrogel e hidrossemeadura. Experimentos foram conduzidos na primavera de 2025 em três locais, com área total de 0,48 ha, classificados nos grupos de aptidão florestal II-IV, utilizando técnicas de zeólita, hidrogel e hidrossemeadura. Após o armazenamento de inverno, a viabilidade das sementes diminuiu em todas as espécies estudadas, com as reduções mais acentuadas observadas em *Calligonum caput-medusae* (67→30%), *Salsola richteri* (30→10%) e *Nitraria schoberi* (40→17%). O teor médio de umidade do solo no perfil de 0-100 cm diminuiu de 61,4% na primavera para 47,1% no outono, enquanto a profundidade do lençol freático aumentou de 2,0 para 2,8 m. Para *Halostachys caspica*, apenas o plantio na

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Received: March 18, 2026 – Accepted: April 20, 2026
Editor: Takako Matsumura Tundisi

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primavera se mostrou eficaz (até 14 plantas por 100 m² quando zeólita e hidrogel foram aplicados). Para *Salsola richteri*, os melhores resultados foram obtidos com a semeadura de outono combinada com a aplicação de zeólita em locais pertencentes aos grupos de adequação florestal II-III (até 38 plantas por 20 m²), enquanto nenhum estabelecimento foi registrado em locais do grupo IV. Os resultados enfatizam a necessidade de uma abordagem diferenciada para a fitomelioração no Deserto de Aralkum.

**Palavras-chave:** halófitas, Mar de Aral, sobrevivência de plantas, germinação de sementes, regime hídrico do solo, ecossistemas áridos, solos salinos.

## 1. Introduction

The desiccation of the Aral Sea represents one of the largest examples of anthropogenic transformation of natural ecosystems, resulting in the exposure of vast areas of the former seabed and the formation of the Aralkum Desert. The exposed substrates are characterized by high salinity, low organic matter content, and high susceptibility to deflation, leading to intensive salt-dust emissions and persistent environmental risks at the regional scale (Adilov et al., 2025). Under such conditions, natural vegetation recovery proceeds extremely slowly and exhibits a strongly mosaic pattern due to the combined effects of salt stress, coarse soil texture, and limited availability of moisture (Kim et al., 2024; Indoitu et al., 2015).

Recent studies conducted on the desiccated bed of the Aral Sea demonstrate that the potential for vegetation establishment varies substantially in space and is largely determined by local soil and hydrological conditions. The use of remote sensing data combined with field observations has enabled the identification of areas with different probabilities of successful plant establishment, which is of key importance for planning restoration activities (Yang et al., 2014). Comparisons between passive restoration and active vegetation introduction indicate that phytomelioration can modify the properties of the soil surface horizon and alter successional trajectories. However, the effectiveness of such interventions depends on the interaction between natural conditions and the applied reclamation techniques (Hüttermann et al., 2009). These findings are consistent with general principles of dryland ecology, according to which restoration success is determined by the correspondence between species' biological traits and the principal environmental limiting factors.

Halophytic shrubs and subshrubs are considered key components in the restoration of saline arid landscapes due to their ability to tolerate high mineralization levels, develop stable root systems, and stabilize surface soil horizons (Wang et al., 2023; Lu et al., 2017). However, the early ontogenetic stages remain a critical phase of phytomelioration under extreme environmental conditions. Seed germination and seedling survival decline sharply under the combined effects of salt and water stress, rendering population recruitment highly sensitive to short-term moisture availability and to agronomic practices that modify the soil water regime (Ren and Tao, 2004).

In arid ecosystems, episodic moisture "pulses" are of fundamental importance: even brief precipitation events may trigger germination, yet rapid water loss due to evaporation often prevents successful rooting and subsequent plant development (Kim et al., 2020). In this context, increasing attention has been paid to restoration practices aimed at enhancing the water-holding capacity of the rhizosphere in degraded lands. The use of superabsorbent polymers has been shown to increase available soil moisture, improve seed germination, and enhance plant survival under water-deficit conditions (Javaid et al., 2024; Matsui et al., 2019). In addition, natural zeolites are regarded as promising soil amendments capable of improving soil physical properties, reducing ionic toxicity, and increasing plant resistance to abiotic stress in arid and saline environments (Qadir et al., 2014). However, the effects of such interventions largely depend on species-specific responses and local habitat conditions, underscoring the need for field-based assessments. Aridity is a key factor controlling the growth of tree species under arid conditions in Kazakhstan (Utebekova et al., 2021). Despite the substantial body of research on vegetation and ecological processes on the desiccated bed of the Aral Sea, the combined influence of sowing and planting seasonality, spatial heterogeneity of environmental conditions, and soil water management practices on the early establishment and survival of halophytic shrubs remains insufficiently investigated. Addressing this gap is essential for improving the effectiveness of phytomelioration programs in the Aralkum Desert, where high variability in early-stage survival substantially limits restoration success.

The objective of the present study was to assess the establishment and survival of halophytic shrubs on the desiccated bed of the Aral Sea under varying soil water regime conditions, taking into account sowing and planting seasonality. The results are discussed within the framework of contemporary concepts of saline arid ecosystem restoration and are intended to provide a scientific basis for optimizing field-based biological stabilization strategies.

## 2. Materials and Methods

### *2.1. Study area*

The study was conducted on the desiccated bed of the Aral Sea (Aralkum Desert, Kazakhstan) under sharply continental arid climatic conditions. The region is characterized by extremely low annual precipitation (less than 120 mm), high evaporative demand, and pronounced seasonal fluctuations in air temperature.

The soil cover is predominantly represented by sandy and sandy loam substrates with varying degrees of salinity. The experimental sites differed in soil texture, salinity regime, and moisture availability, including variations in groundwater depth. Based on the combination of these

characteristics, the sites were classified into conditional categories of suitability for vegetation establishment.

The experimental plots were assigned to forest suitability groups II-IV, reflecting the spatial heterogeneity of soil and hydrological conditions on the desiccated bed of the Aral Sea.

### *2.2. Plant material*

Seeds subjected to standard pre-sowing treatment in accordance with species-specific biological characteristics, as well as nursery-grown seedlings, were used in the experiments. The study included representatives of the genera *Calligonum*, *Salsola*, *Haloxylon*, and *Halostachys*, which are widely distributed in arid and saline ecosystems of Central Asia and are considered promising species for phytomelioration of the desiccated bed of the Aral Sea.

### *2.3. Experimental design*

In spring 2025, halophytic shrubs were planted on experimental plots located on the desiccated bed of the Aral Sea (DBAS), covering a total area of 0.48 ha (three plots of 0.16 ha each) and sowing was also carried out on an area of 0.288 hectares. Additional experiments were established in the nursery of the southwestern branch of the Republican Forest Seed Center (Kazaly, Kyzylorda Region) to produce planting material of salt-tolerant species.

The following treatment variants were applied: control (no amendments), zeolite application, hydrogel application, and their combination (hydroseeding). Zeolite and dry hydrogel were incorporated into sowing rows at a rate of 20 g per linear meter. In the hydroseeding treatment, seeds were mixed with zeolite and hydrogel and subsequently moistened to obtain a homogeneous gel-like mixture prior to application.

Under nursery conditions, the biostimulant "Zircon" was additionally applied: seeds were soaked in a solution at a concentration of 0.025 mL per 100 mL of water for 4 hours before sowing. The total seed-sowing area in the nursery was 7.0 $m^2$.

### *2.4. Soil moisture monitoring*

Soil moisture in the 0-20 cm layer was determined using the gravimetric method 2-3 times per month during the growing season. Values ranged from 3-5% during dry periods to 10-14% after precipitation events. Groundwater depth varied from 1.5 to 3.5 m and was considered in evaluating the potential contribution of capillary rise to plant water availability.

### *2.5. Germination and survival*

Seed germination was assessed under field conditions as the percentage of emerged seedlings relative to the total number of sown seeds. Germination rates ranged from 12% to 35%, depending on season and site conditions, with the highest values recorded under spring sowing. Plant survival was evaluated 30, 60, and 90 days after sowing or planting and was expressed as a percentage of the initial number of plants. By the end of the first growing season, survival ranged from 8% to 28%, with complete mortality recorded at some sites. Assessments were conducted during the early stages of plant establishment within the first growing season.

### *2.6. Statistical analysis*

Statistical analysis was performed using Statistica 13.5 software (TIBCO Software Inc., USA). Analysis of variance (ANOVA) was applied to assess the effects of introduction season, planting/sowing method, soil water management treatment, and site type on germination and survival parameters.

When statistically significant differences were detected, multiple comparisons of mean values were conducted. The level of statistical significance was set at $p < 0.05$.

## 3. Results

### *3.1. Seed quality and viability of halophytic species*

Indicators of seed quality of halophytic species collected in 2024 and re-evaluated in spring 2025 are presented in Table 1. Immediately after collection, seed quality ranged from 30% to 67% depending on species; however, after winter storage, a marked decline in viability was observed across all studied taxa. The most pronounced reductions were recorded for *Calligonum caput-medusae* (from 67% to 30%), *Salsola richteri* (from 30% to 10%), and *Nitraria schoberi* (from 40% to 17%).

At the same time, seeds of *C. caput-medusae* and *N. schoberi* collected and analyzed in 2025 without prolonged

**Table 1.** Seed quality before and after storage (2024 → spring 2025).

| Plant species | Collection period (2024) | Seed quality after collection, % | Seed quality after storage (spring 2025), % | Seed quality class (2024 / 2025) |
|---|---|---|---|---|
| Calligonum caput-medusae | July 2024 | 67 | 30 | III / – |
| Nitraria schoberi | July 2024 | 40 | 17 | II / – |
| Salsola richteri | November 2024 | 30 | 10 | II / – |
| Halostachys caspica | December 2024 | 45 | 30 | II / – |
| Halocnemum strobilaceum | December 2024 | 40 | 28 | III / – |
| Anabasis aphylla | December 2024 | 32 | 14 | II / – |

**Note:** Seed quality was assessed according to national standard methods. Values represent the proportion of viable seeds before storage and after winter storage under dry, ventilated conditions.

storage were characterized by high purity (96%) and germination capacity (44%), respectively, allowing them to be classified as first-quality seeds.

For visual comparison of changes in seed quality after storage across species, the results are presented in Figure 1.

As shown in Figure 1, seed quality decreased after winter storage in all studied taxa, with the most pronounced reductions observed in *Calligonum caput-medusae*, *Salsola richteri*, and *Nitraria schoberi*.

Differences in seed quality among species and assessment periods were statistically significant (ANOVA, $p < 0.05$).

### 3.2. Seasonal soil moisture and groundwater dynamics

Seasonal dynamics of soil moisture within the 0-100 cm profile and groundwater depth at the experimental sites of the desiccated bed of the Aral Sea are presented in Table 2.

According to the data shown in Table 2, the average soil moisture content of the profile was highest in spring and declined toward autumn. Groundwater depth increased from spring to autumn, varying within the range of 2.0-2.8 m.

Seasonal differences in soil moisture were statistically significant (ANOVA, $p < 0.05$), whereas changes in groundwater depth were less pronounced.

### 3.3. Field establishment of halophytic shrubs

The results of establishment and survival of halophytic plants on the desiccated bed of the Aral Sea are presented in Table 3 and Figure 2.

As shown in Table 3, the success of stand establishment on the desiccated bed of the Aral Sea was strongly influenced by plant species, introduction season, applied agronomic treatment, and forest suitability group of the site.

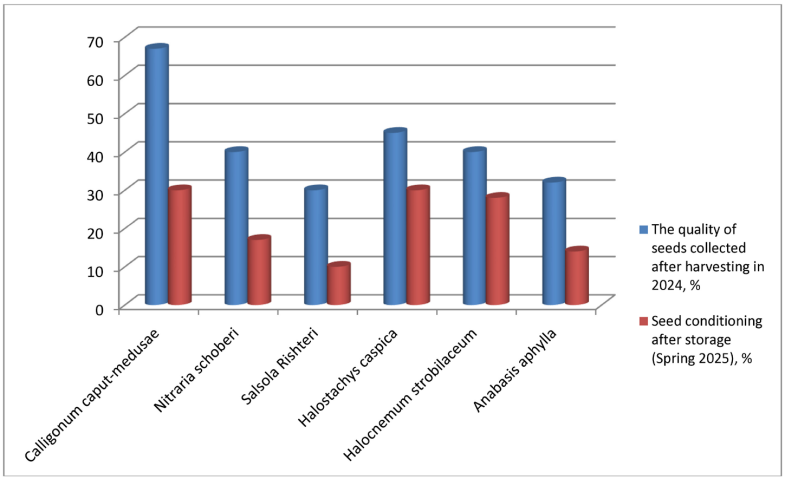



**Figure 1.** Seed quality (viable seeds, %) of halophytic species collected in 2024 before storage and after winter storage (spring 2025).

**Table 2.** Soil moisture and groundwater depth by season on the desiccated Aral Sea bed.

| Season | Site (land suitability group) | Mean soil moisture (0–100 cm), % | Groundwater depth, m |
|---|---|---|---|
| Spring | Site 1 (Group II) | 56.7 | 2.0 |
| Spring | Site 2 (Group IV) | 66.9 | 2.0 |
| Spring | Site 3 (Group III) | 60.6 | 2.0 |
| Spring (mean) | – | 61.4 | 2.0 |
| Summer | Site 1 (Group II) | 53.6 | 2.6 |
| Summer | Site 2 (Group IV) | 53.2 | 2.6 |
| Summer | Site 3 (Group III) | 47.7 | 2.4 |
| Summer (mean) | – | 51.5 | 2.5 |
| Autumn | Site 1 (Group II) | 44.3 | 2.8 |
| Autumn | Site 2 (Group IV) | 49.8 | 2.8 |
| Autumn | Site 3 (Group III) | 47.2 | 2.7 |
| Autumn (mean) | – | 47.1 | 2.8 |

**Note:** Soil moisture values represent mean gravimetric water content across the 0-100 cm soil profile. Groundwater depth was determined by manual augering and refers to the depth from the soil surface to the water table.

**Table 3.** Field establishment outcomes on the desiccated bed of the Aral Sea (DBAS).

| Species | Establishment type | Season | Land suitability group | Treatment | Established plants | Unit |
|---|---|---|---|---|---|---|
| Halostachys caspica | Planting | Spring 2025 | Group III | Zeolite + hydrogel | 14 | plants / 100 m² |
| Halostachys caspica | Planting | Spring 2025 | Group III | Hydrogel | 8 | plants / 100 m² |
| Halostachys caspica | Planting | Spring 2025 | Group III | Control | 7 | plants / 100 m² |
| Halostachys caspica | Planting | Spring 2025 | Group IV | Zeolite + hydrogel | 6 | plants / 100 m² |
| Halostachys caspica | Planting | Spring 2025 | Group IV | Hydrogel | 4 | plants / 100 m² |
| Halostachys caspica | Planting | Spring 2025 | Group IV | Control | 2 | plants / 100 m² |
| Halostachys caspica | Planting | Autumn 2024 | Groups III–IV | All treatments | 0 | plants / 100 m² |
| Salsola richteri | Sowing | Autumn 2024 | Group II | Zeolite | 38 | plants / 20 m² |
| Salsola richteri | Sowing | Autumn 2024 | Group II | Hydroseeding | 14 | plants / 20 m² |
| Salsola richteri | Sowing | Autumn 2024 | Group II | Control | 7 | plants / 20 m² |
| Salsola richteri | Sowing | Autumn 2024 | Group III | Zeolite | 32 | plants / 20 m² |
| Salsola richteri | Sowing | Autumn 2024 | Group III | Hydroseeding | 28 | plants / 20 m² |
| Salsola richteri | Sowing | Autumn 2024 | Group III | Control | 15 | plants / 20 m² |
| Salsola richteri | Sowing | Spring 2025 | Groups II–IV | All treatments | 0 | plants / 20 m² |
| Salsola richteri | Sowing | Autumn 2024 | Group IV | All treatments | 0 | plants / 20 m² |

**Note:** Values represent the number of established plants recorded at the end of the growing season. Zero values indicate complete mortality or absence of establishment. Different sampling units were used for planted (per 100 m²) and sown (per 20 m²) plots.

For *Halostachys caspica*, autumn planting in 2024 proved ineffective at all sites, as no seedling survival was recorded in any forest suitability group. In contrast, spring planting in 2025 resulted in the establishment of viable plants at sites belonging to forest suitability groups III and IV. The highest survival was observed following pre-planting root treatment with a combined slurry based on zeolite and hydrogel, reaching 14 plants per 100 m² in group III sites and 6 plants per 100 m² in group IV sites. The use of hydrogel alone and the control treatment resulted in lower plant survival. At group II sites, no survival of *H. caspica* was recorded under either autumn or spring planting.

For *Salsola richteri*, spring sowing in 2025 did not result in plant survival under any experimental treatment or site type. In contrast, autumn sowing in 2024 demonstrated pronounced differences among treatments and forest suitability groups. At group II sites, the highest survival was achieved with zeolite application (38 plants per 20 m²), whereas hydroseeding and control treatments resulted in substantially lower values. A similar trend was observed at group III sites, where maximum survival was also recorded with zeolite application (32 plants per 20 m²), while hydroseeding showed comparable but slightly lower effectiveness. At group IV sites, autumn sowing of *S. richteri* was ineffective under all treatments, and no plant survival was recorded. Figure 2 illustrates the spatial arrangement of the experimental plots and the correspondence between sowing/planting treatments and forest suitability groups at the study sites on the desiccated bed of the Aral Sea.

The experimental scheme presented in Figure 2 was developed to standardize field conditions and ensure valid comparison of different plant introduction methods under conditions of arid spatial heterogeneity.

The analysis revealed statistically significant effects of plant species, introduction season, and forest suitability group on establishment and survival parameters (ANOVA, $p < 0.05$).

## 4. Discussion

The results obtained confirm that the successful establishment of halophytic shrubs on the desiccated bed of the Aral Sea is determined by the combined effects of water deficit, salt stress, and spatial heterogeneity of the substrate, which create critical constraints for early ontogenetic stages. The limiting role of aridity has been confirmed by dendrochronological studies, in which the water regime is identified as the principal factor determining woody plant growth (Utebekova et al., 2021). In floodplain ecosystems, hydrological instability has likewise been shown to reduce the success of natural regeneration in tree and shrub communities (Dukenov et al., 2023). In arid ecosystems, early developmental stages are particularly vulnerable, as they require the coincidence of favorable moisture conditions with the physiological readiness of seeds to germinate (Fenner and Thompson, 2005).

The influence of biometric seed characteristics on germination has also been demonstrated for woody species, including *Betula jarmolenkoana*, where laboratory germination was statistically associated with morphometric parameters of generative organs (Rakymbekov et al., 2023).

The sharp decline in seed quality after winter storage observed in the present study is consistent with general patterns of seed ecology in desert and semidesert species. According to Fenner and Thompson (2005), seeds of plants from arid habitats often exhibit limited storage longevity

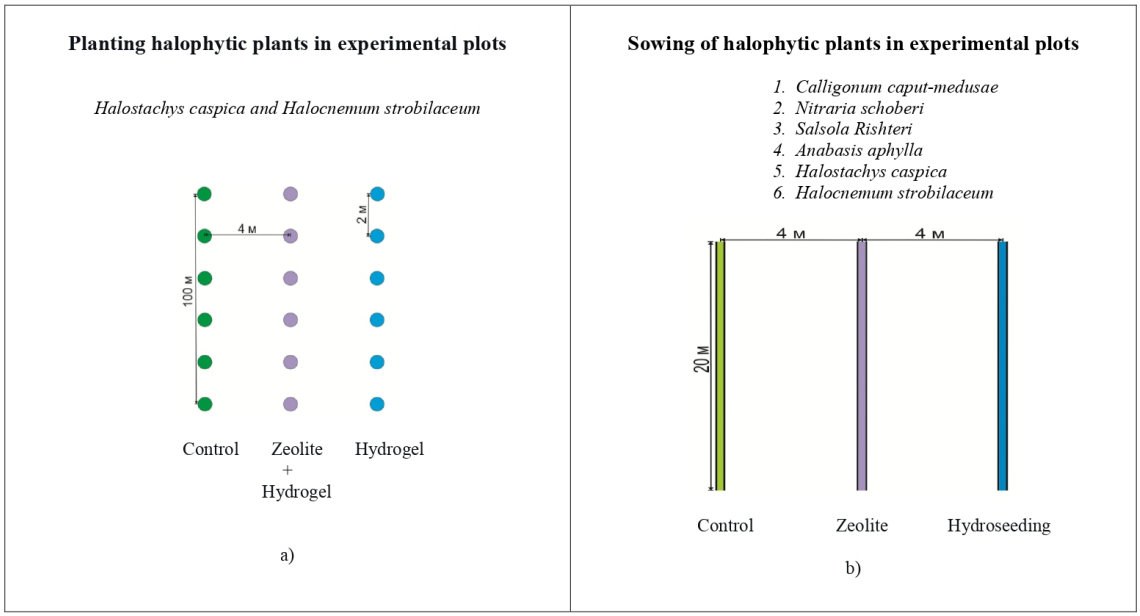



**Figure 2.** Experimental layout of sowing (a) and planting (b) of halophytic species on the desiccated Aral Sea bed (DBAS): plot arrangement, treatments, and sampling units.

due to increased seed coat permeability, accelerated oxidative processes, and degradation of embryonic tissues. For representatives of the genus *Calligonum*, it has previously been demonstrated that pre-sowing treatments and storage conditions significantly influence germination, with the most stable results achieved when seeds are sown in the year of collection (Ren and Tao, 2004). Thus, the present findings support the practical importance of minimizing storage duration in phytomelioration programs in extreme arid environments.

The interpretation of seasonal soil moisture dynamics may be considered within the framework of the "moisture pulse" concept, according to which short-term periods of increased water availability determine the possibility of germination and initial rooting in dry ecosystems (Austin et al., 2004; Collins et al., 2014; Schwinning and Sala, 2004). Despite the presence of groundwater within the root-inhabited zone, its contribution to water supply for young plants was limited, as evidenced by the absence of survival at sites with unfavorable soil and hydrological conditions. This is consistent with the concept of environmental thresholds, beyond which vegetation recovery becomes impossible even in the presence of additional water sources (Reynolds et al., 2007; Löw et al., 2021).

Species-specific responses of halophytic shrubs to agronomic treatments further indicate the necessity of a differentiated approach to the restoration of degraded lands. Increasing soil water-holding capacity through the application of zeolites and superabsorbent polymers reduces osmotic stress during early plant development (Hüttermann et al., 2009; Yang et al., 2014). For halophytes, this is particularly important, as their salt tolerance is based on ion compartmentalization, selective transport of $Na^+$ and $Cl^-$, and osmotic regulation (Flowers and Colmer, 2015; Zhao et al., 2020), and in recretohalophytes, additionally on the functioning of salt glands (Yuan et al., 2016; Wei et al., 2020). These physiological mechanisms operate more effectively under optimal water regime conditions. A similar increase in survival and growth of *Haloxylon aphyllum* under improved soil moisture availability has been reported for arid regions of Kazakhstan (Akhmetov et al., 2022). Review studies also emphasize the potential of zeolites as multifunctional soil amendments that improve both physical and chemical substrate properties (Cataldo et al., 2021; Mondal et al., 2021). However, the absence of plant survival at sites classified as forest suitability group IV indicates that the effectiveness of such treatments is limited and cannot compensate for extreme levels of salinity and substrate degradation.

Overall, the results demonstrate that vegetation restoration on the desiccated bed of the Aral Sea should be based on ecologically grounded, site-adapted strategies that account for the biological characteristics of halophytic species, introduction seasonality, and local soil and hydrological constraints. The application of soil-improving materials may be effective only within a defined ecological range, whereas overcoming threshold conditions requires an integrated approach and long-term monitoring of natural vegetation recovery processes.

## 5. Conclusion

The present study demonstrated that the successful establishment of halophytic shrubs on the desiccated bed of the Aral Sea is determined by the interaction among introduction season, soil water regime, and forest suitability group. Winter seed storage led to a significant decline in

seed quality, whereas freshly collected seeds maintained high viability, supporting the recommendation to sow seeds in the year of collection.

Maximum soil moisture levels were recorded in spring, followed by a decline toward autumn, while groundwater depth varied from 2.0 to 2.8 m. Despite its occurrence within the capillary zone, groundwater did not ensure successful plant establishment at sites with unfavorable conditions.

Pronounced species-specific differences were identified: *Halostachys caspica* exhibited higher survival under spring planting with the application of zeolite and hydrogel, whereas *Salsola richteri* established successfully primarily under autumn sowing with zeolite application at sites of moderate forest suitability. No survival was recorded at group IV sites.

These findings underscore the necessity of a differentiated, site-adapted approach to vegetation restoration in arid saline ecosystems.

Practical recommendation. The most promising approach is autumn planting of halophytic seedlings at sites classified within forest suitability groups I-II (particularly *Haloxylon aphyllum*) with localized application of zeolite or hydrogel, whereas spring sowing without moisture-retention treatments is ineffective.

## Acknowledgements

This research is funded by the Ministry of Ecology and Natural Resources of the Republic of Kazakhstan (No. BR23590517).

## Data Availability Statement

The entire data set that supports the results of this study will be published in the article itself.

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