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SHORT-TERM PERFORMANCE OF *SALICORNIA EUROPAEA* L. IN AN EXTENSIVE GREEN ROOF UNDER FRESHWATER, BRACKISH-WATER, AND SEAWATER IRRIGATION

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ABSTRACT

Extensive green roofs in Mediterranean cities may require irrigation, but the use of saline water is constrained by plant tolerance. This exploratory study assessed the short-term performance of *Salicornia europaea* L., three Mediterranean xerophytes, and one succulent xerophyte in nine outdoor DIADEM-150 green roof modules in Messolonghi, Greece. Three substrate mixtures were combined with freshwater, a 1:1 (v/v) freshwater-seawater mixture, or seawater irrigation; each substrate × water combination was represented by one physical module. Plant height was recorded for 63 plants on five dates from 10 April to 10 June 2025, and complete wilting was documented. Because independent module-level replication was absent, analyses were descriptive. *Salicornia europaea* showed positive mean height change in all brackish-water modules (14.0-14.7 cm) and seawater modules (5.0-16.3 cm), without complete wilting. One of six plants wilted under freshwater irrigation. *Mesembryanthemum acinaciforme* also maintained positive height change under all treatments, whereas *Salvia officinalis*, *Lavandula dentata*, and *Rosmarinus officinalis* 'Prostratus' completely wilted in saline-irrigated modules. The findings provide screening-level evidence supporting *Salicornia europaea* for replicated, long-term evaluation in saline-irrigated extensive green roofs.

Keywords: Extensive green roof; halophyte; saline irrigation; seawater; plant height; Mediterranean climate.

1. INTRODUCTION

Green roofs are increasingly incorporated into urban green infrastructure because they can support stormwater control, thermal regulation, biodiversity, and other ecosystem services [1-4]. Extensive systems are particularly relevant where structural load and maintenance inputs must be limited; however, their shallow substrate profiles expose vegetation to rapid drying, high temperature, and restricted rooting volume. Plant selection is therefore a primary determinant of system persistence and functional performance [5-8].

Mediterranean green roofs face an additional constraint: supplemental irrigation is often required during the warm, dry season, when potable water is least available. Alternative sources, including brackish water and seawater, could reduce potable-water demand, but salt exposure may inhibit growth, accelerate tissue injury, and alter substrate conditions. Drought tolerance should not be treated as equivalent to salinity tolerance, because the two stresses impose overlapping but distinct physiological constraints [9-12].

Halophytes possess mechanisms such as ion compartmentalization, osmotic adjustment, selective ion transport, and succulence that enable growth under elevated salinity [13,14]. *Salicornia europaea* L. is a salt-adapted annual or short-lived species associated with coastal and inland saline habitats [15]. Its agronomic and ecological potential under saline cultivation has been reviewed extensively [16,17], but evidence for its performance in extensive green roof systems remains limited.

Recent green roof studies have demonstrated that seawater or saline water can be used with selected halophytic or salt-tolerant species, including Arthrocnemum macrostachyum, seashore paspalum, and tall fescue, when the irrigation regime and leaching conditions are appropriately managed [18-20]. Nevertheless, species responses cannot be generalized across taxa, substrates, or exposure durations. The performance of S. *europaea* should therefore be evaluated directly within the physical constraints of an extensive green roof system.

The objective of this exploratory study was to characterize short-term plant-height change and the incidence of complete wilting in S. *europaea* under freshwater, brackish-water, and seawater irrigation in outdoor extensive green roof modules. Its response was compared descriptively with those of *Salvia officinalis*, *Lavandula dentata*, *Rosmarinus officinalis* 'Prostratus', and *Mesembryanthemum acinaciforme*. The study was conceived as a preliminary screening exercise; because each substrate × irrigation-water combination was represented by one physical module, treatment effects were not subjected to inferential statistical testing.

2. MATERIALS AND METHODS

2.1 Experimental Site and Green Roof Modules

The experiment was conducted outdoors at the Department of Agriculture, University of Patras, Messolonghi, Western Greece, from April to June 2025. The site is located in a hot-summer Mediterranean climatic zone. During the experimental period, mean daily evaporation was approximately 4.8 mm d^{-1}. The modules were exposed to natural solar radiation and ambient weather conditions; no artificial shading or climate control was applied.

Nine plastic modules measuring 97 × 58 × 25 cm were installed at a 2% slope to facilitate drainage. Each module incorporated the DIADEM-150 multilayer green roof system, comprising a waterproofing and anti-root membrane (FLW-400), protective layer (VLU-300), drainage and water-retention layer (DiaDrain-25H), filtration layer (VLF-150), substrate, and vegetation.

2.2 Substrate and Irrigation Treatments

Three substrate mixtures were evaluated: mixture A, perlite:peat at 1:1 (v/v); mixture B, perlite:peat:vermiculite at 1:1:1 (v/v/v); and mixture C, perlite:peat:vermiculite at 1:1:0.5 (v/v/v). The experiment followed a 3 × 3 treatment structure in which each substrate mixture was combined with one of three irrigation-water treatments. Each combination was represented by one physical module (Table 1).

Table 1: Substrate × irrigation-water structure of the nine experimental modules.

Module	Substrate composition (v/v)	Irrigation-water treatment
A1	Perlite:peat (1:1)	Freshwater
B1	Perlite:peat:vermiculite (1:1:1)	Freshwater
C1	Perlite:peat:vermiculite (1:1:0.5)	Freshwater
A2	Perlite:peat (1:1)	Brackish water
B2	Perlite:peat:vermiculite (1:1:1)	Brackish water
C2	Perlite:peat:vermiculite (1:1:0.5)	Brackish water
A3	Perlite:peat (1:1)	Seawater
B3	Perlite:peat:vermiculite (1:1:1)	Seawater
C3	Perlite:peat:vermiculite (1:1:0.5)	Seawater

Freshwater consisted of municipal tap water and served as the control. Its measured electrical conductivity was approximately 0.30 dS m^{-1} at 20 °C. Brackish water was prepared volumetrically by mixing freshwater and seawater at 1:1 (v/v), and the seawater treatment consisted of undiluted seawater collected from the coastal zone of Messolonghi. Electrical conductivity was not measured directly for the brackish-water and seawater treatments; these treatments are therefore defined operationally by their volumetric seawater content. Accordingly,

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the exact salinity exposure and ion-specific composition of the brackish-water and seawater treatments cannot be quantified, and comparisons among water treatments should be interpreted as responses to operationally defined irrigation-water categories rather than to calibrated salinity levels.

Thirteen controlled water-application events were conducted. During each event, 8 L were applied to each module, corresponding to approximately 14.2 mm over the module surface area of 0.5626 m^2. These were controlled water applications rather than natural rainfall events.

2.3 Plant Material and Measurements

The plant assemblage comprised the halophyte S. *europaea*, the Mediterranean xerophytes S. *officinalis*, L. *dentata*, and R. *officinalis* 'Prostratus', and the succulent xerophyte M. *acinaciforme*. All five species were represented in each module. Each module contained two plants of S. *europaea*, two plants of S. *officinalis*, and one plant each of R. *officinalis* 'Prostratus', L. *dentata*, and M. *acinaciforme*. The complete experiment therefore included 63 plants: 18 S. *europaea*, 18 S. *officinalis*, and nine plants of each remaining species. S. *europaea* material originated from the Messolonghi lagoon area.

Plant height was recorded individually on 10 April, 25 April, 10 May, 25 May, and 10 June 2025. Plant condition was also assessed visually for chlorosis, necrosis, leaf dehydration, growth stagnation, and wilting. A final height of 0 cm indicated complete wilting, defined as the absence of a measurable living shoot.

2.4 Data Analysis

For each plant, initial height, final height, and absolute height change (ΔH) were derived from the first and final monitoring dates. For S. *europaea* and S. *officinalis*, module-level values represent the mean of two plants; for the other species, one plant was present in each module. Height change and complete wilting were summarized by species, module, substrate mixture, and irrigation-water treatment.

Individual plants were observational subsamples nested within modules. Because each substrate × irrigation-water combination was represented by only one physical module, repeated measurements and plants within modules were not treated as independent treatment replicates. No analysis of variance, post-hoc comparison, or other inferential test was applied. All comparisons are descriptive and exploratory. Consequently, the observed differences cannot be attributed statistically to irrigation-water treatment, substrate composition, or their interaction; they are reported only as module-level screening patterns.

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3. RESULTS

3.1 Short-Term Response of *Salicornia europaea*

Salicornia europaea exhibited positive initial-to-final mean height change in all three brackish-water modules, ranging from +14.0 to +14.7 cm, and in all three seawater modules, ranging from +5.0 to +16.3 cm (Fig. 1). No complete wilting occurred under brackish-water or seawater irrigation. Under freshwater irrigation, module-level mean height changes ranged from -8.0 to +10.0 cm. The negative mean in module A1 resulted from complete wilting of one of the two plants in that module. Across the three freshwater modules, one of six S. *europaea* plants completely wilted.

The largest mean height increase was recorded in module B3 under seawater irrigation (+16.3 cm), followed by module B2 under brackish-water irrigation (+14.7 cm). The highest individual final height was 54 cm in module B2. These values describe the observed plants and modules and do not estimate a replicated treatment effect.

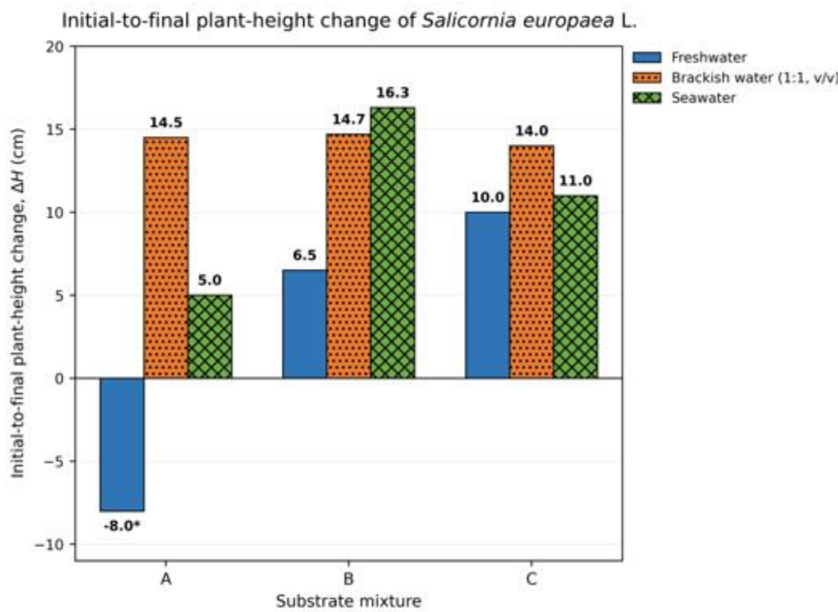

Fig. 1: Initial-to-final plant-height change of Salicornia europaea L. in substrate mixtures A, B, and C under freshwater, brackish-water, and seawater irrigation. Bars represent the mean change of two plants within each physical module. The asterisk denotes complete wilting of one of two plants in module A1. Treatments were not independently replicated at the module level; values are descriptive.

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3.2 Comparative Response of the Tested Species

Mesembryanthemum acinaciforme maintained positive height change in all nine modules, with a range of +5.0 to +25.0 cm and no complete wilting. The largest increases occurred under freshwater irrigation, while smaller but positive changes were recorded under brackish-water and seawater irrigation.

In contrast, all S. officinalis and L. dentata plants completely wilted under both brackish-water and seawater irrigation. All six saline-irrigated R. officinalis 'Prostratus' plants also completely wilted; one of the three plants under freshwater irrigation wilted in module B1. The descriptive ranges and wilting frequencies are summarized in Table 2.

Table 2: Descriptive range of initial-to-final height change (ΔH, cm) and complete-wilting frequency by species and irrigation-water category.

Species	Freshwater	Brackish water	Seawater
Salicornia europaea	-8.0 to +10.0; W 1/6	+14.0 to +14.7; W 0/6	+5.0 to +16.3; W 0/6
Salvia officinalis	+7.5 to +10.5; W 0/6	-12.5 to -11.0; W 6/6	-13.5 to -13.0; W 6/6
Lavandula dentata	+11.0 to +15.0; W 0/3	-23.0 to -15.0; W 3/3	-22.0 to -15.0; W 3/3
Rosmarinus officinalis 'Prostratus'	-25.0 to +4.0; W 1/3	-30.0 to -20.0; W 3/3	-26.0 to -18.0; W 3/3
Mesembryanthemum acinaciforme	+13.0 to +25.0; W 0/3	+13.0; W 0/3	+5.0 to +8.0; W 0/3

W n/N indicates the number of completely wilted plants relative to the number evaluated within each irrigation-water category. Values for S. *europaea* and S. *officinalis* are based on module means of two plants; the remaining species were represented by one plant per module.

4. DISCUSSION

The principal observation was the maintenance of positive short-term height change by S. *europaea* in every brackish-water and seawater module, without complete wilting under either saline-water category. This pattern is biologically plausible because halophytes regulate cellular water relations and ion distribution differently from glycophytes [13,14]. The known ecology and cultivation potential of S. *europaea* further support its candidacy for environments where saline

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exposure is expected [15-17]. Nevertheless, the present experiment did not measure tissue ion concentrations, osmotic adjustment, photosynthesis, biomass, or substrate salinity; the physiological mechanisms underlying the observed response were therefore not tested directly.

The positive response of M. *acinaciforme* under all water treatments indicates that S. *europaea* was not the only species retaining measurable growth. Conversely, the complete wilting of S. *officinalis*, L. *dentata*, and R. *officinalis* 'Prostratus' under saline irrigation demonstrates that Mediterranean drought adaptation did not ensure tolerance of the applied salt exposure. Salinity can restrict water uptake through osmotic effects and can produce ion-specific toxicity, so plant selection for saline-irrigated green roofs must be based on demonstrated salt tolerance rather than xerophytic habit alone [9-11].

The findings are consistent with prior green roof experiments in which saline irrigation was feasible only for selected taxa and under defined management conditions. Arthrocnemum macrostachyum has been evaluated under seawater irrigation in a replicated extensive green roof experiment [18], while seashore paspalum and tall fescue studies have shown that substrate depth, leaching, irrigation scheduling, and cultivar or species selection substantially influence plant performance [19,20]. The present results extend this screening context to S. *europaea*, but they should not be interpreted as evidence that undiluted seawater is universally suitable for green roof irrigation.

The novelty of the present work lies in extending this screening framework to *Salicornia europaea* within a shallow, multilayer extensive green roof and in comparing its response with four co-planted xerophytic species under operationally defined saline-water categories. The contrast between positive height change without complete wilting in *S. europaea* and complete wilting of three Mediterranean xerophytes under saline irrigation provides a practical species-selection signal, but not evidence of a universally superior irrigation treatment.

Several limitations constrain interpretation. First, each substrate × irrigation-water combination was represented by one physical module; the module, not each plant or monitoring date, was the experimental unit. Treatment significance and substrate × water interactions therefore cannot be estimated. Second, the experiment covered only approximately two months in spring and early summer. Third, the electrical conductivity and ionic composition of the brackish-water and seawater treatments were not measured directly. Fourth, substrate electrical conductivity, salt accumulation, leaching fraction, biomass, survival after the final date, and physiological stress indicators were not quantified. Finally, the mixed-species planting design did not include monoculture controls, so interspecific effects cannot be separated from treatment response. Therefore, the actual salt dose and ion-specific exposure of the plants cannot be reconstructed, and no salinity-response threshold can be inferred from the present experiment.

A confirmatory study should use independently replicated modules for each substrate × water treatment, directly characterize irrigation and drainage-water chemistry, monitor substrate salinity and ion accumulation, and continue across seasons. Biomass, canopy cover, survival, visual quality, gas exchange, and tissue ion content would provide stronger evidence than height alone. Such a design would allow valid mixed-model or factorial analysis and would determine whether the observed short-term performance translates into durable green roof establishment.

5. CONCLUSION

Under the conditions of this exploratory study, S. *europaea* maintained positive mean height change in all brackish-water and seawater modules and did not completely wilt under saline irrigation. M. *acinaciforme* also retained positive height change, whereas S. *officinalis*, L. *dentata*, and R. *officinalis* 'Prostratus' completely wilted in the saline-irrigated modules. The principal practical advantage of S. *europaea* is therefore its apparent short-term compatibility with saline irrigation within a shallow, multilayer extensive green roof system.

The principal limitation is the absence of independent module-level replication, compounded by the short monitoring period and incomplete salinity characterization. The findings cannot establish statistical treatment effects, long-term survival, potable-water savings, or the operational suitability of seawater irrigation. They should be applied as screening-level evidence for selecting S. *europaea* and other salt-tolerant species for replicated, long-term green roof trials in Mediterranean coastal environments. Accordingly, the study identifies candidate species for subsequent testing rather than a validated saline-irrigation prescription.

Declaration of interest statement

The authors declare no conflicts of interest.

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