

**Middle East Regional Water Research Cooperation Program (MEWAC)**  
**(“Wasserforschung im Nahen und Mittleren Osten - Modul A“)**

## Joint Final Project Report



**Project title (English):** MEWAC – Collaborative Project EXALT: Coupling thermal desalination and extraction of dewatered salt with hydroponic greenhouse cultivation via heat pumps

**Project title (German):** MEWAC – Verbundprojekt EXALT: Koppelung thermischer Entsalzung and Ausschleusung von entwässertem Salz mit hydroponischer Pflanzenproduktion mittels Wärmepumpen

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## Section 1: JOINT SUMMARY

The EXALT project, supported by the MEWAC funding initiative, aimed to deliver practical solutions to water scarcity in the Middle East through trilateral collaboration between German, Jordanian, and Israeli partners (Figure 1). Crop production in the region is constrained by chronic water scarcity, exacerbated by climate change, recurrent droughts, and salinization of freshwater and soils. In the Jordan River Basin, per capita renewable water availability has declined by more than 80% over six decades, while agriculture remains the largest consumer of water, using roughly half of total freshwater withdrawals in both Jordan and Israel. The two countries pursue divergent strategies to address water scarcity: Jordan depends on declining groundwater and transboundary surface water, supplemented by limited freshwater imports from Israel, whereas Israel relies heavily on large-scale desalination and direct wastewater reuse.



Figure 1: EXALT consortium members during the project kick-off meeting at the University of Hohenheim

In this context, EXALT developed a blueprint for innovative hydroponic greenhouse systems to overcome both water scarcity and salinity constraints. By combining advanced climate control, water recovery, and thermal desalination, the project sought to maximize water-use efficiency, reduce environmental pressures, enhance year-round productivity, and provide a scalable model for arid, subtropical regions. From the outset, the consortium emphasized integrated collaboration across technical, scientific, and capacity-building dimensions, including controlled-environment trials, field assessments, stakeholder engagement, and training of young scientists. EcoPeace Jordan supported these efforts by organizing field trips for researchers, conducting interviews, and assisting with soil sampling campaigns, while a number of universities and public institutions contributed local knowledge, sample analysis, and networking support.

Research at the University of Hohenheim examined the interplay of atmospheric demand, salinity, and plant performance in hydroponic systems. Three experiments with tomato, cucumber, and quinoa demonstrated genotype-specific responses in growth, ion partitioning, and stress tolerance. Salt-tolerant tomatoes effectively sequestered sodium and chloride in the petiole, protecting metabolically active leaf tissues, while cucumbers showed lower ionic homeostasis and increased vulnerability under high vapour pressure deficit (VPD). Evapotranspiration was strongly influenced by both VPD and light regime, with LED lighting reducing water loss relative to metal halide lamps. These findings underscore the importance of coordinating humidity, light, and salinity management to optimize plant performance and water-use efficiency.

At the University of Jerusalem, experiments compared nutrient uptake in recirculating deep-water culture and nutrient film technique systems. Leaf nutrient concentrations generally reflected solution composition, yet NFT systems maintained optimal nutrient levels even when solution concentrations exceeded targets. Preliminary studies on chelate dynamics suggested interactions that could limit micronutrient availability, highlighting the importance of nutrient management under low-input and saline conditions.

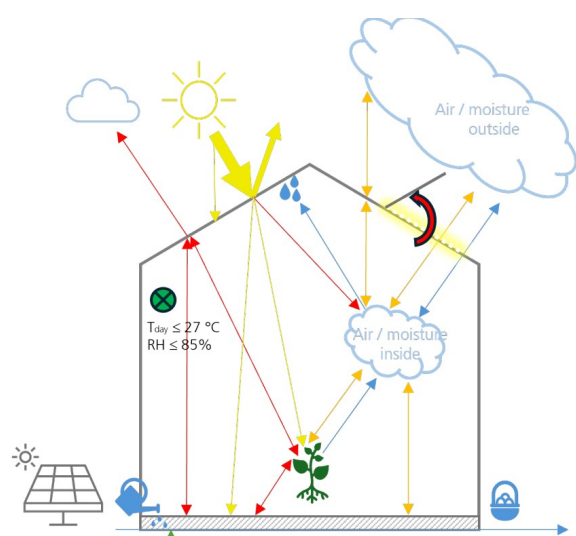


Figure 2: Conceptual representation of a ventilated greenhouse for Modelica analysis of water and energy fluxes

Fraunhofer research focused on greenhouse energy efficiency and climate control (Figure 2). Thermal screens improved heat retention, LED lighting reduced electrical demand, and partial photovoltaic shading lowered heat gain while allowing recovery of water from condensation. Simulation studies of a fully controlled growing environment (FCGE) indicated potential for year-round cultivation, wastewater elimination, and substantial reduction of external water requirements. FCGE systems demonstrated high yields, significant water savings, and resilience under semi-arid and saline conditions.

Collectively, the consortium showed that hydroponic systems with integrated climate and water-recovery technologies could reduce daily water demand by up to  $2.25 \text{ L m}^{-2}$ , nearly matching the annual irrigation allocation for protected vegetables in the Jordan Valley. Applied across an estimated 4,000 ha of greenhouse cultivation, these technologies could

save roughly 19–22 million  $\text{m}^3$  of water annually—about 17% of the total supply from the King Abdullah Canal and equivalent to the freshwater needs of several hundred thousand people.

At the same time, crop- and genotype-specific salt uptake was shown to enable biological removal of salts through harvested biomass, reducing or eliminating the need for energy-intensive brine management under moderate salinity conditions. Together, these findings demonstrate that closed-loop hydroponic systems can simultaneously address water scarcity and salinity constraints while substantially lowering energy demand and operational costs.

Despite geopolitical tensions limiting in-region mobility and field activities, the consortium maintained continuous communication, shared methodologies, and harmonized workflows, reflecting a common understanding of regional water and agricultural challenges. Capacity-building activities included MSc, BSc, and doctoral-level research projects, remote mentoring, and cross-institutional supervision. These efforts strengthened human capital across Israel, Jordan, and Germany, creating a cadre of trained professionals ready to implement water-efficient agricultural technologies and support future science–industry collaboration.

Through technical innovation, environmental monitoring, and capacity development, EXALT advanced sustainable greenhouse production, disseminated environmentally innovative technologies, and fostered long-term professional networks. By addressing both water scarcity and salinity, the project contributes to regional water security, demonstrates the value of cross-border cooperation, and provides a replicable model for sustainable agriculture under challenging conditions. Even under restricted mobility and political constraints, the consortium's integrated approach delivered measurable contributions to technology transfer, capacity building, and resilient agricultural practices.

## Section 2: SCIENTIFIC OR TECHNICAL RESULTS

### 2.1 Project context

Crop production in the Near and Middle East is constrained by chronic water scarcity that is exacerbated by climate change and increasingly severe droughts (Fragaszy et al. 2022). Long-term data and basin-wide assessments indicate that per capita renewable water availability in the Jordan River Basin has declined by more than 80% over the past six decades, placing all riparian states well below the absolute water scarcity threshold (HaskoningDHV and EcoPeace Middle East 2015). Nonetheless, agriculture remains the largest consumer of water in the region. In Jordan, the agricultural sector accounts for approximately 51% of total freshwater consumption (MWI 2022), a figure that has declined from historical highs of 70% due to extreme scarcity and rising domestic demand (UNICEF Jordan and Economist Impact 2022). Similarly, in Israel, agriculture utilizes roughly 49% of total water withdrawals (Zaide and Israeli Water Authority 2025).

The two nations have, however, adopted markedly divergent strategies for freshwater supply. Jordan remains heavily dependent on declining groundwater reserves and transboundary surface water resources, a structural vulnerability highlighted in regional water security analyses (HaskoningDHV and EcoPeace Middle East 2015). Its most critical lifelines are the Disi Aquifer—a fossil, non-renewable groundwater source pumped over 325 km to Amman—and the Yarmouk River, whose flows are frequently affected by regional climate variability and upstream abstractions (MWI 2023). To bridge a national water deficit of nearly 400 million cubic meters (MCM), Jordan currently purchases approximately 100 MCM of freshwater annually from Israel under the 1994 Peace Treaty, while simultaneously advancing its National Water Carrier project, which aims to desalinate Red Sea water by 2028 (Jordan Times 2025).

Israel, by contrast, has transitioned toward a “manufactured water” economy, in which five large-scale Mediterranean desalination plants now provide nearly 80% of domestic freshwater supply. In a global first achieved in 2025, Israel’s national water company, Mekorot, fully operationalized the “Reverse Water Carrier,” enabling the pumping of surplus desalinated water into the Sea of Galilee to stabilize lake levels, ecological conditions, and strategic water reserves (Surkes 2025).

Regarding recycled water, Jordan employs an indirect reuse system where treated effluent from several centralized plants - primarily Khirbet As-Samra, but also Al-Baqa’a, Jerash, and Abu Nusair - is discharged into the Zarqa River and its tributaries. These flows are blended with fresh surface runoff in the King Talal Dam before distribution (MWI 2023). This indirect method is a “grey knowledge” area for water accounting, as significant volumes are lost to evaporation or unmetered riparian withdrawals along riverbeds, making the official figure of 14% to 16% of total supply from treated wastewater likely an underestimate of actual use (MWI 2022). Israel utilizes a direct reuse model, treating roughly 90% of wastewater to tertiary standards and pumping it via dedicated networks, such as the Shafdan project, directly to farms (Zaide and Israeli Water Authority 2025).

In both countries, the reliance on treated wastewater introduces a persistent “salinity tax.” Conventional treatment does not remove dissolved salts like sodium ( $\text{Na}^+$ ) and chloride ( $\text{Cl}^-$ ), which accumulate in the root zone. This anthropogenic salinity worsens the region's natural salinity caused by the weathering of ancient marine sediments and the upwelling of brines rich in calcium ( $\text{Ca}^{2+}$ ), magnesium ( $\text{Mg}^{2+}$ ), sulfates ( $\text{SO}_4^{2-}$ ), and bicarbonates ( $\text{HCO}_3^-$ ). Conventional cultivation systems often struggle under these conditions; limited availability of high-quality irrigation water exacerbates yield gaps, sometimes leading to total crop failure (Ammari et al. 2013). Improving water-use efficiency under salinity stress and adopting climate-smart agricultural practices is therefore critical not only for maintaining the overall national water balance but also for sustaining crop productivity.

Hydroponic greenhouse cultivation offers a promising alternative, as it decouples plant production from fertile soil while using water more efficiently than open-field systems (Resh 2022). In controlled systems, evapotranspiration can be tightly managed, and water recovery through condensation can significantly reduce irrigation demand. However, in regions with increasingly

saline water sources, hydroponic systems face limitations: salt accumulation in the nutrient solution restricts plant growth and necessitates periodic flushing, generating nutrient-rich brine that can exacerbate environmental salinization. Existing desalination technologies, such as reverse osmosis, are energy-intensive, costly, and produce concentrated brine streams that require careful management (Lattemann and Höpner 2008).

The EXALT project was initiated in this context to explore an integrated solution capable of simultaneously addressing water scarcity and salinity-induced constraints. The project combines advanced greenhouse climate control, water recovery, and thermal desalination in a single system based on heat pump technology. By recovering both sensible and latent heat from greenhouse air, the system improves year-round climate control while simultaneously generating fresh condensate water. The extracted heat is subsequently used to drive a thermal desalination process, concentrating saline feedwater to a point where dewatered salt can be safely removed from the water cycle.

This integrated approach aims to enable sustainable hydroponic production using locally available saline water sources in arid, subtropical regions such as Jordan and Israel, reducing environmental pressures, increasing water-use efficiency, enhancing year-round crop productivity, and providing a scalable model for saline agriculture. By targeting both the key constraints of water availability and salinity, EXALT contributes not only to crop production but also to national water security and sustainable resource management. The need to invest in water-efficient and climate-smart agriculture is broadly recognized and promises a good return on investment (World Bank and Ministry of Agriculture and Ministry of Environment of the Hashemite Kingdom of Jordan and Partnership for Market Readiness 2021).

## 2.2 Objectives

The overarching objective of EXALT was to develop, test, and evaluate a combined system coupling thermal desalination with hydroponic greenhouse cultivation via heat pumps. This was broken down into the following specific scientific, technical, and applied objectives:

### 1. Improve water-use efficiency in hydroponic greenhouse systems

- Recover condensed water from air dehumidification to reduce overall irrigation demand.
- Enhance nutrient-use efficiency by lowering nutrient solution salinity through condensate dilution.

### 2. Enable the use of saline surface or groundwater for greenhouse-based plant production

- Investigate plant growth performance across a salinity gradient to identify species- and cultivar-specific tolerance limits.
- Determine how multiple stresses (temperature, humidity, salinity) affect plant physiology and productivity.

### 3. Develop an innovative refrigeration circuit for greenhouse climate control

- Actively extract sensible and latent heat from greenhouse air to maintain optimal temperature and humidity year-round.
- Evaluate environmentally friendly refrigerants and engineer key components based on measured cooling demand.

### 4. Integrate greenhouse cooling with a thermal desalination process

- Use the heat rejected from the heat pump condenser to drive desalination.
- Achieve brine concentration levels that allow extraction of dewatered salt, eliminating liquid brine discharge.

### 5. Design and assess modular system outlines for diverse environmental conditions

- Produce detailed configurations for three case study sites in each participating country.
- Evaluate system performance across climate regimes and operational scenarios.

#### **6. Facilitate knowledge transfer and stakeholder engagement**

- Conduct workshops, training courses, and stakeholder consultations.
- Support capacity building among young scientists and regional practitioners.

In addition to these technical and scientific objectives, EXALT was designed to contribute to regional water security, foster collaboration between Israeli, Jordanian, and German research and industry partners, disseminate innovative hydroponic and desalination technologies, and support capacity building among young scientists and stakeholders. These aims directly align with the broader goals of the MEWAC program and provide a framework for assessing the project's societal and regional impact alongside its technical achievements.

### **2.3 Cross-Border Collaboration and Political Challenges**

The EXALT project was conceived as a tightly integrated cross-border effort, bringing together Israeli and Jordanian partners to jointly develop and test innovative hydroponic greenhouse systems in a region defined by both shared environmental challenges and complex political realities. From the outset, the project aimed to foster intensive cooperation across technical, scientific, and capacity-building dimensions, including field assessments, greenhouse measurements, stakeholder engagement, and the training of young scientists. These activities were designed to enable knowledge transfer, strengthen professional networks, and build a shared understanding of site-specific conditions, reflecting the principle, emphasized by EcoPeace Middle East, that water scarcity and climate adaptation in the Jordan Valley require transboundary cooperation.

Despite the strong scientific rationale and clear mutual benefits of collaboration, the project operated within a highly volatile geopolitical context that severely constrained joint activities. Escalating political tensions and periods of heightened violence across the region limited opportunities for direct engagement. Efforts to bring researchers together from both countries were repeatedly postponed or cancelled, and the planned integration of additional Jordanian academic partners into field or laboratory work proved unfeasible. While professional interest in collaboration remained strong, particularly among Jordanian researchers and practitioners, heightened social and political pressures, along with personal safety concerns, prevented participation in several planned activities.

Two major regional developments further disrupted collaboration. The killing of Palestinian journalist Shireen Abu Akleh in May 2022 intensified regional tensions and public sensitivities around cooperative initiatives. This was followed by the Hamas attack on Israel on 7 October 2023 and the subsequent escalation in Gaza, which made cross-border activities and joint gatherings politically and socially untenable. These developments directly led to the cancellation of planned events, including the trinational status seminar linked to the MEWAC programme. The broader political climate also affected partners outside the region; in Germany, for example, a collaborator at Fraunhofer reportedly resigned amid heightened social and institutional pressures associated with the conflict.

Nonetheless, the EXALT consortium sustained communication and coordination throughout the project. Continuous virtual exchanges, regular technical updates, and informal consultations allowed knowledge sharing, capacity development, and professional networking to continue despite the constrained conditions. These efforts uphold MEWAC and EcoPeace principles of maintaining cross-border cooperation during periods of political crisis and lay the foundation for renewed collaboration and the future implementation of sustainable hydroponic systems when conditions allow.

## 2.4 Detailed representation of scientific and technical results

### 2.4.1 Combined effects of vapor pressure deficit and salinity on plant growth (Hemanth Puppala, Jörn Germer, Folkard Asch)

Under carefully managed irrigation and the implementation of water-saving technologies, transpiration constitutes the major component of water use in crop production systems. Consequently, the most effective entry point for reducing the water footprint in protected agriculture is a deeper understanding of the environmental factors that determine plant transpiration rates. Although it is well established that transpiration increases with light intensity, temperature, and vapour pressure deficit (VPD), far less is known about how active manipulation of VPD in protected cultivation affects plant transpiration and development, particularly under conditions of varying salinity in hydroponic systems.

To address this knowledge gap, three experiments were conducted at the Phytotechnikum research facility of the University of Hohenheim. These experiments investigated the combined effects of VPD and salinity on plant growth and on the uptake and distribution of sodium (Na), chloride (Cl), and potassium (K). Special attention was given to physiological responses and ion partitioning mechanisms under different atmospheric demands and salinity levels, with the overall aim of improving our understanding of how these stresses interact to influence plant performance.

The first experiment explored genotypic variation in tomato and cucumber with regard to their responses to salinity and VPD. Plants were grown hydroponically, and the results highlighted clear genotype-dependent differences in growth performance and stress tolerance under combined stress conditions.

The second experiment examined the effects of VPD and salinity on growth and ion distribution in hydroponically grown tomato plants. Detailed ion analyses of leaf tissues showed that, in the salt-resistant genotype, the petioles were the primary accumulation sites for Na and Cl. This indicates their potential role in ion sequestration and in mitigating salinity-induced stress in the metabolic leaf tissues.

The third experiment investigated the interactive effects of VPD and salinity on quinoa grown under different light sources—ceramic metal halide lamps (CMHL), CMHL combined with LED, and LED alone—while maintaining the root-zone temperature between 15 and 20 °C. This experiment aimed to understand how atmospheric demand interacts with salinity stress under different lighting regimes that are increasingly common in controlled-environment agriculture.

All experiments were conducted in controlled-environment chambers at the University of Hohenheim. To emulate nutrient conditions typical of low-input cultivation systems, the INTEGAR nutrient solution recipe was used to prepare low-concentration hydroponic solutions. Plants were grown in recirculating deep-water culture (DWC) systems, a soilless method in which roots are submerged in a continuously aerated nutrient solution. This system ensures stable water and nutrient availability while avoiding substrate-related variability, thereby enabling consistent and reproducible environmental and physiological measurements.

#### **2.4.1.1 Genotypic Responses to Combined Effects of VPD and Salinity in Hydroponically Grown Tomato and Cucumber**

The first experiment investigated how different relative air humidity levels, expressed as VPD, and salinity interact to affect growth, evapotranspiration, and ion uptake in two tomato and two cucumber genotypes. VPD represents the difference between the saturation vapor pressure and the actual vapor pressure of the air, thereby indicating the atmospheric evaporative demand. Because it integrates both temperature and humidity, VPD serves as a robust predictor of plant transpiration rates. A high VPD corresponds to low ambient humidity and thus stronger atmospheric demand.

Two tomato genotypes (Saluoso, Sweeterno) and two cucumber genotypes (Addison, Proloog; Rijk Zwaan Seeds, Netherlands) were cultivated for 24 days in a low-concentration nutrient solution ( $40 \text{ mg N L}^{-1}$ ,  $3.25 \text{ mg P L}^{-1}$ ) under two humidity regimes: high humidity (RH 80%, VPD 1.9 kPa) and low humidity (RH 40%, VPD 3.1 kPa). Plants were exposed to two levels of root-zone salinity (0 and 30 mM NaCl). Nutrient depletion was controlled using a feed-and-deplete strategy, where nutrient solution was renewed once nitrogen declined to  $5 \text{ mg N L}^{-1}$ .

High VPD substantially increased evapotranspiration and stimulated biomass production in tomato, whereas cucumber showed only minor responses to atmospheric demand. In tomato, high VPD promoted both leaf and root biomass, leading to larger leaf areas and enhanced dry matter accumulation. This response was particularly pronounced in the Saluoso genotype, which nearly doubled its leaf and root biomass compared to low-VPD conditions. In contrast, cucumber biomass and partitioning were largely unaffected by VPD, suggesting limited physiological plasticity to increasing evaporative demand.

Salinity strongly suppressed growth across species but with clear genotypic differences (Figure 3, 4). In cucumber, 30 mM NaCl reduced total biomass by approximately 60% irrespective of VPD, with leaf tissues being most affected. In tomato, the growth-promoting effect of high VPD diminished under saline conditions; however, total biomass remained comparatively stable, consistent with moderate salt tolerance. Taken together, these results indicate contrasting acclimation strategies: tomato maintained functional growth and transpiration under the combined stresses, whereas cucumber reached its salinity threshold even at moderate NaCl levels, showing pronounced sensitivity.

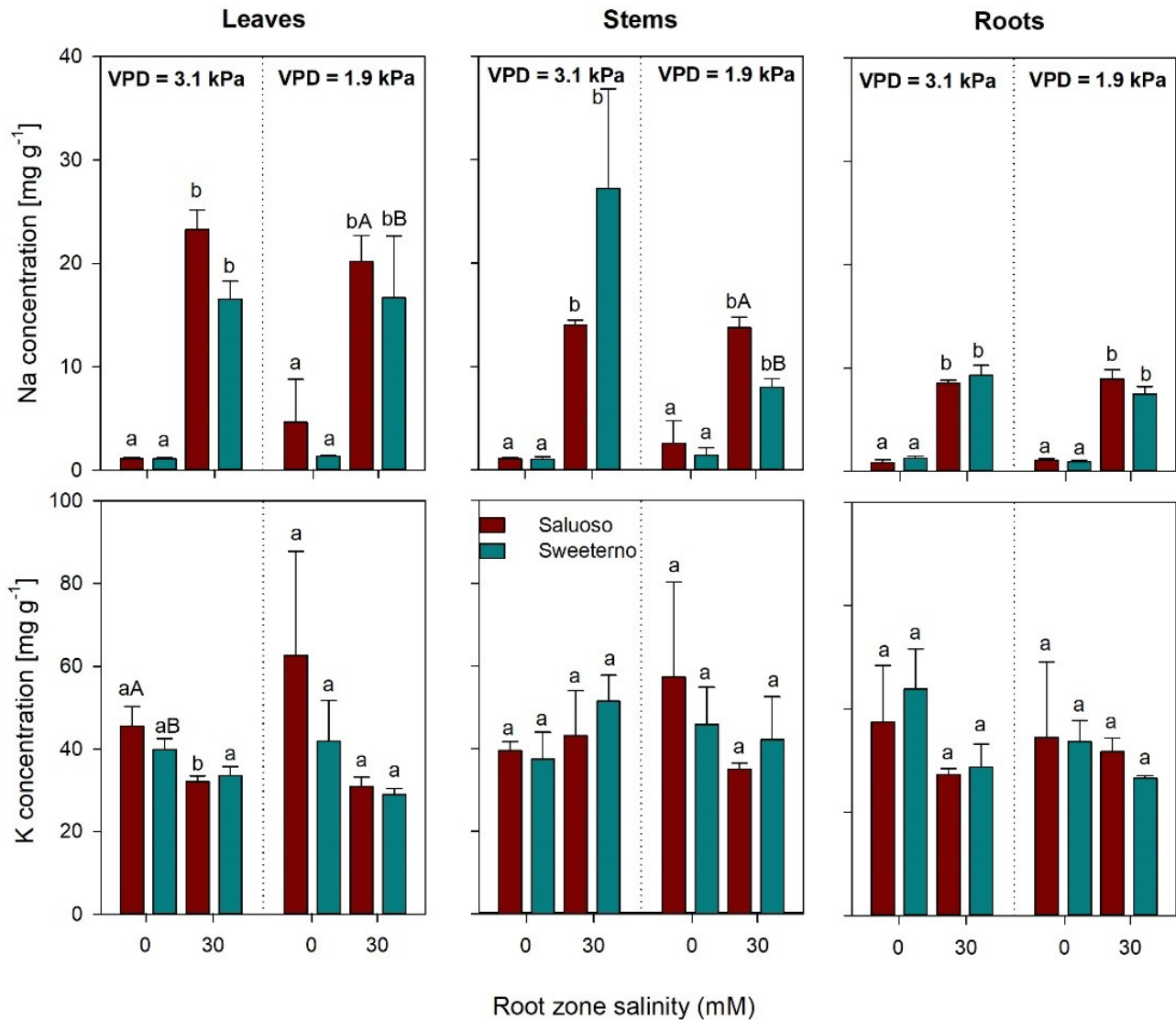


Figure 3: Sodium and potassium concentrations in leaves, stems, and roots of two tomato genotypes (*Saluoso* and *Sweeterno*) grown under two levels of root-zone salinity (0 and 30 mM NaCl) and two contrasting vapor pressure deficits (VPD). Different lowercase letters indicate significant differences within a genotype between salinity treatments. Different uppercase letters indicate significant differences between genotypes under the same VPD and salinity conditions.

Ion analysis revealed that salinity significantly increased sodium accumulation in all plant organs, with tomato exhibiting higher Na<sup>+</sup> concentrations than cucumber, particularly in older leaves. This accumulation was more pronounced under high VPD, suggesting enhanced mass flow-driven transport of ions due to increased transpiration. While potassium concentrations in tomato remained largely unaffected by VPD or salinity, cucumber showed reduced K<sup>+</sup> levels under saline conditions, contributing to lower K<sup>+</sup>/Na<sup>+</sup> ratios and increased ionic stress. These species-specific patterns of ion distribution underpin the differential tolerance observed and emphasize the importance of genotype selection when optimizing hydroponic systems under saline and high-VPD environments.

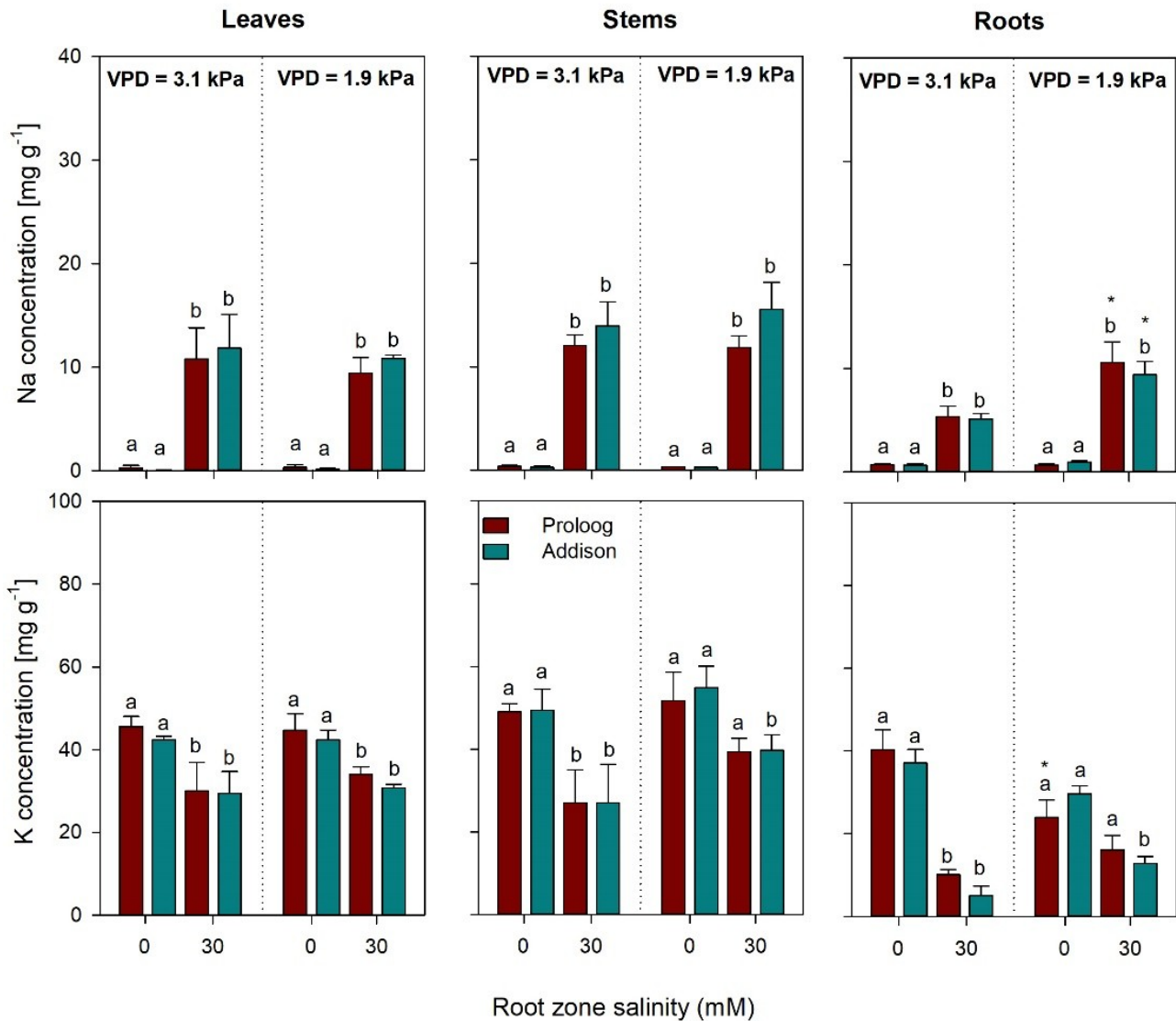


Figure 4: Sodium and potassium concentrations in leaves, stems, and roots of two cucumber genotypes (Proloog and Addison) grown under two root-zone salinity levels (0 and 30 mM NaCl) and two contrasting vapor pressure deficits (VPD). Data represent means  $\pm$  standard error ( $n = 3$ ). Different lowercase letters indicate significant differences within a genotype between salinity treatments. Different capital letters indicate significant differences between the two genotypes within the same VPD and salinity level.

These results suggest tomatoes are better suited for hydroponic systems that recover transpired water, even under saline conditions, while cucumbers are more vulnerable to salinity stress.

### 2.4.1.2 Effects of salinity and vapor pressure deficit on growth and ion partitioning in hydroponically grown tomato plants

This experiment focused on the leaf—the primary organ for photosynthesis and also one of the most sensitive sites of salinity-induced stress. To obtain a more detailed understanding of ion dynamics, leaves were separated into petioles and leaf blades, and the concentrations of sodium (Na), chloride (Cl), and potassium (K) were quantified in each tissue type. This approach allowed the assessment of ion buffering capacity within different leaf compartments and its contribution to salinity tolerance in two tomato genotypes.

Additionally, the experiment investigated how vapor pressure deficit (VPD), in combination with salinity, influences evapotranspiration and leaf development, thereby shaping overall physiological performance.

Two tomato genotypes—Saluoso and Sweeterno (Rijk Zwaan Seeds, Netherlands)—were grown for 30 days in a low-concentration nutrient solution (40 mg N L<sup>-1</sup>, 3.25 mg P L<sup>-1</sup>). Plants were exposed to two air humidity regimes representing low (RH 40%, VPD 3.2 kPa) and high humidity (RH 80%, VPD 0.7 kPa), and two salinity treatments (0 and 40 mM NaCl). Nutrient depletion was controlled using a feed-and-deplete strategy, whereby the nutrient solution was renewed once nitrogen concentration declined to 5 mg N L<sup>-1</sup>.

The combined effects of salinity and VPD had a pronounced influence on leaf growth, ion partitioning, and physiological behavior, with clear genotypic differences (Figure 5). Salinity substantially reduced leaf biomass and leaf area in both genotypes; however, Sweeterno consistently maintained greater dry matter accumulation and larger leaf areas, demonstrating a higher degree of salt tolerance.

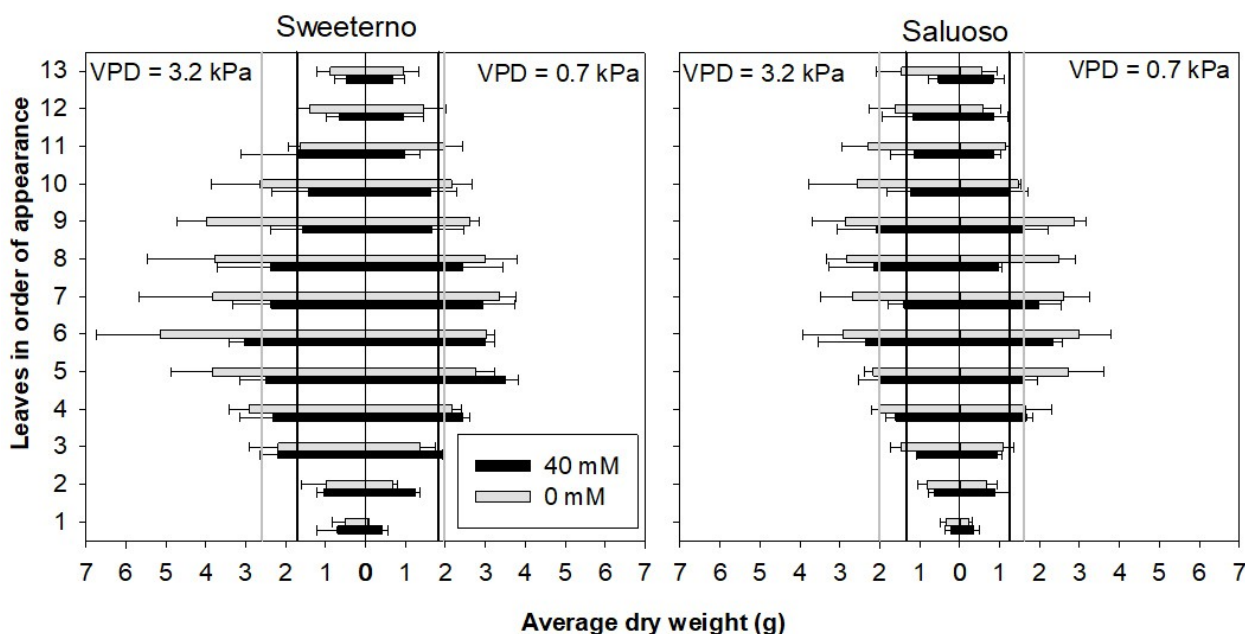


Figure 5: Average leaf dry weight of two tomato genotypes, Sweeterno and Saluoso, subjected to root zone salinity of 0 and 40 mM under high and low VPD. Error bars represent the standard error ( $n = 3$ ). The vertical lines indicate the average of all leaves.

High VPD exacerbated the negative effects of salinity, particularly in Saluoso, where young expanding leaves showed strong reductions in biomass and leaf expansion. In contrast, Sweeterno continued to sustain moderate leaf development even under 40 mM NaCl and high VPD, suggesting an enhanced ability to maintain osmotic balance and leaf hydration under elevated evaporative demand.

Across treatments, SPAD values remained relatively stable, indicating that growth limitations were primarily driven by ionic and osmotic stress rather than chlorophyll degradation.

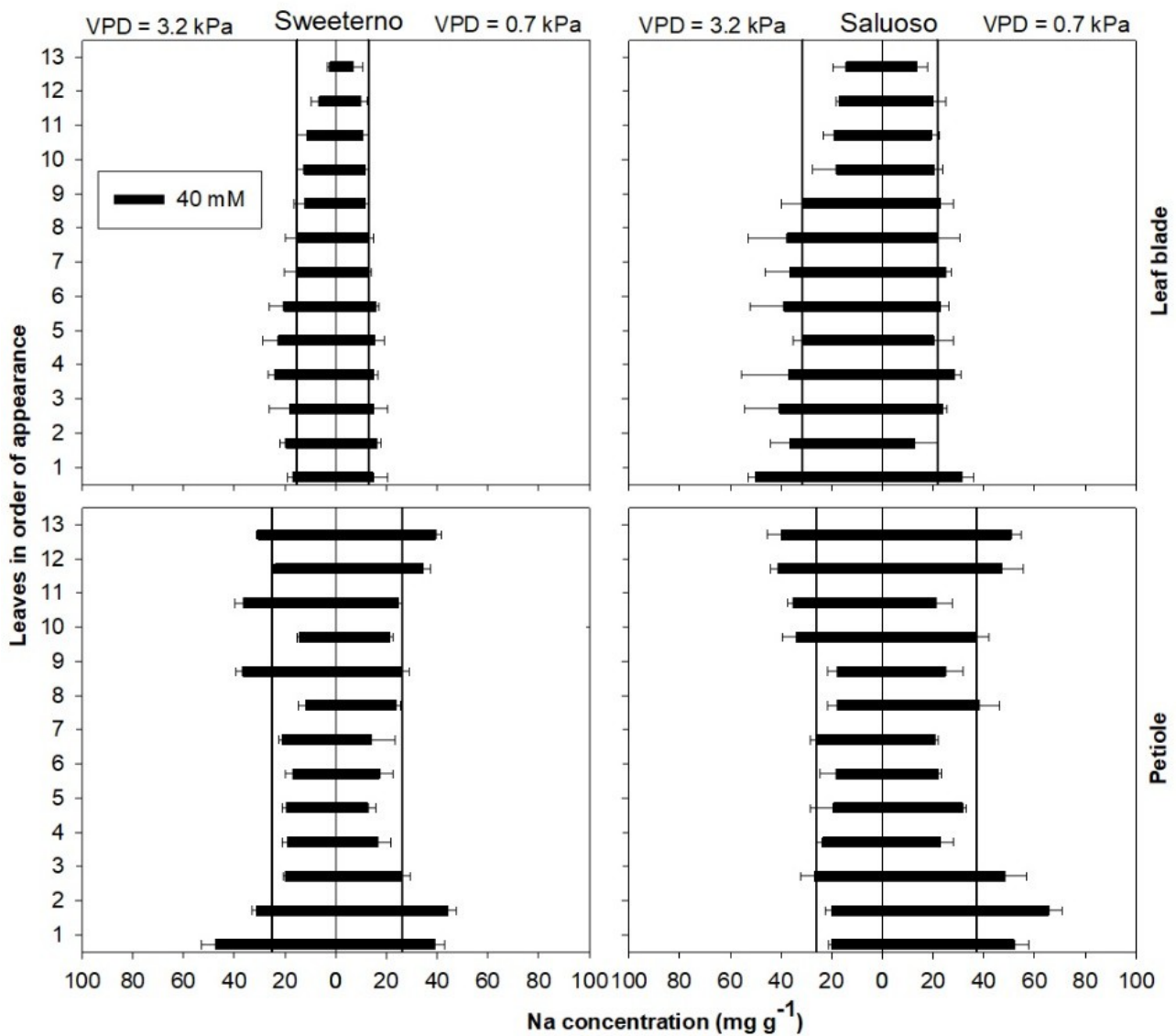


Figure 6: Average sodium ( $\text{Na}^+$ ) concentration in leaf blades and petioles of two tomato genotypes, Sweeterno and Saluoso, grown under 40 mM root zone salinity and contrasting vapor pressure deficits (high and low VPD). Error bars represent standard error ( $n = 3$ ). Vertical lines indicate the mean  $\text{Na}^+$  concentration across all leaves.

A clear tissue-specific pattern of ion partitioning was observed, highlighting the petiole as a primary buffering organ for sodium ( $\text{Na}^+$ ) (Figure 6) and chloride ( $\text{Cl}^-$ ) (Figure 7). The salt-tolerant genotype, Sweeterno, consistently restricted  $\text{Na}^+$  accumulation to the petiole under both VPD conditions, thereby limiting ion translocation to the photosynthetically active leaf blade. In contrast, Saluoso showed disrupted  $\text{Na}^+$  compartmentation, particularly under high VPD, with elevated  $\text{Na}^+$  concentrations in the leaf blades of older leaves, indicating reduced control over ion transport. Chloride distribution followed a similar trend: Sweeterno maintained stable petiole-dominated accumulation, while Saluoso exhibited VPD-dependent shifts toward the leaf blade. These contrasting patterns underscore the importance of effective tissue-level ion compartmentation in conferring salinity tolerance and protecting mesophyll function under combined salinity and atmospheric demand stress.

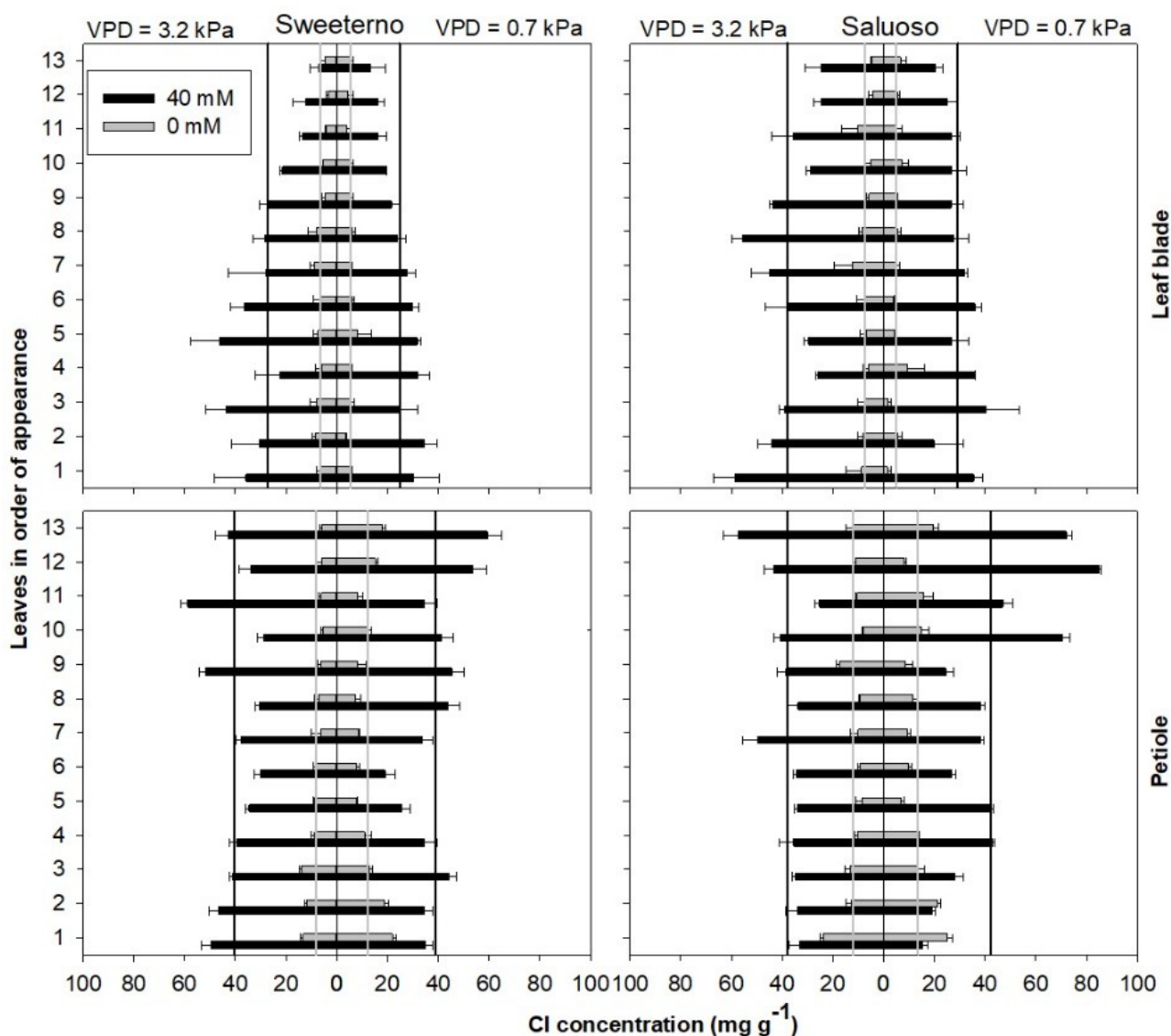


Figure 7: Average chloride ( $\text{Cl}^-$ ) concentration in leaf blades and petioles of two tomato genotypes, Sweeterno and Saluoso, grown under root zone salinity of 0 and 40 mM and contrasting vapor pressure deficits (high and low VPD). Error bars represent standard error ( $n = 3$ ). Vertical lines indicate the mean  $\text{Cl}^-$  concentration across all leaves.

Potassium ( $\text{K}^+$ ) concentrations declined under saline conditions in both genotypes, highlighting competitive interference from  $\text{Na}^+$  (Figure 8). Nevertheless,  $\text{K}^+$  remained preferentially stored in the petiole regardless of VPD or cultivar. Sweeterno maintained consistently higher  $\text{K}^+/\text{Na}^+$  ratios across leaf positions compared to Saluoso, reflecting stronger ionic homeostasis and more effective maintenance of metabolic integrity under stress. Although the combined  $\text{Na}^+ + \text{K}^+/\text{Cl}^-$  ratios showed less variation between genotypes, the superior  $\text{K}^+/\text{Na}^+$  balance in Sweeterno underscores its enhanced physiological resilience. Collectively, these findings identify the petiole as a critical ionic buffer and demonstrate that stable ion partitioning, particularly under fluctuating VPD, is a key determinant of salinity tolerance in tomato.

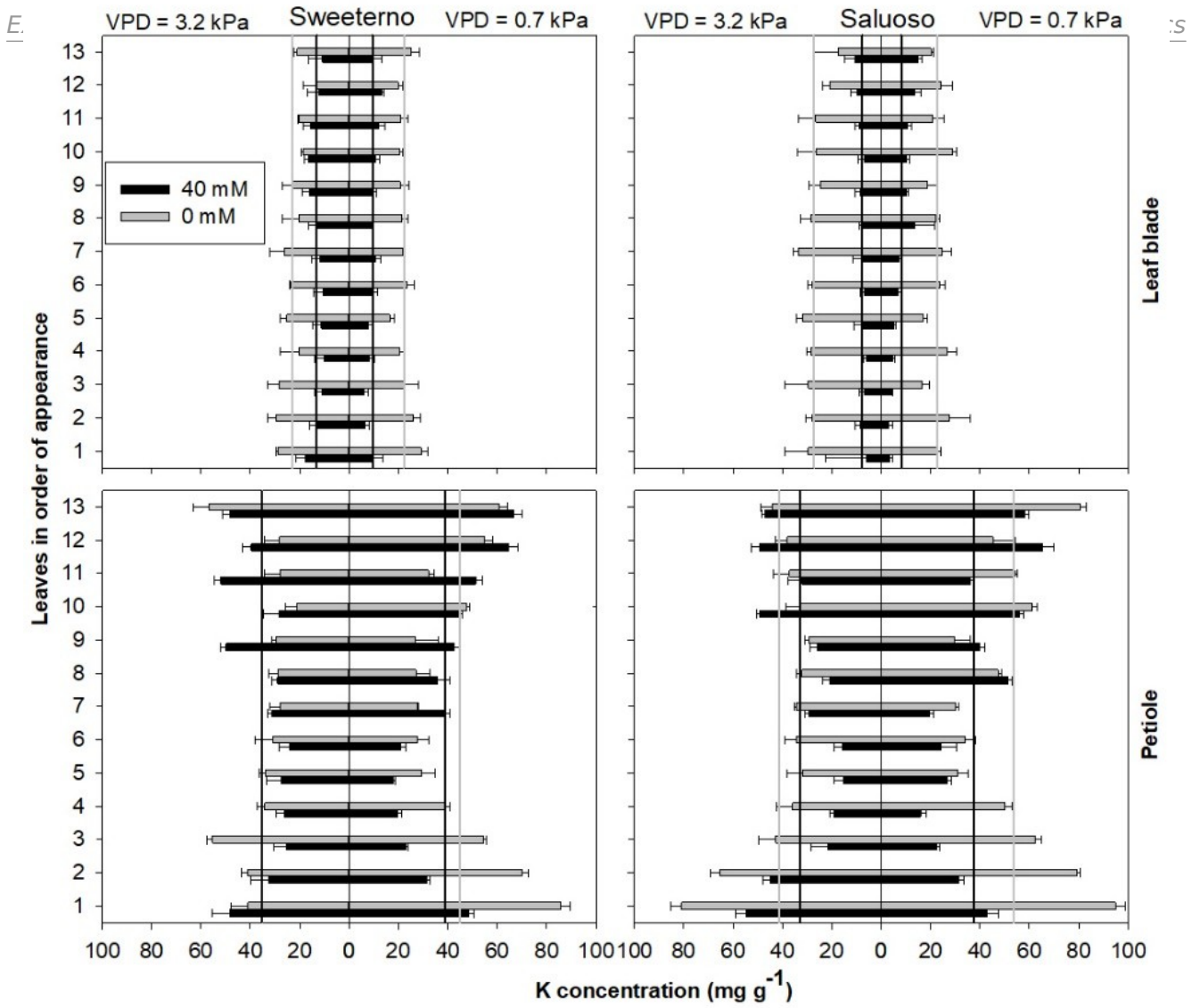


Figure 8: Average potassium ( $K^+$ ) concentration in leaf blades and petioles of two tomato genotypes, Sweeterno and Saluoso, grown under 40 mM root zone salinity and contrasting vapor pressure deficits (high and low VPD). Error bars represent standard error ( $n = 3$ ). Vertical lines indicate the mean  $K^+$  concentration across all leaves.

### **2.4.1.3 Interactive Effects of Vapor Pressure Deficit, Salinity, and Light Source on Growth and Ion Uptake in Hydroponically Grown Quinoa Under Controlled Root-Zone Temperature**

This experiment investigated the interactive effects of vapor pressure deficit (VPD), salinity, and light source on the physiological performance of quinoa grown hydroponically under a controlled root-zone temperature of 15–20 °C. Plants were exposed to two salinity levels (0 and 100 mM NaCl) and three lighting regimes: ceramic metal halide lamps (CMHL), light-emitting diodes (LED), and a combined CMHL + LED system. After 28 days of growth, plants were harvested and analyzed for transpiration dynamics, biomass accumulation, and ionic uptake. Concentrations of sodium (Na), chloride (Cl), and potassium (K) were quantified in distinct plant organs, including leaf blades, petioles, side shoots, stems, and roots, enabling detailed assessment of ion partitioning patterns. This approach allowed a comprehensive evaluation of how atmospheric demand and light quality interact with salinity stress to influence water relations, growth behavior, and ion homeostasis in quinoa, thereby providing valuable insights into its adaptive mechanisms under controlled hydroponic conditions.

Plant dry weight in quinoa varied substantially in response to the combined effects of VPD, salinity, and light source. Under non-saline conditions (0 mM NaCl), biomass production was highest under CMHL and CMHL + LED lighting, particularly at high VPD, indicating that elevated atmospheric demand together with favourable light quality enhanced carbon assimilation and overall growth. In contrast, LED lighting consistently resulted in lower biomass. The application of 100 mM NaCl caused a marked reduction in dry weight across all light treatments, with the most pronounced decrease observed under LED, especially at low VPD. This indicates that low evaporative demand, when combined with salinity stress, imposes strong limitations on plant growth, whereas CMHL and CMHL + LED lighting partially buffered these adverse effects.

Leaf area exhibited similar trends to biomass, with strong dependence on environmental conditions (Figure 9). Under non-saline conditions, the largest leaf areas were recorded under CMHL and CMHL + LED, particularly at high VPD, highlighting the synergistic effect of high atmospheric demand and favourable light spectra in promoting leaf expansion. LED lighting led to consistent reductions in leaf area across both VPD levels. Salinity (100 mM NaCl) significantly reduced leaf expansion under all lighting conditions, with the strongest decline occurring under LED at low VPD, where canopy development was severely restricted. Under CMHL and CMHL + LED, salinity-induced reductions in leaf area were less pronounced, suggesting that superior light quality mitigated some of the negative effects of saline stress.

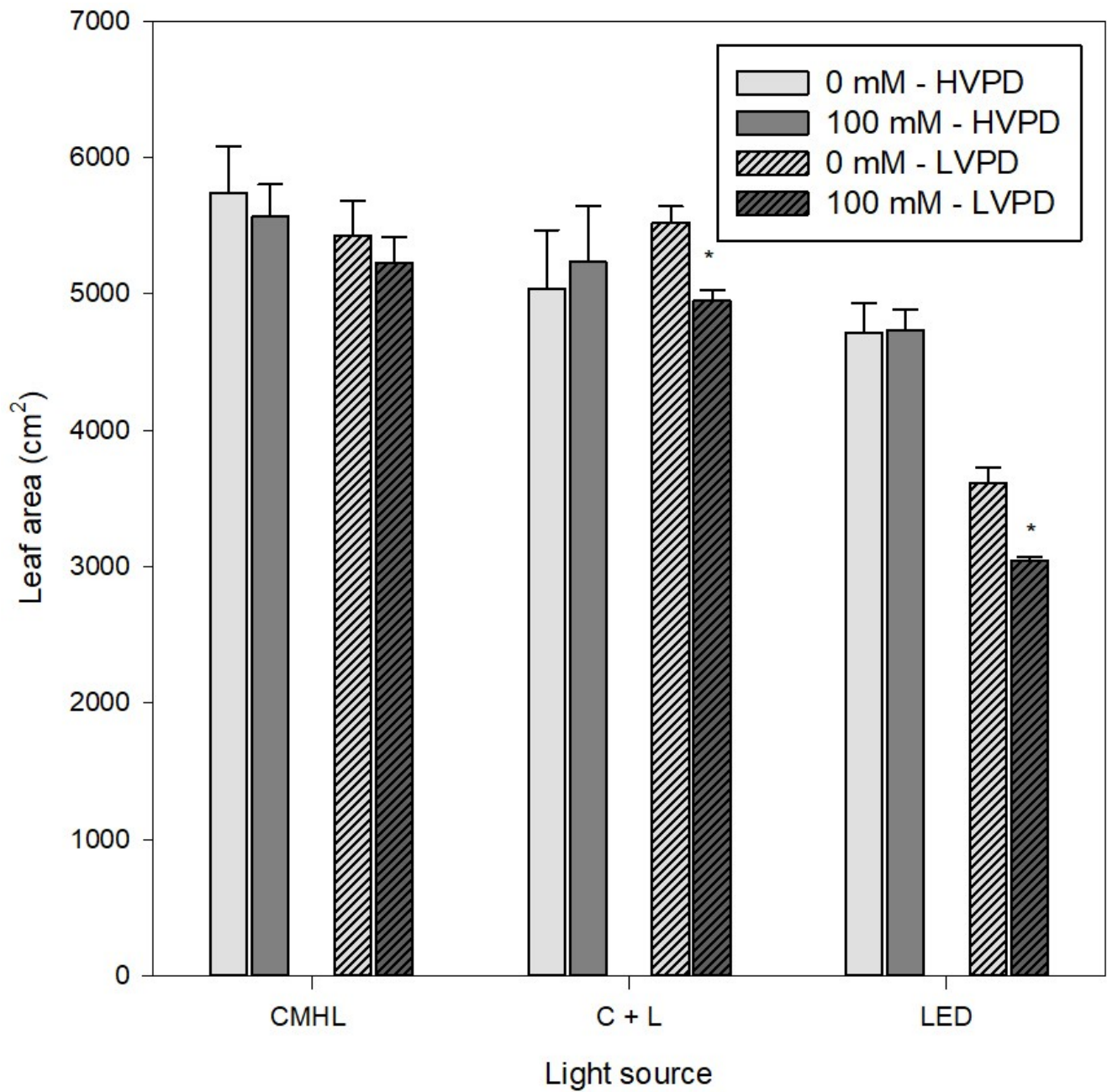


Figure 9: Average leaf area of quinoa (cv. Vikinga) grown under root zone salinity of 0 and 100 mM NaCl, two vapor pressure deficit (VPD) conditions (high and low), and three light sources (CMHL, LED, and CMHL + LED). Error bars represent standard error ( $n = 3$ ).

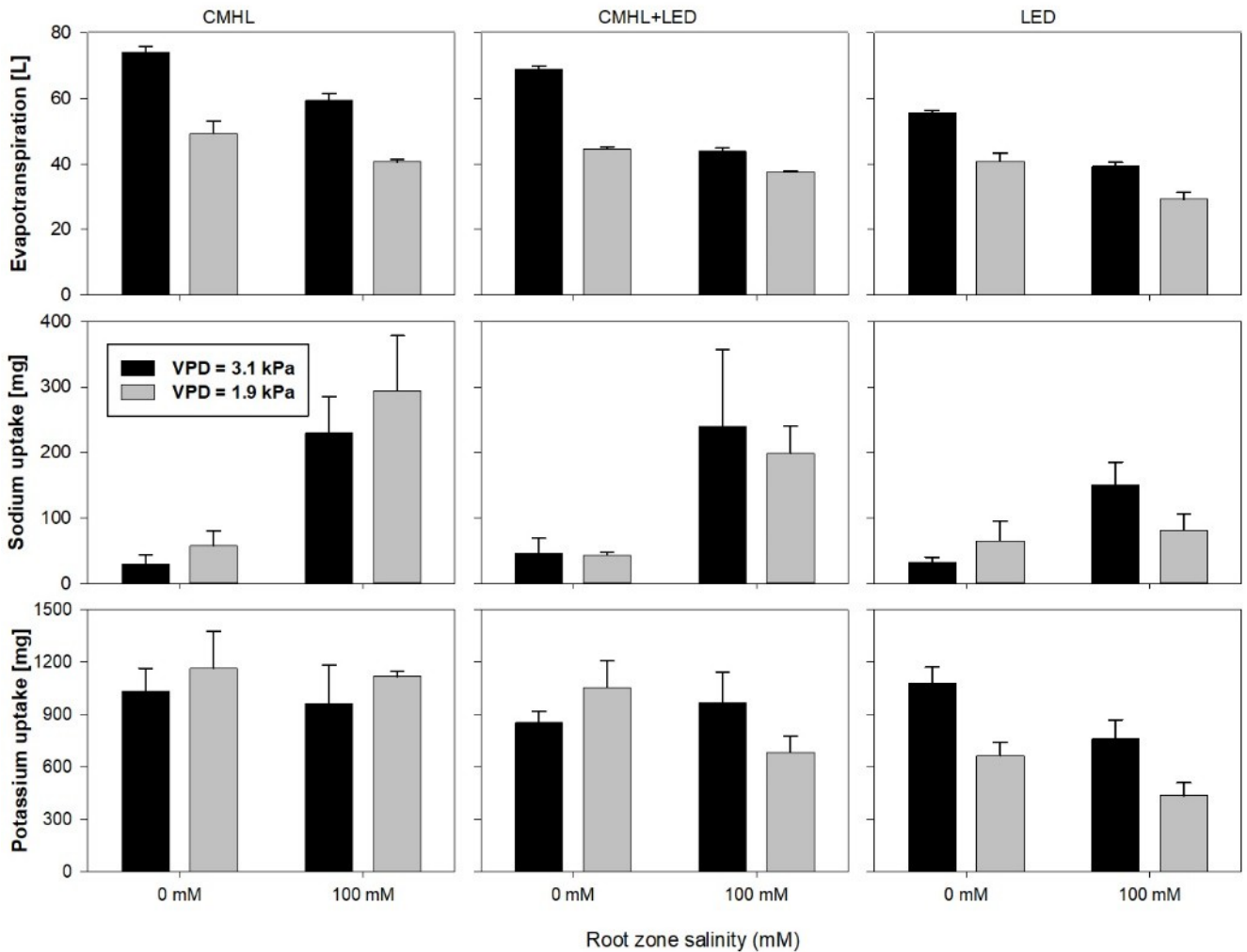


Figure 10: Cumulative water loss via evapotranspiration and total sodium ( $\text{Na}^+$ ) and potassium ( $\text{K}^+$ ) uptake into the biomass per hydroponic set-up for two vapor pressure deficit (VPD) environments ( $3.6 \text{ kPa} = \text{high VPD}$ ;  $1.3 \text{ kPa} = \text{low VPD}$ ), two root zone salinity levels (0 and 100 mM NaCl), and three light sources (CMHL, CMHL + LED, and LED).

Evapotranspiration rates were strongly influenced by both VPD and light regime (Figure 10). Across all lighting treatments, evapotranspiration was substantially higher under high VPD than under low VPD, reflecting the increased atmospheric demand and corresponding rise in transpirational flux. Plants exposed to CMHL exhibited the highest evapotranspiration, followed by CMHL + LED, whereas LED consistently produced the lowest rates. Salinity reduced evapotranspiration under both VPD conditions, reflecting restricted water uptake and likely stomatal regulation under osmotic stress. The reduction was particularly pronounced under low VPD, indicating that low atmospheric demand further limited water movement through the plant, thereby constraining transpirational cooling and nutrient transport.

Overall, the results demonstrate that the interaction between light source and atmospheric demand plays a decisive role in shaping quinoa performance under saline conditions. While optimal lighting and high VPD can partially counteract the negative effects of salinity, the combination of LED lighting, low VPD, and high salinity imposes the strongest physiological constraints. These findings underline the importance of integrated environmental control—particularly coordinated management of humidity, lighting, and salinity—for maintaining plant performance in hydroponic systems.

### 2.4.2 Nutrient dynamics in hydroponic systems (Moshe Shenker, Omer Levi)

In EXALT, hydroponics serves as the biological core of an integrated system designed to operate with saline feedwater while minimizing brine discharge. Because salinity directly affects nutrient availability, root function, transpiration, and overall plant performance, a detailed understanding of nutrient-solution dynamics was essential for assessing system feasibility and guiding engineering decisions.

The focus was on quantifying how nutrient composition evolves over time in closed hydroponic systems, particularly when irrigated with saline water representative of the Jordanian and Israeli case-study sites.

Two complementary experimental approaches were employed:

1. Controlled growth-chamber trials: Climate parameters (temperature, humidity, and day-night regime) and nutrient composition were precisely regulated. Within this setup, four nutrient solutions were tested. Two of these (Cooper and M&R) are commonly used formulations, primarily applied in research. The third solution consisted of the Cooper formulation supplemented with 20% excess chelate to simulate free chelate accumulation in the nutrient solution. The fourth solution (Is-Moag) is a formulation recommended for and widely used in commercial hydroponic farms in Israel. This experimental design enabled monitoring of individual nutrient elements over time, both in the presence and absence of plants. Measurements included pH, electrical conductivity (EC), concentrations of macro- and micronutrients, and water loss through evapotranspiration. Geochemical modelling (Geochem-PC) was applied to determine nutrient speciation. Based on these results, saturation indices of the nutrient solutions with respect to various mineral solids were calculated to assess the likelihood of precipitation reactions triggered by nutrient oversaturation. This approach provided critical insights for EXALT by:
  - Distinguishing nutrient depletion caused by plant uptake from losses due to precipitation or chemical instability,
  - Identifying how salinity and water chemistry affect micronutrient chelates (Fe, Mn, Zn, Cu),
  - Determining which nutrient recipes remain stable during extended recirculation cycles, and
  - Evaluating the risk of imbalances in closed systems operating with saline input water.
2. Observations in commercial hydroponic farms: These measurements were conducted under less controlled, more realistic conditions, validating the growth-chamber results and ensuring their applicability to typical greenhouse operations in arid regions.

Together, these studies established the plant-response baseline required for the engineering components of EXALT. By clarifying tolerance ranges, nutrient-solution stability, and nutrient dynamics in closed-loop hydroponic systems, the results provide a foundation for better integrating plant hydroponic requirements into the design of the heat-pump system, including cooling, dehumidification, and desalination processes. This integration of agronomic knowledge with technical development is central to EXALT's objective of enabling productive hydroponic cultivation in regions where saline water represents the only viable irrigation source.

### 2.4.2.1 Controlled growth-chamber trials

Nutrient concentrations fluctuated over the growth cycle in the controlled growth-chamber trials. Figure 11 illustrates these dynamics for calcium (Ca) as an example, while similar trends were observed for nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), sulfur (S), sodium (Na), boron (B), iron (Fe), zinc (Zn), manganese (Mn), copper (Cu), and molybdenum (Mo).

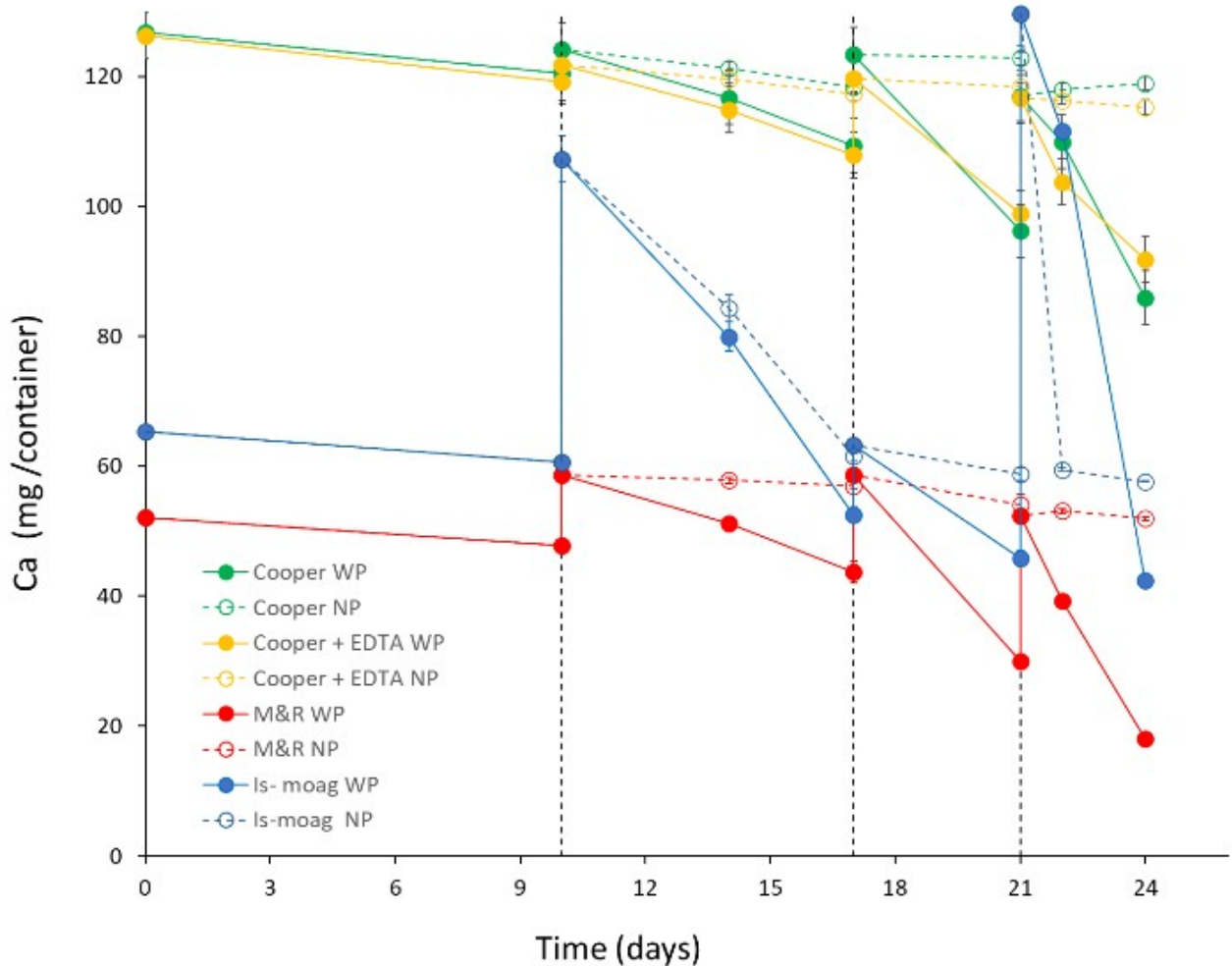


Figure 11: Calcium amount (calculated as solution volume multiplied by measured concentration) in four nutrient solutions with tomato plants (cv. M82; WP, full symbols and solid lines) or without plants (NP, empty symbols and dashed lines) over 24 days in the controlled growth chamber. Vertical lines indicate nutrient solution renewals. Error bars represent standard errors ( $n = 5$ ).

Based on the data from containers with plants, together with plant analyses conducted at the end of the growing period and the measured root and shoot biomass (not shown), the total input amount of each nutrient was partitioned into:

- the portion taken up and accumulated in the roots,
- the portion translocated and accumulated in the shoots,
- the portion remaining in the nutrient solution, and
- by difference, the portion lost through precipitation in unavailable forms.

Figure 12 illustrates this partitioning for calcium (Ca), and similar calculations were performed for all nutrients. For the commercial nutrient solution, most of the observed Ca depletion was due to precipitation rather than plant uptake. As indicated in Table 1, this precipitation most likely occurred in combination with phosphorus (P).

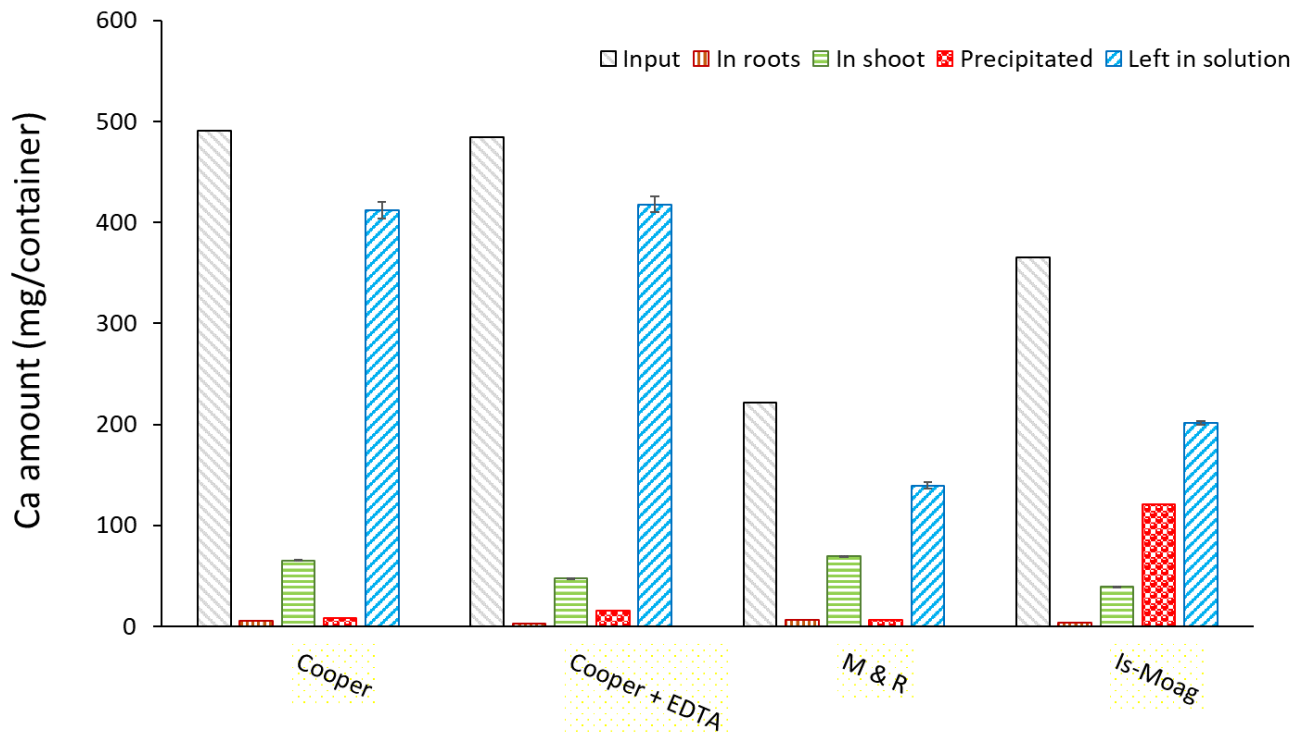


Figure 12: Calcium supplied during the 24-day tomato growth period and its partitioning among four components: accumulation in roots, accumulation in shoots, residual Ca in the nutrient solution, and Ca lost through precipitation. Error bars indicate standard errors ( $n = 5$ ); in some cases, error bars are too small to be visible.

Based on the average depletion rate of each nutrient, the amount lost per week for seven nutrients is summarised in Table 1, expressed as a percentage of the total input amount. The suspected coprecipitating components for each nutrient, as identified through geochemical modelling, are shown in the table as well.

Table 1: Nutrient depletion rates (% of original concentration) in containers with plants (WP) and without plants (NP), alongside the components suspected to coprecipitate with each nutrient to form solid, unavailable phases (calculated for the no-plant scenario).

		Cooper pH 6		Cooper + EDTA pH 6		M&R pH 6.7		Is – Moag pH 7.5	
		% deplet. / week *	Precip. with **	% deplet. / week	Precip. with	% deplet. / week	Precip. with	% deplet. / week	Precip. with
P	NP	1.2 <sup>C</sup>	Ca, H, Fe	1.8 <sup>A-B</sup>	Ca, H, Fe	3.9 <sup>B-C</sup>	Ca, H, Fe	6.6 <sup>A</sup>	Ca, H, Fe
	WP	19.0 <sup>B</sup>		30.8 <sup>B</sup>		100 <sup>A</sup>		37.9 <sup>B</sup>	
Ca	NP	0.1 <sup>B</sup>	P, H	3.3 <sup>B</sup>	P, H	9.4 <sup>A</sup>	P, H	18.6 <sup>C</sup>	P, H
	WP	19.0 <sup>B</sup>		18.3 <sup>B</sup>		55.0 <sup>A</sup>		29.4 <sup>C</sup>	
Mg	NP	0.2 <sup>A-B</sup>	Fe	0.7 <sup>A</sup>	Fe	0.8 <sup>B</sup>	Fe	1.0 <sup>A-B</sup>	Fe
	WP	15.1 <sup>B</sup>		21.7 <sup>A-B</sup>		77.0 <sup>A</sup>		23.7 <sup>B</sup>	
Fe	NP	17.0 <sup>C</sup>	P, OH, Cu, Mg	7.8 <sup>B</sup>	P, OH, Cu, Mg	3.0 <sup>A</sup>	P, OH, Cu, Mg	6.1 <sup>B</sup>	P, OH, Cu, Mg
	WP	43.8 <sup>A</sup>		14.7 <sup>A-B</sup>		10.6 <sup>A-B</sup>		7.5 <sup>B</sup>	
Cu	NP	4.2 <sup>A</sup>	Fe	5.1 <sup>A</sup>	Fe	0 <sup>A</sup>	Fe	4.3 <sup>A</sup>	Fe
	WP	76.8 <sup>A</sup>		48.3 <sup>A</sup>		37 <sup>A</sup>		9.3 <sup>A</sup>	
Mn	NP	3.2 <sup>A</sup>	P	8.2 <sup>A-B</sup>	P	10.2 <sup>B</sup>	P	7.7 <sup>A-B</sup>	P
	WP	78.4 <sup>B</sup>		61.2 <sup>B</sup>		95.3 <sup>A</sup>		59.4 <sup>B</sup>	
Zn	NP	21.3 <sup>A</sup>	Fe	17.4 <sup>A</sup>	Fe	9.6 <sup>A</sup>	Fe	4.9 <sup>A</sup>	Fe, P
	WP	83.9 <sup>B</sup>		57.4 <sup>B</sup>		89.6 <sup>B</sup>		7.5 <sup>A</sup>	

\* % depletion is calculated per 7 days. \*\* potential precipitation partners as identified by speciation modelling (saturation index,  $SI > 0.6$ ), calculated for each nutrient solution in its original composition and pH

The treatment with a 20% chelate excess relative to Fe concentration supported the hypothesis, resulting in reductions of 42%, 28%, 13%, and 12% in leaf Zn, Fe, Cu, and Mn concentrations, respectively, compared to the standard Cooper nutrient solution. These findings indicate that excess chelate can competitively bind micronutrient cations, reducing their plant availability—a risk that becomes more pronounced in long-term recirculating systems such as those relevant to EXALT.

### 2.4.2.2 Commercial hydroponic farm assessment

To evaluate nutrient dynamics under practical commercial hydroponic farm conditions—where laboratory access is limited, fertilizer-grade chemicals contain impurities, and monitoring is often infrequent—three hydroponic lettuce farms were selected based on recommendations from the Ministry of Agriculture and Rural Development (Dr. Mollie Sacks). All farms cultivated lettuce (cv. Salanova, and Lalique in one site). Two farms used Deep-Water Culture (DWC), and one used Nutrient Film Technique (NFT). Climate control in these commercial greenhouses was minimal (fans and evaporative cooling pads only).

The farms represented different climatic and water-quality contexts:

- **Bney-Atarot** (32.02°N, 34.91°E): NFT system; tap water used.
- **Ben-Shemen** (31.95°N, 34.92°E): DWC system; tap water used.
- **Yotvata** (29.89°N, 35.05°E): DWC system; extremely hot arid zone; saline water treated by reverse osmosis before use.

All farms recycled the nutrient solution. Water was added to compensate for volume losses, and fertilizers were added based on grower judgment, typically relying on coarse EC measurements. In the first two farms, nutrient solutions were periodically discarded, whereas in Yotvata the high cost of desalinated water led to continuous recycling for extended periods (years).

Composite nutrient-solution samples were taken every 3–7 days over 3–5 week growth cycles. Samples were analysed for electrical conductivity (EC), pH, and elemental composition. Plants were also sampled at harvest, washed, dried, digested, and analysed for nutrient content.

The actual nutrient-solution composition fluctuated substantially during the growth cycle and often deviated markedly from the target recipe. Selected examples are shown in Figure 13. In some cases, the deviations were extreme. For instance, in the Yotvata farm, concentrations of Mn, Mo, Zn, and Fe were on average 524-, 60-, 40-, and 3.6-fold lower than the target values. Macronutrient deviations were more moderate: N ranged from 3.3 times above to 1.8 times below the target concentration; Mg was consistently about twice the target concentration; and P was consistently 54–76% below the desired level. In Bney-Atarot, deviations were generally larger and mostly above target values, with EC levels reaching extremely high values (15–20 dS/m). In Ben-Shemen, deviations were smaller, typically 30–300% to the target concentrations. Sodium, a non-nutrient ion, ranged from 65–69 mg/L in Yotvata, around 100 mg/L in Ben-Shemen, and 400–950 mg/L in Bney-Atarot. Chloride concentrations were similar in magnitude to the Na concentration in each solution.

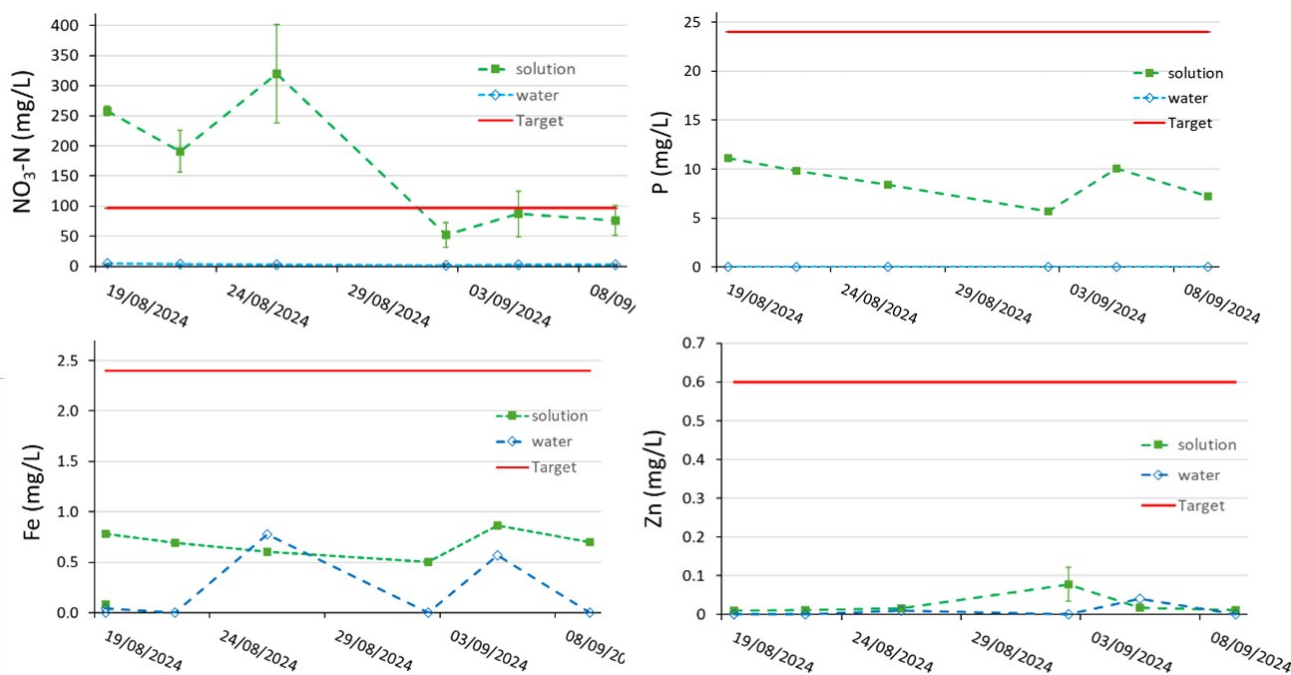


Figure 13: Concentrations of NO<sub>3</sub>-N (upper left), P (upper right), Fe (lower left), and Zn (lower right) in the nutrient solution and in the supplied water, compared to the target concentration (red horizontal line) in the Yotvata hydroponic system over an entire growing cycle. For the nutrient solution, means and standard error bars ( $n = 4$ ) are shown; where error bars are not visible, they are smaller than the symbol.

Although deviations in the plant-leaf nutrient concentrations were generally smaller than those observed in the nutrient solutions, significant deficiencies still occurred for several nutrients (e.g., Fe and K in Yotvata) and excessive concentrations were found for others (e.g., B in Yotvata). These deviations largely corresponded to the nutrient-solution status in the DWC systems but not in the NFT system. Interestingly, in the NFT system, even when solution concentrations exceeded target levels, leaf nutrient concentrations remained within optimal ranges (P, Zn, B) or were slightly below optimal (K, Ca, Mg, Cu, Fe). This likely reflects the higher oxygenation, faster turnover, and thinner boundary layers characteristic of NFT systems, which may buffer plants from some solution imbalances.

Additional effort was invested in quantifying chelate accumulation in the nutrient solutions. The working hypothesis was that plants reduce chelated Fe(III) to Fe(II) during uptake, leaving unbound chelate in the solution. Since new Fe additions are accompanied by equimolar amounts of chelate, prolonged recirculation was expected to lead to accumulation of free chelate, potentially binding Mn, Cu, and Zn and restricting their availability. This effect was anticipated to intensify with time after solution renewal. Indeed, Cu and Zn deficiencies were detected in Yotvata plants, consistent with this mechanism.

A chromatographic method for chelate quantification was developed, and preliminary analyses were performed. However, this work could not be completed because the funding ministry (MOST) declined the project extension and reduced the budget. Attempts to complete this task through alternative funding sources are ongoing, but no final results are available at present.

## 2.4.3 Climate management and water recovery (Alexander Morgenstern, Joachim Went, Wiktorija Geca)

### 2.4.3.1 Refrigeration cycle and desalination

As a first, still simplified intermediate step, a semi-open greenhouse concept was evaluated using Excel-based calculations (Figure 14). In this approach, a membrane heat exchanger was assumed to transfer a portion of the moisture from the exhaust air to the incoming outside air through thermodynamic contact (assumed efficiency up to 80%; see Figure 14). Following this exchange, the supply air was actively cooled. The analysis demonstrated that such a concept is technically feasible in principle; however, the associated water losses remain substantial and cannot be neglected. While simplified estimates based on seasonal variations in outdoor temperature and humidity provided useful initial insights, the focus was subsequently shifted toward detailed system simulations using the object-oriented simulation software Modelica<sup>1</sup>.

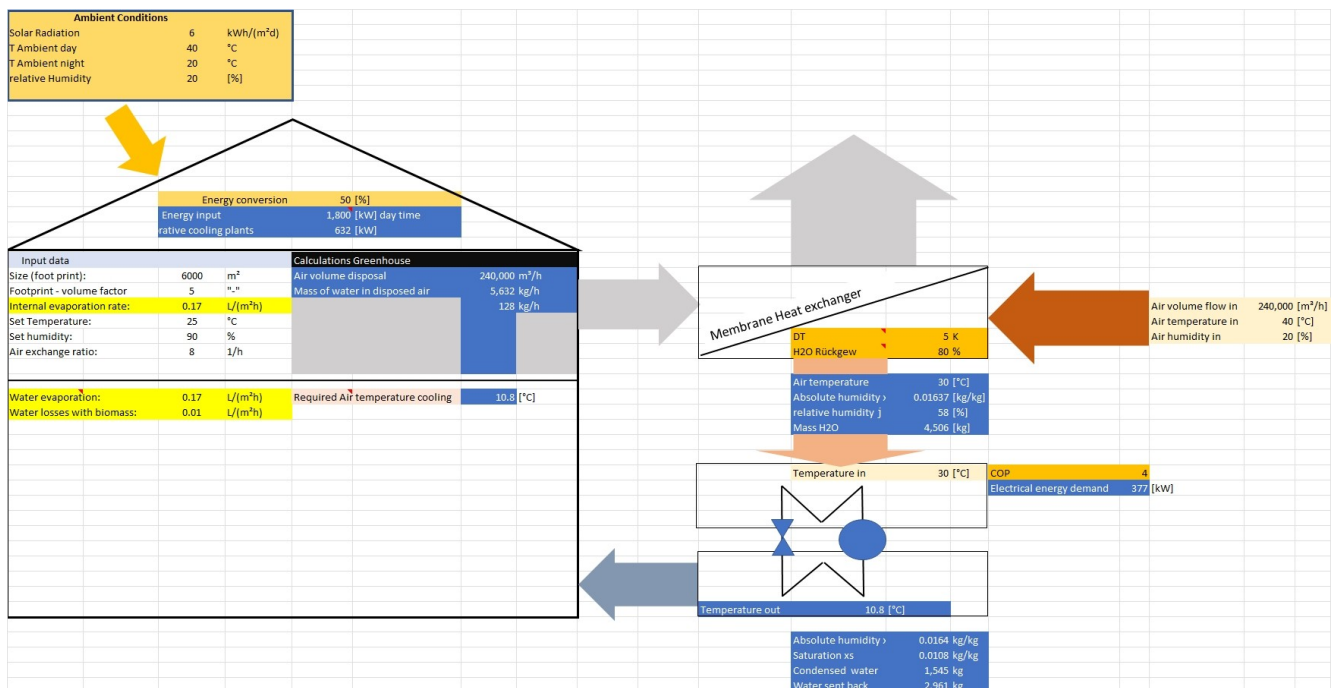


Figure 14: Conceptual design of a membrane heat exchanger for recovering moisture from greenhouse exhaust air

To gradually develop an overall concept for a hydroponic greenhouse, the basic greenhouse system was first examined to represent the individual interacting processes. The left illustration in Figure 15 serves as a conceptual representation of these interactions. In this depiction, ventilation—or air exchange with the environment—is still included. In an ideally closed hydroponic greenhouse, however, this process would be eliminated and replaced by cooling, condensation, and recirculation of the recovered condensate.

An approach for simulating such a greenhouse using Modelica is shown in the right illustration in Figure 16. The greenhouse model, formulated with the Greenhouse Library and designed to simulate a controllable microclimate greenhouse with regulated temperature and humidity, was presented by Altes-Buch et al. (2019). The original concept was developed for application in a European climate, where thermal energy is primarily supplied via a heat exchanger.

<sup>1</sup> Modelica Association (2023): Modelica® Language Specification version 3.6. <https://modelica.org/>

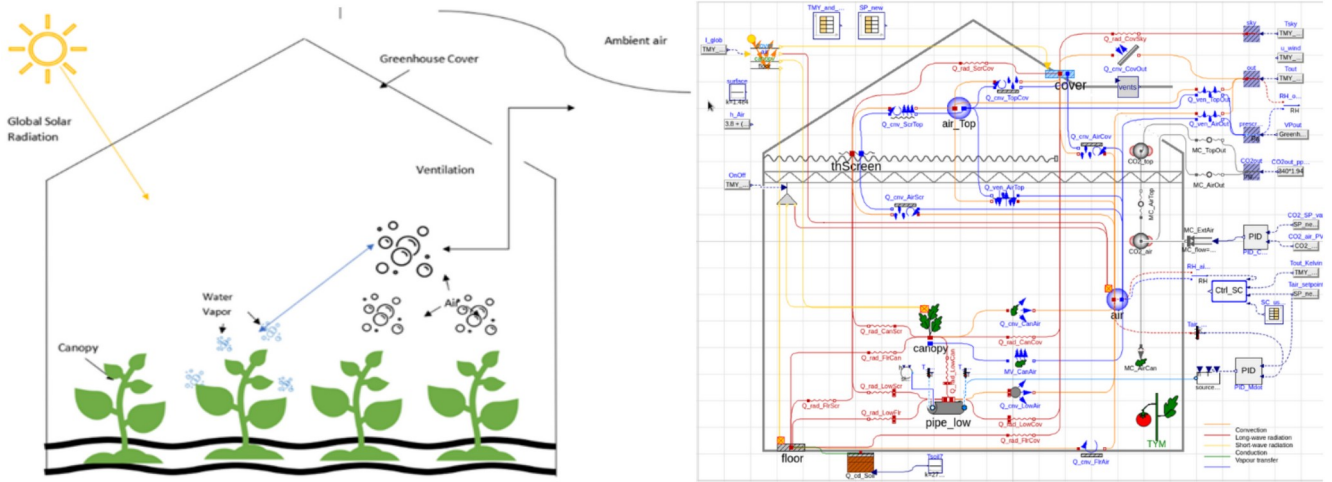


Figure 15: Basic principle of a traditional greenhouse (left) and simulation of a greenhouse with Modelica [Altes-Buch, 2019] (right)

Based on this fundamental understanding, the cooling process was modeled as a key mechanism to enable active dehumidification and water recovery within the greenhouse. By replacing ventilation-driven moisture removal with controlled cooling and condensation, the model allows recovery of water vapor from the greenhouse air and its reintegration into the irrigation cycle. This step represents a crucial transition from conventional greenhouse operation toward a closed-loop hydroponic system adapted to water-scarce, saline environments.

**System concept and system simulation**

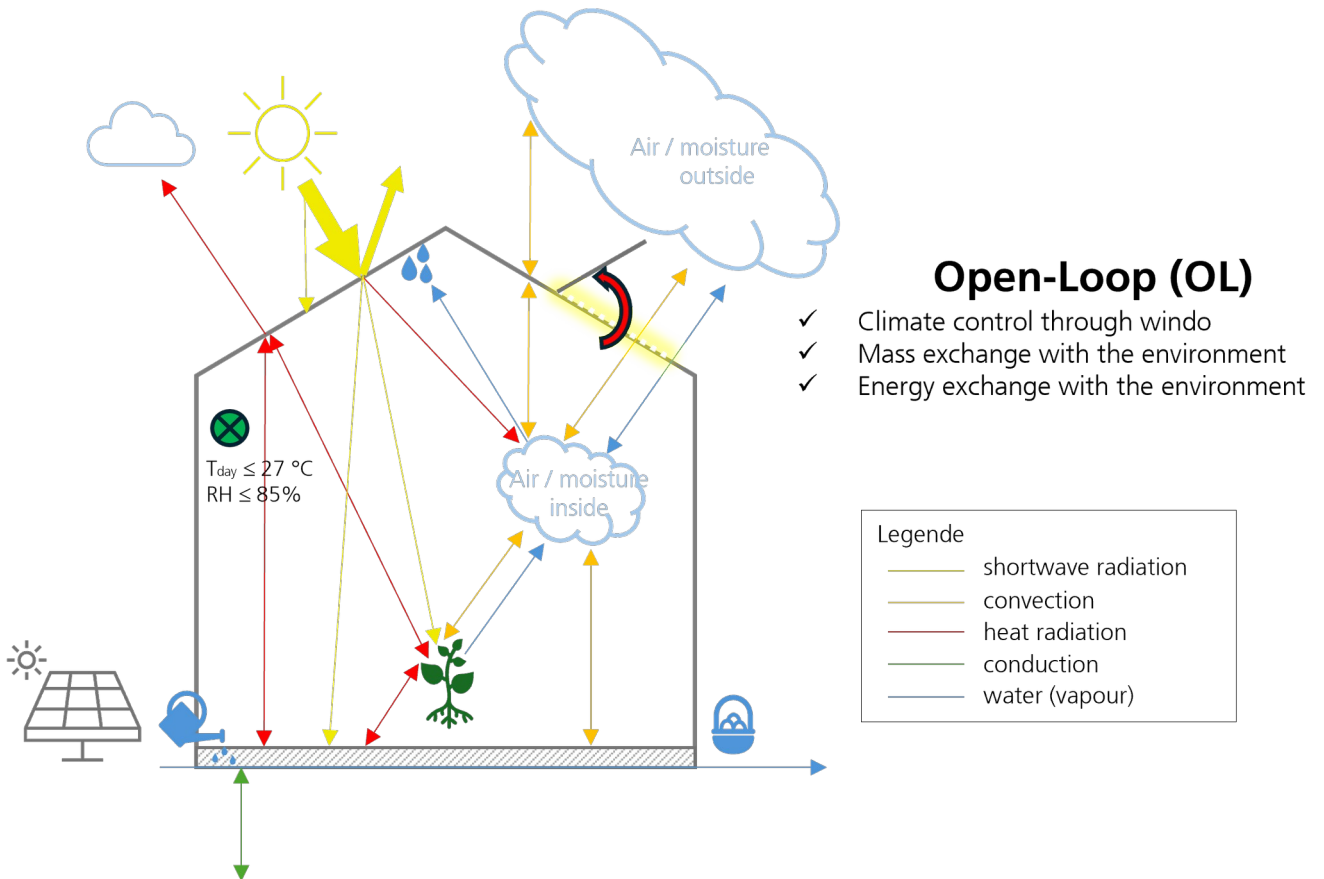


Figure 16: Simplified analysis of a ventilated greenhouse

In the initial simplification only the effects of ventilation and cooling were considered (Fig. 16). The objective was to simulate the microclimate developing within a ventilated and shaded greenhouse at a representative location in Jordan. In addition, an option for supply-air cooling was included in the model to evaluate its influence on greenhouse temperature, humidity, and overall microclimatic conditions.

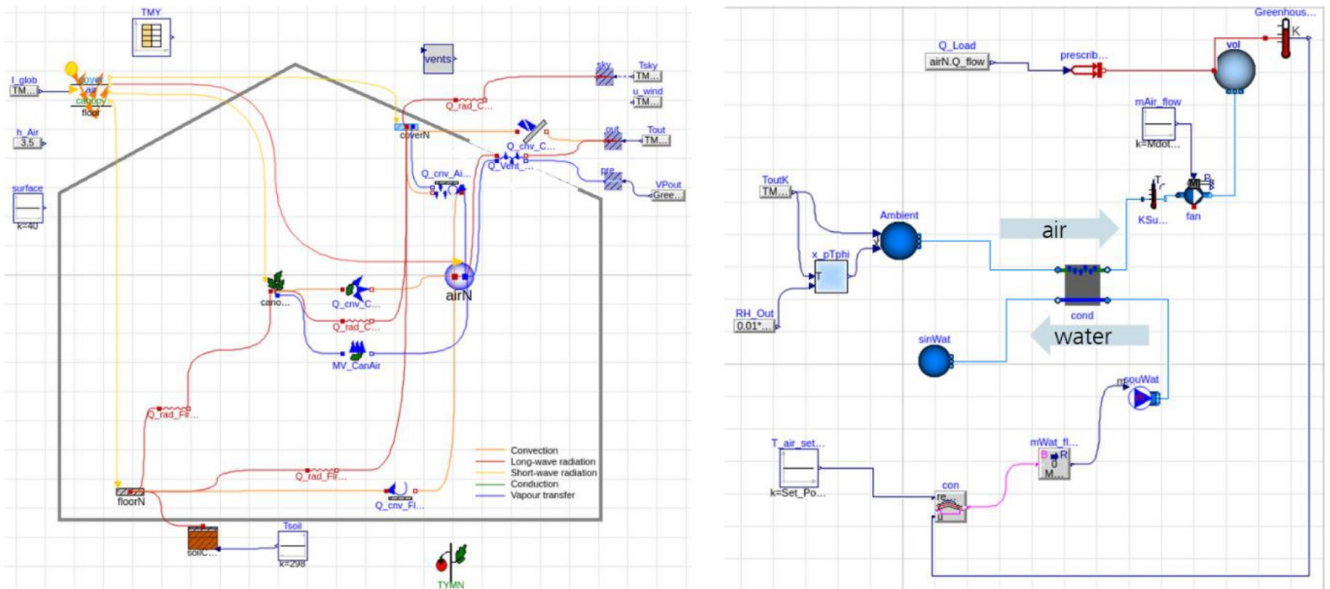


Figure 17: System representation of the simplified model with ventilation and supply-air cooling in Modelica (left) and a detailed depiction of the supply-air cooling (right)

The following figure 18 shows the temperature profiles for a representative summer day in June at the Jordan Valley location. The graphic displays the resulting temperature profile just below the roof for a greenhouse with the cooling option (yellow curve) and without cooling (red curve). The green curve illustrates the temperature profile in the plant area. From the supply air temperature profile,  $T(\text{supply air})$ , it is evident that cooling was continuously active from approximately 10:45 until about 19:00. At other times in the morning and evening, the supply air cooling was only intermittently activated, when the maximum indoor temperature of  $30^{\circ}\text{C}$  was exceeded.

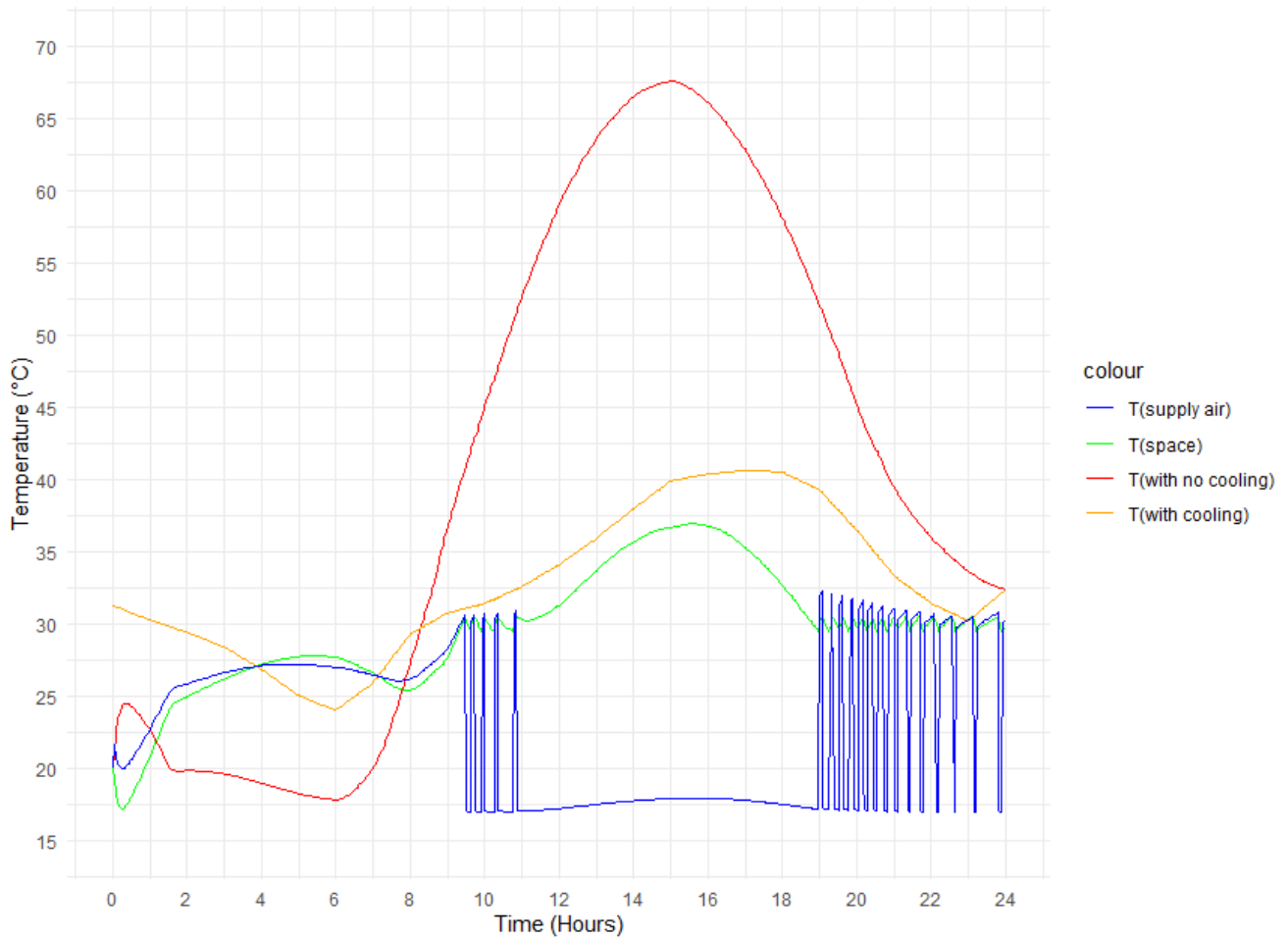


Figure 18: Example temperature profiles for a representative day in June at the Jordan Valley location. The yellow curve represents greenhouse temperatures with continuous supply-air cooling, the red curve shows temperatures without cooling, the green curve depicts temperatures in the plant area, and the blue curve indicates the supply-air temperature.

The course of the supply-air temperature indicates short periods of active cooling after 9:30 a.m., continuous cooling operation from approximately 10:50 a.m. to 7:00 p.m., followed by intermittent cycling until midnight (Fig. 18). The openings opened or closed as soon as the internal temperature rose above 30 °C or fell below 30 °C. A comparison between the red line, which shows the temperature without opening the ventilation opening, and the yellow line illustrates that this type of ventilation and evaporative cooling is effective.

**Table 2: Assumed boundary conditions for the modelled greenhouse in the Jordan Valley (Latitude 31.038322, Longitude 35.487517)**

Construction Venlo Type	Parameter	Value	Cover	Parameter	Value	Cover	Parameter	Value
Mean greenhouse cover slope	$\varphi$	25 degree	Emission coefficient	$\epsilon_{cov}$	0.84	PAR transmission coefficient	$\tau_{Cov,PAR}$	0.85
Surface of the cover including side walls	A cov	142 m <sup>2</sup>	NIR reflection coefficient	$\rho_{Cov,NIR}$	0.13	Specific heat capacity	$C_{p,Cov}$	840 J/(kg·K)
Floor surface area	A sur	40 m <sup>2</sup>	PAR reflection coefficient	$\rho_{Cov,PAR}$	0.13	Density	$\rho_{Cov}$	2600 kg/m <sup>3</sup>
Mean height of the greenhouse	h	4 m	NIR transmission coefficient	$\tau_{Cov,NIR}$	0.85	Thickness	$t_{Cov}$	0.004 m

Floor	Parameter	Value
Emission coefficient	$\epsilon_{flr}$	1
NIR reflection coefficient	$\rho_{flr,NIR}$	0.5
PAR reflection coefficient	$\rho_{flr,PAR}$	0.65
Thermal conductivity	$\lambda_{flr}$	1.7 W/(m·K)
Specific heat capacity	$C_{p,flr}$	880 J/(kg·K)
Density	$\rho_{flr}$	2300 kg/m <sup>3</sup>

Canopy	Parameter	Value
Convective heat exchange coefficient	$U_{can}$	5 W/(m·K)
Emission coefficient	$\epsilon_{can}$	1
<b>Ventilation properties</b>		
Specific roof ventilation area	$A_{roof}/A_{flr}$	0.1 m <sup>2</sup>
Ventilation discharge coefficient	$C_d$	0.75
Global wind pressure coefficient	$C_w$	0.09
Greenhouse leakage coefficient	$C_{leakage}$	0.0001
Vertical dimension of a single vent opening	$h_{vent}$	0.68 m

### 2.4.3.2 Modular concept development

The selection of tomato as the target crop was based on two main considerations. First, tomato is the most extensively researched vegetable crop in protected agriculture and one of the most important and widely grown greenhouse vegetables in the target countries, ensuring strong market potential. Second, tomatoes exhibit a broad range of responses to salinity, making them a suitable model crop for assessing system performance under saline irrigation conditions.

In parallel with the development of refrigeration cycles and desalination concepts, current production systems were assessed and the salt tolerance of various tomato varieties was investigated. These results provided a decisive basis for the final evaluation and comparison of the different system concepts.

To compare alternative system designs, multiple scenarios were developed, of which the three most promising were analyzed in detail. For potential real-world implementation in the target region, the focus was exclusively on closed greenhouse systems. Due to the local scarcity of water, concepts involving extensive air exchange with the environment were not considered further because of their inherent unsustainability. Moisture losses through ventilation—commonly used to control temperature, humidity, and CO<sub>2</sub> levels in greenhouses in most of the world's major production regions—are unacceptable under arid subtropical conditions, where limited water resources must primarily meet the current and future needs of the population.

The developed concepts, or scenarios, follow an approach that combines various technical solutions to optimize greenhouse climate control, with the aim of maximizing crop yield while minimizing water consumption. At the same time, a significant share of the energy required for these measures is intended to be generated on-site via the greenhouse envelope. For

benchmarking purposes, Scenario 1 represents a traditional greenhouse and serves as the reference state-of-the-art system.

### Scenarios Considered

1. The reference case is a greenhouse with ventilation openings (OL – open loop), which represents a conventional greenhouse design with passive climate control. In contrast to the foil-covered tunnels commonly used in Jordan, the reference case in our approach has a glass cover.
2. Glazed, energy-optimized greenhouse with active climate control (CL-15 – closed loop at 15°C): Incorporates enhanced insulation, controlled cooling, and active environmental regulation to optimize growth conditions and reduce water use.
3. Fully controlled growing environment (FCGE): A completely decoupled system that isolates the greenhouse from external radiation, humidity, and heat fluctuations, allowing precise control of all environmental parameters.

Further investigations addressed the impact of partial shading with photovoltaics integrated into the greenhouse cover, optimized climate control strategies using tailored temperature profiles, and the use of LED lighting as an alternative to conventional high-pressure sodium lamps.

The simulations were based on a greenhouse model with a floor area of 6,000 m<sup>2</sup>, reflecting a typical size for the target regions in Jordan and Israel. Simulations were conducted over a one-year period using local weather data obtained from OpenMeteo and Meteonorm.

The results indicate that both the energy-optimized greenhouse and the fully controlled growing environment (FCGE) have substantial potential for application in arid regions, where access to fresh water is limited and available irrigation sources typically contain a significant salt load. These system concepts demonstrated markedly reduced water consumption and enable sustainable crop production, such as tomatoes, even under highly restrictive environmental and hydrological conditions.

Regarding tomato yield, the simulations produced the following dry matter yields for the 6,000 m<sup>2</sup> greenhouse:

- Scenario 1: 21.8 t/a
- Scenario 2: up to 32.6 t/a
- Scenario 3: 40.5 t/a

*Table 3: Summary of the key parameters of the considered scenarios based on a 6,000 m<sup>2</sup> greenhouse. The yield data are given as fruit dry matter\*.*

Scenario	Yield in t/a	Water demand in l/h	Relation water/dry mass in m <sup>3</sup> /t	Added amount NaCl in g/h
1	21.8	1030	410	360
2	32.6	70	19	25
3	40.5	90	19	32

\*Based on fresh mass data in HortiDaily (2021) New record yield for Dutch greenhouse: 121 kg per m<sup>2</sup>. HortiDaily. <https://www.hortidaily.com/article/9379440/new-record-yield-for-dutch-greenhouse-121-kg-per-m2/> and HortiDaily (2024) Norway: No-venting in greenhouse pushes tomato yield to 160 kg per m<sup>2</sup>. HortiDaily News. <https://www.hortidaily.com/article/9682635/norway-no-venting-in-greenhouse-pushes-tomato-yield-to-160kg-per-m2/>

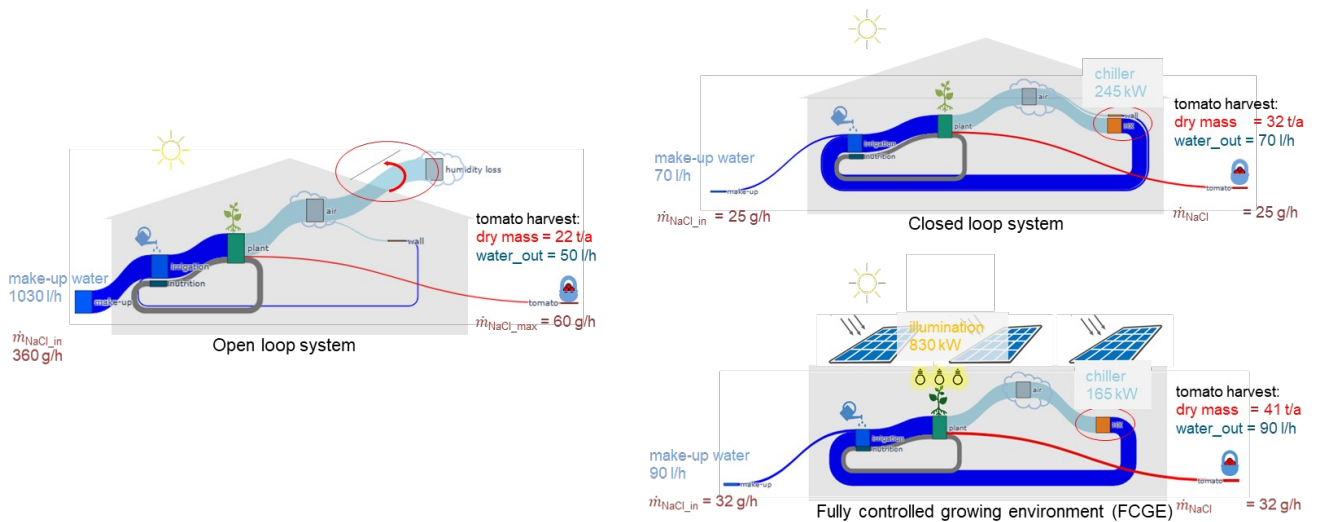


Figure 19: Visualization of material flows in Sankey diagrams of the main results for the three scenarios considered

The higher water demand in Scenario 3 results from the extended “day phase” enabled by artificial lighting, which prolongs the growth period and consequently increases yield. Despite the substantially higher investment and operational costs, greenhouse variants with technical climate control demonstrate clear economic advantages (see Figure 20). Economic analysis indicates that Scenario 2 achieves 36% higher profits in the first year due to increased productivity, while Scenario 3 attains 30% higher profits compared to Scenario 1, even accounting for the additional energy requirements of artificial lighting. However, when considering only the technical expenses in relation to water savings—over 90% reduction (619 m<sup>3</sup>/a for Scenario 2 versus 9,032 m<sup>3</sup>/a in a traditional greenhouse) at a water cost of \$0.50/m<sup>3</sup>—and the avoidance of saline concentrate discharge, the economic justification based solely on these factors appears limited, particularly at electricity prices of \$0.09/kWh. Additional benefits, such as increased supply reliability and the ability to extend the growing season year-round, have not yet been factored into this assessment.

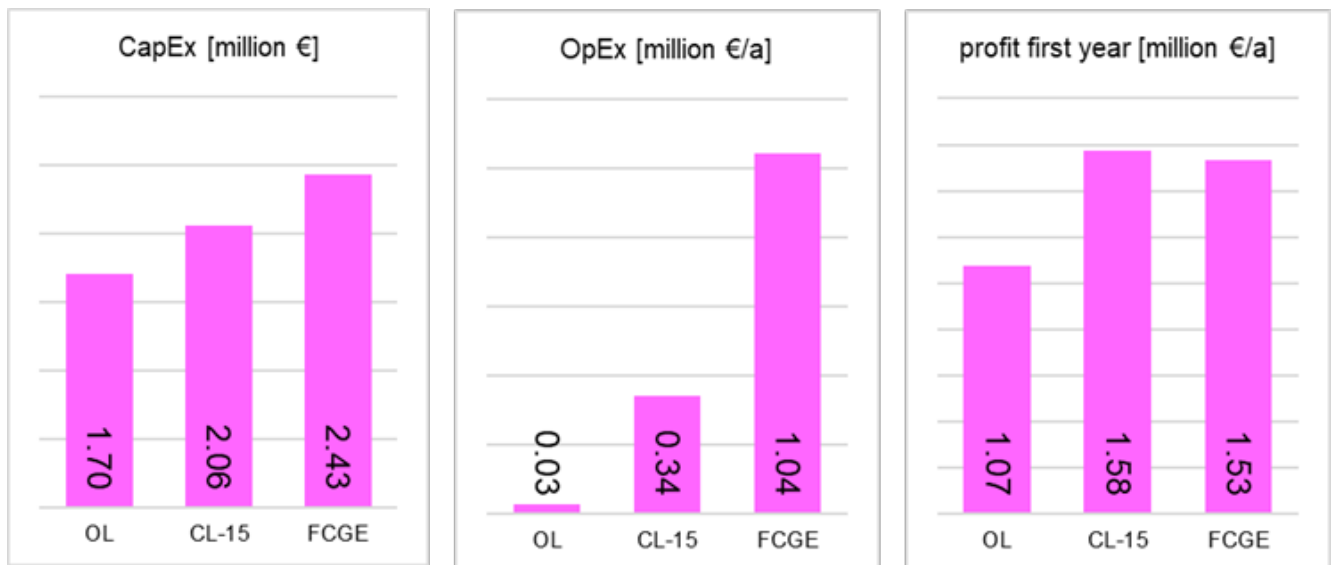


Figure 20: Overview of the economic evaluation of the three scenarios

The use of a thermal screen for insulation during the cold season and partially at night, a common practice in greenhouse cultivation, significantly improves the heat balance and helps reduce or avoid potential yield losses during these periods. Switching to LED lighting substantially lowers the electrical energy demand, while partial shading with photovoltaics (PV) on the greenhouse

cover—up to 50% of the area at the investigated locations in Jordan—does not negatively affect yield. Instead, shading reduces heat gain into the greenhouse, thereby lowering the demand for climate control, while a larger PV area can supply a greater share of the energy required for lighting and environmental regulation. Additionally, climate control and the associated condensation allow recovery of a substantial portion of water from the air, which can be reused in irrigation, forming the basis for significant reductions in externally supplied water.

Simulation studies indicate a marked advantage for a fully controlled growing environment (FCGE). Compared to the other EXALT concepts, the following improvements appear particularly promising:

- Direct coupling of photovoltaics.
- Use of PAR-transmissive, transparent solar modules.
- More efficient lighting, for example switching from sodium vapor lamps to LEDs, which can reduce operational effort by approximately 50%.
- Intelligent operating strategies.
- Utilization of waste heat from cooling systems for drying.
- Elimination of wastewater (brine) for recirculation.

The advantages of a fully controlled growing environment include:

- PV installation on the building roof can exceed energy demand (0.2 kW/m<sup>2</sup> vs. 0.1 kW/m<sup>2</sup> required).
- Year-round cultivation is possible with seasonally adjusted cooling and heating.
- Increased resilience against climate change impacts due to controlled growing conditions.

Regarding desalination, the drastically reduced intake of fresh water from the slightly brackish King Abdullah Canal water presents a favorable situation: desalination becomes unnecessary. The salt load is strongly diluted by the high volume of condensate recovered from the greenhouse, preventing negative effects on plant growth. All salts are incorporated into the plant biomass and removed at harvest, avoiding salt accumulation and eliminating the need for brine disposal.

## 2.5 Discussion and future prospects

The results indicate that both the energy-optimized greenhouse and the fully controlled growing environment (FCGE) have substantial potential for application in arid regions, where access to fresh water is limited and available irrigation sources typically contain a significant salt load. These system concepts demonstrated markedly reduced water consumption and enable sustainable crop production, such as tomatoes, even under highly restrictive environmental and hydrological conditions.

### 2.5.1 Potential of the EXALT approach to increasing water security in the Near and Middle East - across national borders

The potential to lower the water footprint of agricultural production in the target region results from the current water usage and the reduction potential by implementation of alternative production technologies. Due to the fact that there is a lack of available data on the greenhouse area in the region, the inner- and interannual dynamic of the area and because approaches published so far on the GIS assessment of the area we base our estimations on few numbers published and assumptions. The greenhouse area in the Jordan valley on the Jordan side is about 3,500 ha (Mansour et al. 2014; Shammout et al. 2018a), while we assume a total greenhouse area of 4,000 ha on both sides of the lower Jordan river.

Planning water-sustainable greenhouse agriculture in the Jordan Valley requires precise information on actual crop water use. While such information is only poorly documented in institutional datasets and region-specific agronomic studies remain limited, the available evidence is nevertheless sufficient to establish a reliable order of magnitude for greenhouse water demand. According to the Jordan Valley Authority (JVA) water quota system, vegetable cultivation is allocated approximately  $3,600 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$  (Van Den Berg et al. 2016). When expressed as a daily average, this corresponds to roughly  $1 \text{ L m}^{-2} \text{ d}^{-1}$ , assuming uniform application over the entire year. However, this simplified calculation neglects the fact that cropping periods do not extend year-round and that a substantial fraction of greenhouse area is not actively irrigated due to infrastructure and service space.

Empirical data from greenhouse tomato production in the Jordan Valley indicate a seasonal irrigation depth of approximately 300 mm per production cycle, which corresponds to average daily water applications of about  $2.3 \text{ L m}^{-2} \text{ d}^{-1}$  during the winter season and  $2.9 \text{ L m}^{-2} \text{ d}^{-1}$  during the spring season (Shammout et al. 2018b). Based on these observations, an average vegetation period of approximately 230 days and a mean daily water consumption of about  $2.5 \text{ L m}^{-2} \text{ d}^{-1}$  can be assumed for protected vegetable production in the Jordan Valley.

Robust datasets from greenhouse production systems in Almería, Spain, operating under comparable semi-arid Mediterranean climate conditions, confirm that this magnitude of water use is realistic and representative for intensive protected agriculture (Fernández et al. 2007; Gallardo et al. 2013). This range is further supported by a comprehensive review on irrigation and fertigation management in Mediterranean greenhouses, which reports similar crop water demands for tomato and other high-value vegetables (Nikolaou et al. 2021).

Based on these figures, a water-saving potential of  $2.25 \text{ L m}^{-2} \text{ d}^{-1}$  corresponding to 90% of  $2.5 \text{ L m}^{-2} \text{ d}^{-1}$  as derived for the EXALT concept, represents a reduction equivalent to nearly the entire annual irrigation allocation for protected vegetable crops in the Jordan valley. The regional water saving potential, as estimated in Table 4, can be validated by a water-use efficiency of 5 kg dry mass per  $1 \text{ m}^3$  of water taken up by the plants and a biomass water content of approximately 90% (Kläring and Krumbein 2013; Schwarz et al. 2014).

When extrapolated to an estimated 4,000 ha of protected agriculture in the Jordan Valley, this equates to approximately 19 million  $\text{m}^3$  of water saved per year. Since yields in FCGE are significantly higher than in conventional protected cultivation, the potential for water savings is substantial. In the absence of robust regional yield statistics, the yield gap can only be approximated using scientific trial data, which typically exceed regional farm averages. For

example, Al-Khateeb et al. (2024) report tomato yields of approximately 20 kg m<sup>-2</sup> under protected cultivation. If FCGE systems achieve yields several times higher than these values (as indicated in Table 3), the same production volume could be obtained from a substantially smaller cultivation area. Under this assumption, a reduction of cultivated area by up to five-sixths would be possible, corresponding to potential water savings on the order of 22 million m<sup>3</sup> (Table 4).

*Table 4: Estimation of the cultivation area and water consumption under the current cultivation in tunnel greenhouses and in fully controlled growing environments*

	Water demand L m <sup>-2</sup>	Vegetation cycle days year <sup>-1</sup>	Yield kg m <sup>-2</sup>	Area ha	Water consumption mio. m <sup>3</sup>	Production t
Current practice	2,5	230	20	4000	23	80000
FCGE	0,25	340	120	667	1	80000

This volume is highly significant in the context of regional water management. It corresponds to roughly 17% of the total annual irrigation water supplied through the King Abdullah Canal<sup>2</sup>, and represents a volume comparable to the yearly freshwater demand of several hundred thousand people. Consequently, even partial implementation of water-recovery-based greenhouse systems could substantially alleviate pressure on freshwater resources, reduce dependence on blended or treated wastewater, and improve the overall resilience of the Jordan Valley's agricultural water balance.

The results of the studies on salinity stress across different species and genotypes demonstrated that careful crop and cultivar selection can enable substantial uptake of salts from the nutrient solution. In combination with the significantly reduced make-up water demand (Fig. 19), this finding led to the abandonment of the initial objective to remove dewatered salt from the water cycle using heat pump-driven desalination. Instead, salt removal is effectively achieved through incorporation into plant biomass, which is continuously exported from the system via harvest. This biological salt removal pathway results in a considerably lower energy demand and, consequently, reduced operational costs.

Heat pump-driven salt removal remains a viable option in locations where the available irrigation water has a higher salinity level that exceeds the salt uptake capacity of plants without compromising productivity. In both approaches, the hydroponic nutrient solution can be fully recirculated without discharge. However, this requires particularly careful nutrient and ion management.

The successful implementation of FCGE systems requires several enabling conditions beyond their technical feasibility. Ideally, an FCGE should be established in locations where natural conditions—such as rocky terrain, naturally saline or degraded soils, or other constraints—make conventional crop production unfeasible. Establishing a full-scale prototype in such a location would not only demonstrate the water-saving and production potential of FCGE systems under real operating conditions, but also serve as a reference for stakeholders across the agricultural value chain. Beyond proof of concept, the prototype would function as a study and learning environment, enabling knowledge transfer, capacity building, and informed decision-making by farmers, investors, water authorities, and policymakers.

Adoption of FCGE systems also entails a social and organizational transformation. Operation requires trained and educated personnel capable of managing integrated technologies, including renewable energy generation, climate and cooling systems, irrigation and nutrient management, and high-intensity crop production. Targeted training programs, institutional support, and the development of new professional profiles within agriculture are therefore essential to ensure the systems are effectively operated and maintained.

From the outset, sustainability must be a primary objective. Chemical inputs should be minimized, resource recycling and cradle-to-cradle principles applied, and the overall environmental footprint

<sup>2</sup> Based on the King Abdullah Canal net supply of 174 mio m<sup>3</sup> (MWI 2023), of which total of 45 mio m<sup>3</sup> is pumped to Amman (Al-Mashgabah 2015).

of FCGE systems kept as low as possible. This ensures that intensive production does not come at the cost of long-term ecosystem degradation. The economic, educational, and technical efforts required to implement FCGE systems are balanced by the potential costs of inaction: declining natural water resources, increasing soil degradation, and the absence of alternative strategies to sustain settlements and agriculture in the region. In this context, FCGE systems represent a forward-looking alternative to maintain agricultural productivity, enhance water security, and build resilience in water-stressed regions.

### **2.5.2 Strengthening Regional Cooperation in Water Management and Applied Research**

A central objective of the MEWAC funding initiative is to support and promote cooperation between the participating countries in the water sector, as well as to strengthen collaboration between science and industry across national borders. EXALT was explicitly designed as a trinational project to contribute to this objective through joint system development, coordinated research activities, and shared capacity-building measures.

During the project period, however, rapidly escalating geopolitical tensions in the region significantly constrained the possibilities for direct cross-border collaboration. Planned joint field activities, in-person meetings, and trilateral workshops could not be implemented as intended, and the involvement of additional regional academic and industrial partners became increasingly difficult. These limitations were external to the project and beyond the control of the consortium.

Despite these constraints, EXALT maintained a cooperative framework through continuous dialogue, virtual exchange formats, and coordinated scientific workflows among partners in Israel, Jordan, and Germany. The project generated jointly developed concepts, shared datasets, and harmonised methodologies that reflect a common understanding of regional water and agricultural challenges. Importantly, the collaboration demonstrated that technically integrated solutions for water-efficient agriculture can be co-developed across borders, even under adverse political conditions.

Beyond maintaining scientific cooperation, EXALT made substantial contributions to the dissemination of innovative environmental technologies and to capacity development in line with the objectives of the MEWAC funding initiative. The project generated and communicated new knowledge on water-efficient greenhouse systems, closed-loop hydroponics under saline conditions, and the integration of climate control with thermal desalination. These innovations were disseminated through peer-reviewed journal publications, international conference presentations, and stakeholder-oriented exchanges, ensuring visibility within both the scientific community and applied research networks.

Capacity development constituted a core achievement of EXALT. A large number of MSc and BSc theses, as well as doctoral-level research activities, were conducted within the project framework, involving students and early-career researchers from Germany, Israel, and, where feasible, the wider region. These young scientists acquired interdisciplinary expertise spanning plant physiology, hydroponic system management, climate modelling, desalination technologies, and water-energy-food nexus thinking. Field visits, workshops, and joint research supervision—although constrained by geopolitical developments—enabled professional exchange across institutions and disciplines and fostered long-term human capital development in the water and agricultural sectors.

While direct cross-border mobility within the Middle East was severely limited, the project nonetheless contributed to regional capacity building by producing transferable knowledge, open scientific outputs, and trained experts who are now embedded in academic and applied research institutions. In this way, EXALT supported the dissemination of environmentally innovative technologies and strengthened the foundation for future science-industry cooperation when political conditions allow.

Taken together, these outcomes demonstrate that EXALT not only advanced technical solutions for water-efficient agriculture, but also strengthened the human and institutional capacities needed to sustain future regional cooperation in the water sector.

## 2.6 References

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## Section 3: PUBLICATIONS, PATENTS, INVENTIONS

### Peer reviewed journal articles

Puppala HK, Germer J, Asch F (2025) Genotypic Responses to Combined Effects of VPD and Salinity in Hydroponically Grown Tomato and Cucumber. *Plant-Environment Interactions* 6:e70064. <https://doi.org/10.1002/pei3.70064>

Puppala HK, Asch F, Germer J (submitted) Effect of Salinity and vapor pressure deficit on growth and ion partitioning in hydroponically grown tomato plants. *Scientia Horticulturae*.

Puppala HK, Asch F, Germer J (forthcoming) Interactive effects of vapor pressure deficit, salinity, and light source on growth and ion uptake in hydroponically grown quinoa under controlled root – zone temperature. *Environmental and Experimental Botany*.

### Oral presentations

Puppala, Hemanth Kumar; Asch, Folkard; Germer, Jörn (2025): Effect of VPD and Salinity on Growth and Ion partitioning in Hydroponically Grown Tomato Cultivars. Oral presentation at Tropentag 2025 conference, 10 – 12.09.2025, Bonn, Germany.

Puppala, Hemanth Kumar; Germer, Jörn; Asch, Folkard (2024): Cultivar-specific responses to salinity: Investigating growth and ion distribution dynamics in *Solanum lycopersicum* L. under variable VPD Conditions. Oral presentation at the Water Security and Climate Change conference, 9 – 11.10.2024, Gießen, Germany.

### Poster presentations

Puppala, Hemanth Kumar; Germer, Jörn; Asch, Folkard (2024): Cultivar-specific responses to salinity: Investigating growth and ion distribution dynamics in *Solanum lycopersicum* L. under variable VPD Conditions. Poster presentation at the Water Security and Climate Change conference, 9 – 11.10.2024, Gießen, Germany.

Puppala, Hemanth Kumar; Asch, Folkard; Germer, Jörn (2023): Effect of salinity on growth and ion concentration of two genotypes of *Solanum lycopersicum* L. and *Cucumis sativus* L. under contrasting VPD levels. Poster presentation at Tropentag 2023 conference, 20 – 22.09.2023, Berlin, Germany.

### MSc thesis

Gawasker Gandimalla (2026): Ion Transport Dynamics and Growth Responses of Tomato Cultivars under Salinity Stress and Variable VPD. MSc thesis, University of Hohenheim, Stuttgart.

Geca, Wiktoria (2024): Modellierung und Simulation verschiedener Szenarien zur Klimakontrolle von Gewächshäusern in Jordanien mit Modelica. MSc thesis, Technische Universität Hamburg.

Omer Levi (2025): Differential dynamics of nutrients solutions: New insights into hydroponic farming. MSc thesis, The Hebrew University of Jerusalem.

### BSc thesis

Bernhard, Ann Sophie (2023): Effekte der Lichtqualität auf die Wachstumsphysiologie von zwei Tomatensorten. BSc thesis, Universität Hohenheim, Stuttgart.

Ahlenstorf, Gabriel Christopher (2023): Einfluss von Luftfeuchtigkeit und Salzstress auf die Nährstoffaufnahme von hydroponisch wachsender Quinoa. BSc thesis, Universität Hohenheim, Stuttgart.

*Gandimalla, Gawasker (forthcoming): Ion Transport Dynamics and Growth Responses of Tomato Cultivars under Salinity Stress and Variable VPD. MSc thesis, University of Hohenheim, Stuttgart.*

*Münst, Marc (2023): Einfluss von Lichtqualität und Infrarotstrahlung auf die Nährstoffaufnahme von hydroponisch wachsenden Tomaten. BSc thesis, Universität Hohenheim, Stuttgart.*

*Rauchenberger, Steffen (2024): Auswirkungen unterschiedlicher Lichtquellen auf die Temperaturumwelt, das Wachstum und die Evapotranspiration hydroponisch wachsender Quinoa. BSc thesis, Universität Hohenheim, Stuttgart.*

*Schmidt, Alexandra (2024): Influence of air humidity and salt stress on growth and nutrient uptake of hydroponically grown quinoa and eggplant. BSc thesis, Universität Hohenheim, Stuttgart.*