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Mitigating Water Salinity in the Jordan Valley: Experimental Evidence for the Effectiveness of Electronic Water Treatment on Irrigation Water Quality and Crop Productivity

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ABSTRACT

Water salinity is a major challenge for Jordanian farmers in the Jordan Valley negatively impacting crop yield and soil health. One potential solution to this issue is electronic water treatment (EWT): a novel technology that uses radio wave transmissions to alter the electric charge of dissolved ions and prevent the build-up of salt compounds. This reduce water salinity enabling the use of saline water for irrigation without the adverse effects of salt toxicity in plants. To test the effectiveness of this technology, we evaluated the Max Grow electronic treatment device in an experimental trial cultivating cucumbers (*Cucumis sativus* L.) at a research farm located in the north Jordan Valley. Our goal was to determine whether plants irrigated with electronically-treated saline water (high-salinity treated waste water [HSTWW]) can exhibit similar growth to plants treated with low-salinity groundwater (LSGW), which is only attainable through desalination methods or by purchasing expensive water from private suppliers. Two sets of cucumber plants were grown: one group was irrigated with saline water (1000–1200 ppm) treated by the Max Grow device, and the other group was irrigated with high quality LSGW purchased from an outside source with low salinity (300 ppm). Plant length, stem thickness, and yield were monitored over 8 weeks for both groups. Statistical analysis showed significant improvements in plant length and yield in the Max Grow–treated group with no notable difference in stem thickness. These findings suggest that the Max Grow system can provide irrigation quality comparable to costly desalination methods at a lower cost, thereby offering a scalable and energy-efficient solution for saline-prone agricultural regions. Adoption of this technology could enhance agricultural resilience, reduce energy consumption, and support sustainable water management in arid environments.

1 | Introduction

Water salinity is among the most significant threats to global agricultural productivity, impacting soil structure, crop yields, and water availability. The Food and Agriculture Organization (FAO) estimates that over 20% of irrigated land worldwide is affected by salinity leading to substantial economic losses and reduced food security [1]. Jordan, in particular, is experiencing a challenging water salinity crisis within one of the country's

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primary agricultural centers: the Jordan Valley. This fertile region sits in the northwest corner of the country. It serves as a principal source of economic livelihood for Jordan's rural population and a core supplier of food to a country that imports the majority of its foodstuffs. However, the country's extremely arid climate along with acute water scarcity have increased the salinity of irrigation water within the Jordan Valley. Increased water salinity threatens the productivity of the entire valley and, by extension, the long-term sustainability of the country's agricultural sector.

Intense water scarcity, population growth, overextraction of freshwater resources, and climate change have all placed severe pressure on existing surface and groundwater sources. Groundwater pressure is particularly severe in Jordan: 10 of 12 main aquifers are depleted beyond recharge, average groundwater levels decline = 2 m $year^{-1}$ (hotspots 5–20 m), and over-abstraction is = 200 MCM $year^{-1}$ relative to safe yield [2]. Independent recent assessments likewise document chronic overabstraction and long-term groundwater level declines across major basins [3]. Consequently, Jordan's government and farmers have begun to rely on alternative sources of water to augment limited irrigation supplies–primarily reused treated wastewater (TWW) and brackish groundwater. However, TWW is highly saline, and long-term usage of this resource has led to increasing water salinity in the Jordan Valley. As groundwater is depleted, the concentration of dissolved salts increases, thereby raising the salinity of extracted groundwater for irrigation purposes. The resulting water salinization is a serious strategic obstacle for Jordan's agricultural sector, and many existing solutions remain infeasible due to intense climate and socioeconomic factors in the Jordan Valley. Desalination is the most common method for addressing water salinity, but high capital and energy costs render it inaccessible to the small farmers who make up a majority of operations in the Jordan Valley. In our deployment, the in-line electronic water treatment (EWT) hardware cost was = €2500 and required no membranes, chemicals, or high-pressure pumps; routine power draw is low, so ongoing operating costs are minimal. By contrast, brackish-water RO (BWRO) commonly reports operating costs of approximately US$0.39–0.66 per m^3 at municipal scales (costs rise at small scale due to loss of economies) and specific energy consumptions of approximately 0.6–3.5 kW h m^{-3} depending on feed salinity, recovery, and design [4–6]. Electrodialysis (ED) for low-to-moderate salinity brackish feeds typically falls in the approximately 0.2–1.8 kW h m^{-3} range and has shown 30%–75% lower energy than RO at electrical conductivity (EC) = 1.6–4.7 mS cm^{-1}; small-plant CAPEX at approximately 1 m^3 h^{-1} has been estimated at approximately US$3200 (ED) vs. approximately US$6400 (RO) [7, 8]. For our greenhouse flow (= 2.5–3.0 m^3 h^{-1}), these ranges make EWT substantially less expensive to purchase and operate when the goal is conditioning rather than salt removal. EWT including magnetic and electromagnetic field conditioning, has gained renewed attention as a low-energy, in-line method to mitigate mineral scaling/fouling and condition saline feeds. Unlike desalination (RO/ED), EWT does not remove salts; rather, field exposure alters precipitation/crystallization behavior and near-surface electrochemistry, which can reduce scale formation and improve system usability at negligible power draw relative to RO/ED when the goal is conditioning, not salt removal [9]. Recent reviews and experiments report inhibited $CaCO_3$ precipitation and reduced membrane fouling under applied electromagnetic fields in water-treatment contexts, including RO treating challenging effluents [9–11]. In agriculture and protected horticulture, several recent studies indicate that field-treated brackish water can reduce salinity-stress indicators and improve growth/yield under certain conditions, though results remain system-specific and require routine salinity monitoring [12–16]. Overall, EWT is an emerging and low-capital option for farmers where the objective is to moderately condition saline sources and mitigate scaling in fertigation hardware; it should be positioned as complementary to, not a replacement for, desalination when true salt removal is required.

The importance of the Jordan Valley and the challenges it is facing necessitates further study into alternative solutions to water salinization. This paper's objective is to test EWT effectiveness treating saline irrigation water for agriculture in the Jordan Valley within a soilless agriculture system. Our study makes several contributions to the ongoing debate around water salinity within Jordan. To the best of our knowledge, this will be the first study to field test an EWT device on saline irrigation water in the Jordan Valley. This study contributes to the scientific understanding of irrigation management by evaluating EWT's effectiveness in reducing salt accumulation in irrigation water for soilless agriculture. Our experiment is also designed to be reproducible among small farmers in Jordan for greater transparency that allows farmers to test this technology for themselves as a precursor to adopting this technology. In this manner, our results will have a greater applicability in other contexts for further testing and verification.

2 | Materials and Methods

2.1 | Study Area and Water Salinization

The Jordan Valley is an agricultural center for the country and it relies on three primary water sources: the King Abdullah Canal (KAC), TWW, and brackish groundwater. The KAC is the main surface water conveyance system. It runs north-to-south along the length of the entire Jordan Valley transporting freshwater from Lake Tiberias and the Yarmouk River. The KAC is supplemented by TWW originating from the As-Samra Wastewater Treatment Plant, which discharges to the Zarqa River; flows are then stored in King Talal Dam (KTD) and conveyed to the KAC for irrigation in the Jordan Valley [17]. TWW is, therefore, a vital component of the Jordan Valley irrigation supply and, consistent with typical TWW chemistry, often shows elevated Na^+ and Cl^-, which can increase soil salinity if not actively managed (Table 1) [17]. In parallel, groundwater aquifers supply most of Jordan's freshwater; brackish groundwater is also an important irrigation source, particularly in the southern Jordan Valley, and is characterized by higher salinity and mineral content [21].

Water salinization is a primary driver of soil salinization in arid agroecosystems, lowering crop productivity, degrading soil structure, and threatening long-term sustainability [22]. In the Jordan Valley context, these processes translate into osmotic stress, ion toxicity (notably Na^+/Cl^-), nutrient imbalance, and poorer soil physical condition—factors that depress yields. As a strategic response for high-value crops, soilless/protected horticulture decouples roots from saline field soils and enables precise fertigation and salinity control [23]. Consequently, developing effective

TABLE 1 | Salinity characteristics of Jordan Valley irrigation sources (KAC blended water, treated wastewater, and brackish groundwater)—EC ranges, salinity concentration, and dominant ions [18–20].

Water source	Electrical conductivity (EC) range (dS/m)	Salinity concentration (ppm)	Primary salt contaminants
King Abdullah Canal: blended water	1.2–2.5	768–1600	Sodium, chloride, nitrate, sulfate, calcium, magnesium
Treated wastewater	2.5–4.5	1600–2880	Sodium, chloride, nitrates
Brackish groundwater	3–10	1920–6400	Sodium, calcium, sulfates

and affordable salinity-mitigation options remains essential for the Valley's agricultural sustainability.

2.2 | A Lack of Options for Mitigating Water Salinization

Desalination remains a primary method for treating saline water. Although Jordan's government and researchers have characterized desalination as one of the most important nonconventional sources of water for relieving Jordan's water scarcity, its implementation has remained limited [24, 25]. Several factors limit desalination as a reliable salinity-mitigation option in the Jordan Valley, including geography, energy and capital costs, scale and farm structure, pretreatment and O&M requirements, and inland brine-management constraints. The primary reason is geography: with the exception of a small coastline in Aqaba, Jordan, is an entirely landlocked country, making large scale seawater desalination impractical for rural contexts in the far north of the country [26]. The relatively low contribution of the agricultural sector to the country's GDP (6.9% in 2024) has no doubt made investment into rural desalination infrastructure too costly to justify, and desalination of brackish (TDS = 1000–10,000 mg/L; often ~1–10 dS/m EC in irrigation practice) and saline water remains limited [27–29]. Small scale desalination has been in use in Jordan for many years, but it has not been capable of providing a significant source of freshwater because decentralized desalination units for brackish water—either from groundwater wells or from the KAC—are expensive and beyond the capital investment capabilities of most Jordanian farmers. Some farmers have been able to implement desalination for their farming operations: approximately 52 desalination plants were in operation in 2015 by farmers with an additional 44 public desalination stations for drinking water [26, 27]. The value of cash crops, such as bananas, dates, and strawberries, has been shown to create favorable economic conditions to implement expensive RO desalination, but these conditions are not representative of the entire Jordan Valley and are limited to a small subset of farms with the capital to invest in this technology [30]. This is evinced by the high proportion of desalination plants owned by large private farms: around 35 of the 52 desalination plants are privately-owned systems that supply larger scale farming operations, such as banana plantations, with the financial capital to operate expensive desalination systems [26, 29, 31]. Some initiatives have been made to investigate and improve off-grid desalination or to design modular systems powered by renewable energy, but implementation remains limited [32, 33]. Even though Jordan has an abundance of renewable energy resources, solar- and wind-powered desalination remain theoretical prototypes with no large-scale adoption largely due to financial constraints [34–39].

2.3 | EWT and Magnetic Water Treatment (MWT)

While RO desalination remains costly for most Jordan Valley farms, EWT/MWT offers a low-energy, in-line conditioning approach. In saline contexts, field exposure has been reported to enhance salt leaching from the root zone, improve soil water retention and structure, and—under some conditions—improve germination, nutrient status, growth, and yield. These effects are system-specific (device, field strength, flow, crop, and salinity), but have been demonstrated in recent greenhouse and field studies [40–42]. EWT/MWT does not remove dissolved salts; rather, it conditions the water and precipitation behavior, indirectly reducing salt stress and scaling in fertigation systems. Several studies have published experimental evidence showing that electromagnetic signals significantly reduced the negative effects of salinity on crop yield and germination and even improved crop growth in arid climates similar to the Jordan Valley such as Tunisia and Palestine [13–15]. Field trials in Greece and Malta using the same EWT unit (Max Grow) reported improved plant growth and mitigation of soil- and water-salinity effects [43–46]. Other studies have shown mixed outcomes for electromagnetic treatment of saline irrigation water, underscoring system-specific responses and the need for careful monitoring and replication [47–49]. Our results extend this evidence base in a Mediterranean setting and provide a Jordan case study indicating that an in-line EWT device can be an effective, viable option for addressing salinization.

2.4 | Experimental Design

Our experiment compared two irrigation-water sources: low-salinity groundwater (LSGW; = 100 mg/L TDS) purchased from a supplier, and a high-salinity TWW from the KAC–KTD system (= 1200 mg/L TDS), hereafter referred to as high-salinity TWW. The high-salinity TWW was passed through an EWT unit (Max Grow) immediately before distribution to the designated laterals (treatment), whereas the LSGW was delivered without EWT to the remaining laterals (control).

This design tests whether applying EWT to a typical Jordan Valley irrigation source with elevated salinity can match plant performance achieved with LSGW, and, by extension, whether a low-cost EWT unit offers a practical alternative to purchasing low-salinity water or using energy-intensive desalination. All other management factors (crop variety, fertigation program, and greenhouse operations) were held constant across treatments.



FIGURE 1 | Greenhouse setup with coco-peat grow bags and 12 irrigation laterals. The central four laterals received saline water after electronic water treatment (EWT); the remaining laterals operated without EWT.

2.5 | Experimental Setup

The experiment was conducted during September–November, 2024 on greenhouse cucumber, a staple in Jordanian and wider Mediterranean diets and a crop that is highly sensitive to salinity. The trial was carried out by MIRRA (a Jordanian NGO focused on sustainable irrigation technologies) at its research farm in the north Jordan Valley. All plants were grown in a soilless coco-peat system (slabs), a medium with high porosity and water-holding capacity, but with cation-exchange properties and inherent salts that can influence crop responses to saline irrigation (Figure 1). When the EC of irrigation water exceeds approximately 2–2.5 dS m^{-1}, Na^+ and Cl^- tend to accumulate in the root zone, causing osmotic stress and ion toxicity that reduce growth, water uptake, and yield [50, 51]. Without adequate leaching, frequent EC monitoring, or recirculation, salts may build up to phytotoxic levels overtime [52].

To test whether an EWT device can mitigate salinity effects from locally available water sources, the greenhouse was divided into three sections controlled by manifold valves V1–V3. V1 and V3 (outer sections; control) supplied LSGW (EC = 0.15 dS/m) without EWT. V2 (central section; treatment) supplied high-salinity treated waste water (HSTWW; EC = 1.5–2.0 dS m^{-1}) after passage through the EWT unit. Each section contained four irrigation laterals (total laterals = 12). Each lateral irrigated 34 grow bags, each bag holding five cucumber plants (Figure 2). All sections used the same cultivar, fertigation program, irrigation schedule, and greenhouse operations, ensuring that the only experimental factor differing between sections was the water source/treatment (LSGW vs. EWT-treated HSTWW).

EWT was applied using a Max Grow device (Figure 3). The unit applies radio frequency (RF) signals spanning approximately 1 kHz to 3 MHz to the flowing water and is designed to alter ion aggregation and nucleation behavior, thereby reducing formation of scale-forming precipitates (e.g., calcium carbonate and sodium chloride). The device was installed in-line on the HSTWW submain upstream of valve V2, supplying EWT–treated HSTWW to the four central laterals (treatment); the LSGW line supplying valves V1 and V3 bypassed the device (control). The unit has no moving parts, filters, or routine calibration,

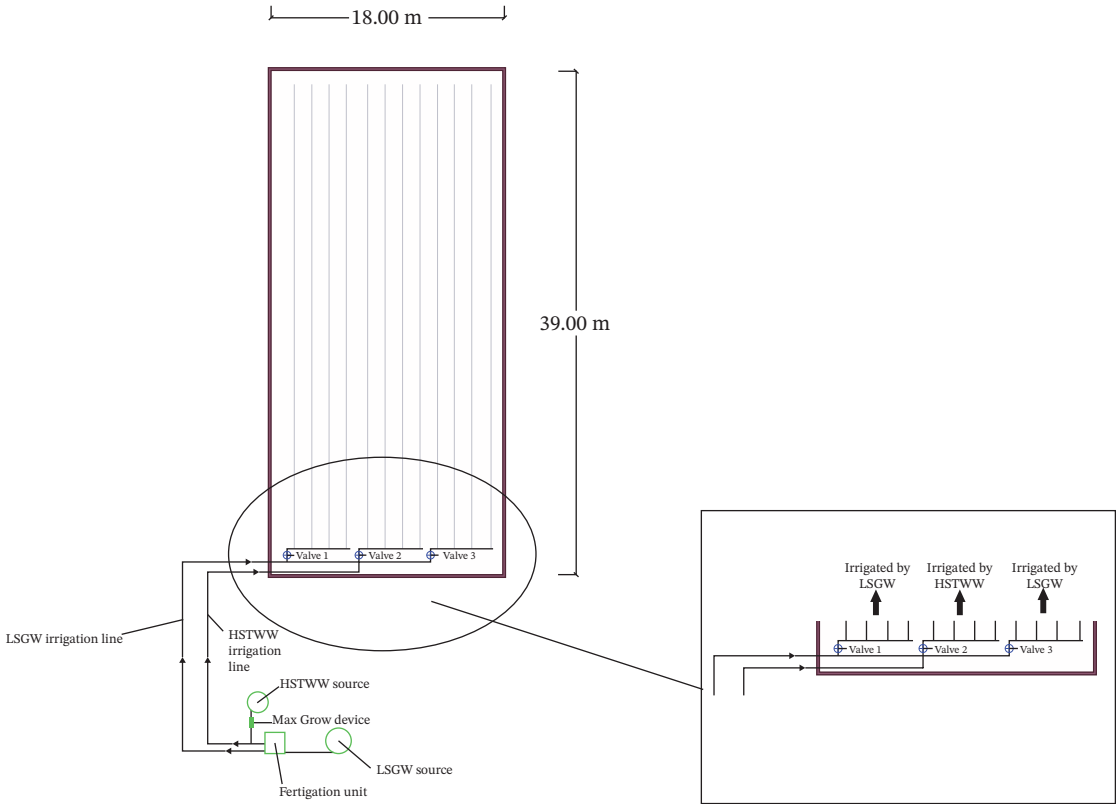


FIGURE 2 | Experimental irrigation layout and flow paths in MIRRA's greenhouse (18 m × 39 m). HSTWW path: HSTWW is routed through the Max Grow EWT and the fertigation unit to the HSTWW irrigation line, supplying V2 and the four central laterals (treatment). LSGW path: LSGW bypasses the EWT and supplies V1 and V3, irrigating the remaining laterals (control). The manifold shows V1–V3; arrows denote flow direction. Inset: lateral assignment—V1 = LSGW, V2 = HSTWW, V3 = LSGW. Total laterals = 12.



FIGURE 3 | In-line electronic water treatment (EWT) unit (Max Grow) mounted on the irrigation main upstream of the greenhouse distribution manifold.

facilitating integration into existing irrigation networks without plumbing redesign. It was powered from a 220 V AC supply and operated at a flow of 2.5–3.0 $m^3\,h^{-1}$ through = 1-inch (= 25 mm) plastic piping. Although copper pipe is recommended for optimal energy coupling, this setup used plastic piping and the unit operated as intended. Treatment is applied during a single pass (continuous, in-line) as water traverses the RF field.

2.5.1 | Licensing and Permissions

The Max Grow EWT device (manufacturer: MG Salinity Solution Ltd, Larnaca, Cyprus) was used under standard research use; no additional license or permission was required. The device was purchased and operated strictly according to the manufacturer's instructions. The authors have no financial or personal relationship with the manufacturer, and no proprietary firmware or algorithms were accessed or modified.

2.6 | Data Collection

Our evaluation of the EWT device proceeded in two parts: first, we took water samples before and after the electronic treatment and recorded the EC and pH in order to evaluate the devices' technical performance in the field. To quantify the impact of the EWT device on crop growth, we took a simple random sample of cucumber plants from all 12 lateral lines. The length (cm), stem thickness (cm), and yield (kg) from each of these plants were recorded each week for a total of 8 weeks.

This trial focused on growth responses and water-quality changes (EC, pH). We did not assay differential salt accumulation in the edible product (e.g., Na^+/Cl^- in cucumber tissue) or in root-zone leachate; therefore, the study cannot quantify treatment differences in salt residues in fruit. Because salinity effects frequently accumulate across seasons—and short-cycle cucumbers in fresh coco-peat may not reveal between-treatment differences—detecting any divergence in salt loads typically requires multi-season monitoring of leachate EC/ions and substrate/soil EC under identical fertigation and leaching fractions [53–58]. This scope limitation is recorded, and procedures for tissue and leachate assays are outlined in the Discussion for future replications.

2.7 | Statistical Methodology

To accurately measure the effect of EWT on crop growth, we applied a linear mixed model with random effects to account for subject repeated measures each week, as well as fixed effects to account for time changes throughout the cucumber's growth cycle. We fitted three separate linear mixed models for each of the three separate growth indicators. The model for each of the growth indicators is defined as:

$$y_{it} = \beta_0 + \beta_1 m_i + p_i + t'\delta + \varepsilon_{it}, \quad (1)$$

where y_{it} is the response (plant length, stem thickness, or yield), m_i is an indicator variable with value 1 if the subject i received treated water with the Max Grow device, and 0 otherwise. The term $t'\delta$ represent time fixed effects for each week of measurements and ε_{it} is experimental error. To test the significance of the treatment effect on each growth indicator, we fit a null model that includes all terms as the equation above except the treatment factor variable. We ran an ANOVA test between these two models and tabulated the results.

3 | Results and Discussion

3.1 | Empirical Results

The salinity levels within water samples measured before and after receiving EWT reduced by between 6.0% to 24.0% (Table 2). These results demonstrate the effectiveness of using electronic signals to decluster salt compounds and prevent ions from accumulating into larger and insoluble precipitates. The water samples' pH, on the other hand, did not drop significantly compared to pretreatment samples. However, even a small reduction in pH is likely due to changes in the ionic equilibrium of the water which is evidence of the EWT device disrupting the bonding

TABLE 2 | Irrigation water quality before and after electronic water treatment (EWT) across sampling dates in a Jordan Valley greenhouse (September–November, 2024).

	Before Max Grow			After Max Grow			Purchased water		
Sample	**pH**	**EC (dS/m)**	**EC (ppm)**	**pH**	**EC (dS/m)**	**EC (ppm)**	**pH**	**EC (dS/m)**	**EC (ppm)**
Sample 1 (September 8, 2024)	8.85	1.51	966.4	8.84	1.39	889.6	8.06	0.15	96
Sample 2 (September 15, 2024)	8.97	0.75	480	8.94	0.7	448	8.03	0.08	51.2
Sample 3 (September 22, 2024)	8.77	0.78	499.2	8.65	0.59	377.6	8.73	0.09	57.6
Sample 4 (September 29, 2024)	8.79	0.75	480	7.48	0.57	364.8	9.05	0.11	70.4
Sample 5 (October 6, 2024)	9.31	0.8	512	9.25	0.63	403.2	9.4	0.11	70.4

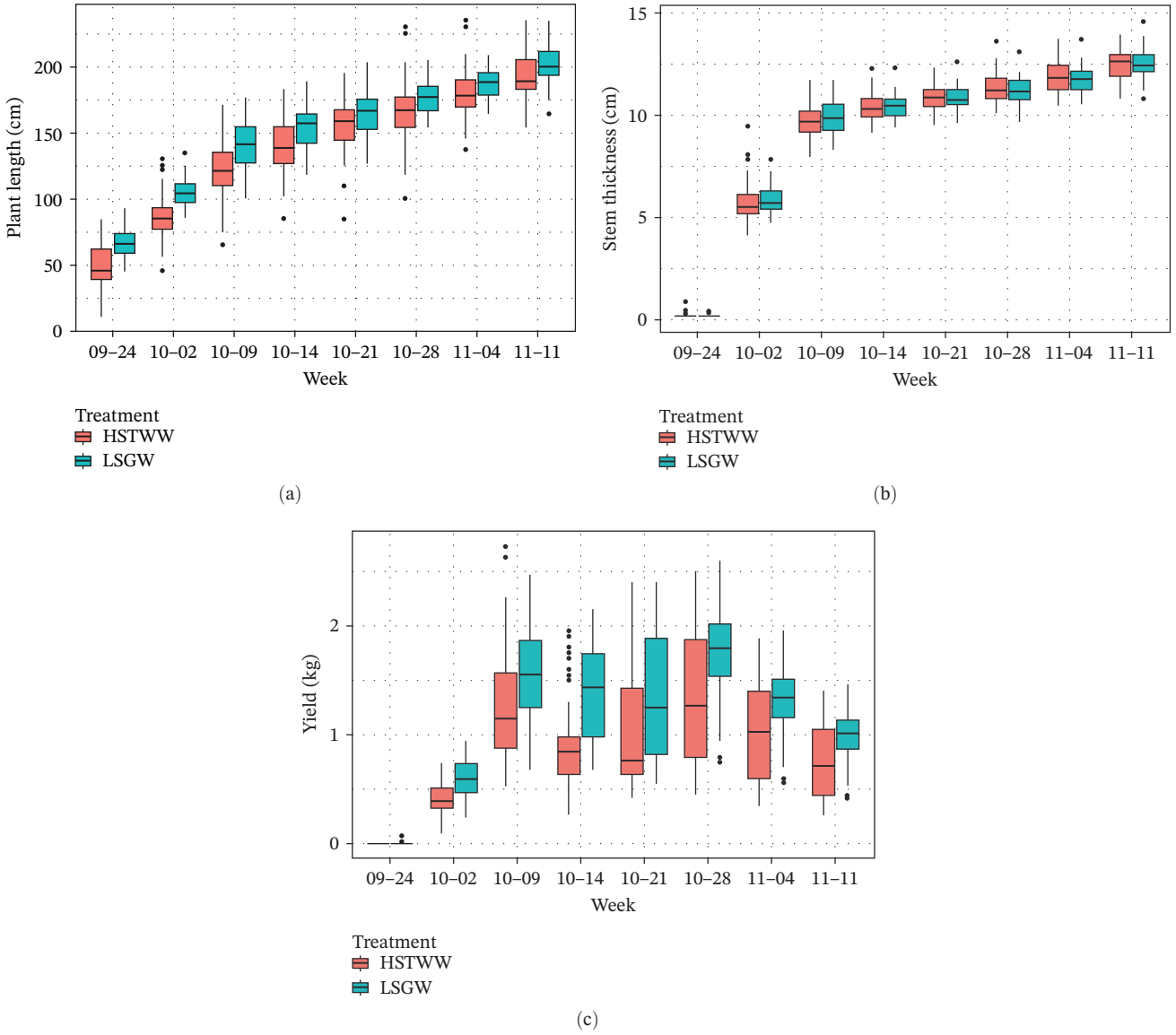


FIGURE 4 | Growth and yield of greenhouse cucumber under electronic water treatment (EWT) versus low-salinity control across weekly assessments (September–November, 2024). Box-and-whisker plots show (a) plant length, (b) stem thickness, and (c) weekly fruit yield. Boxes show the interquartile range (IQR; Q3 − Q1), the center line is the median, whiskers extend to the smallest and largest observations within 1.5 × IQR of the lower and upper quartiles, and points beyond the whiskers are outliers. Colors: teal = EWT (treated saline water) and red = control (purchased low-salinity freshwater).

patterns of key compounds like carbonate or bicarbonate. Even slight improvements in pH can be beneficial in high-pH soils where nutrient availability from phosphorus, iron, and manganese is limited.

Across weekly measurements, cucumbers irrigated with EWT-treated HSTWW generally showed equal or faster growth than plants under LSGW (Figure 4). By the final assessment (November 11, 2024), group means for plant length and stem thickness were closely aligned, with substantial overlap in the distributions (Figure 5). Overall, EWT-treated HSTWW produced nearly the same readings and performance as LSGW, with on-average gains at several intervals.

While growth performance was comparable or improved under EWT-treated HSTWW, edible-tissue and leachate ion profiles were not measured, so treatment differences in salt accumulation cannot be inferred from these data.

The results of the linear mixed models allow us to parse the effects of time, water treatment, and experimental error while also accounting for endogeneity induced by repeated measures on the same observation. Results indicate that cucumber plants cultivated with saline water from local sources, but treated with an EWT device experienced similar growth patterns as plants irrigated with high quality and low saline water. To test the significance of the treatment effect on each growth indicator, we fit a null model that includes all terms in Equation (1) except the treatment factor variable. We ran an ANOVA test between these two models and tabulated the results (Table 3). For plant length and yield, models with the treatment factor had a statistically significant F-statistic which indicates that the model with the added treatment factor adds significant improvement to the model; these models also have a lower AIC and BIC which indicates a more robust fit to the data.

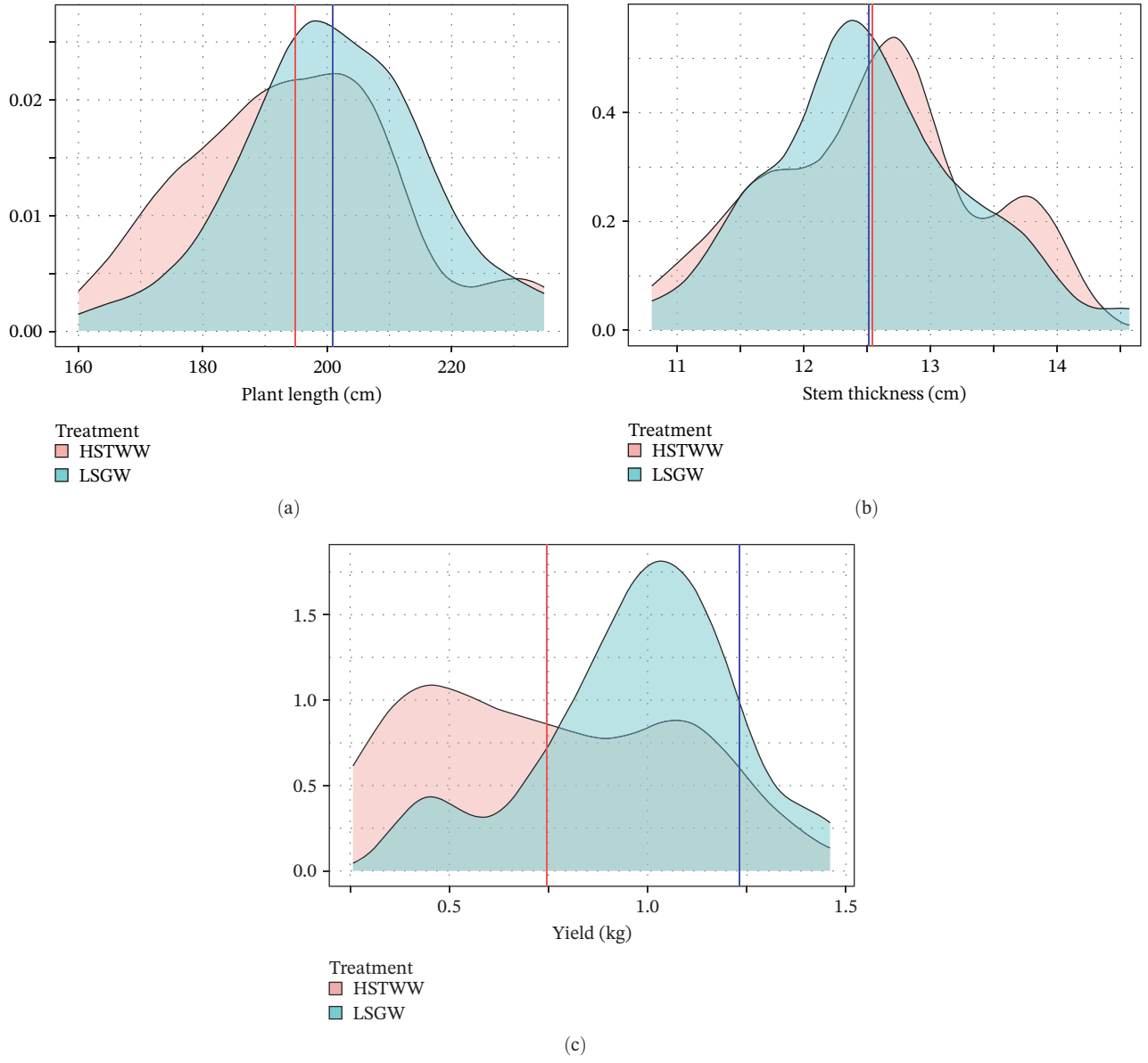


FIGURE 5 | Final-assessment distributions of cucumber growth and yield by treatment (November 11, 2024). Shaded curves show kernel density for (a) plant length, (b) stem thickness, and (c) fruit yield; the vertical lines mark treatment means (blue = EWT, red = low-salinity control). The *y*-axis denotes probability density.

TABLE 3 | ANOVA results for testing the EWT treatment effect via likelihood-ratio X^2 comparisons of nested mixed-effects models.

Outcome (response variable)	Model	AIC	BIC	Chi-Squ. (X^2)
Plant length	Null model	7816.1	7864.8	—
	Model with treatment	7795.2	7848.7	22.9***
Stem thickness	Null model	1731.4	1780.1	—
	Model with treatment	1733.4	1787.0	0.0
Yield	Null model	2425.9	2474.6	—
	Model with treatment	2413.2	2466.8	14.6***

Note: Reported metrics include AIC, BIC, and Chi-square (X^2) for the null model (without treatment) versus the model with treatment. Lower AIC/BIC indicates better fit. X^2 values are from LRT comparing the model with treatment to the nested null model.
Abbreviations: AIC, akaike information criterion; BIC, Bayesian information criterion; LRT, likelihood-ratio test.
*$p < 0.05$.
**$p < 0.01$.
***$p < 0.001$.

TABLE 4 | Linear mixed-effects estimates for cucumber growth indicators under electronic water treatment (EWT) versus low-salinity control.

Parameter/statistic	Plant length model	Stem thickness model	Yield model
β_1 (EWT treatment effect)	13.02 (7.90, 18.14)	0.006 (−0.18, 0.19)	0.42 (0.21, 0.62)
Intraclass correlation	0.53	0.42	0.27

Note: EWT = electronic water treatment (applied to HSTWW); control = LSGW. β_{EWT} is the fixed effect comparing EWT to control; positive values indicate a higher outcome under EWT. Values are estimates with 95% confidence intervals [95% CI]. Models were fit by REML to repeated weekly observations with a random intercept for plant; 95% CIs are based on model-based standard errors. ICC = intraclass correlation; proportion of total variance attributable to between-plant differences. Units: plant length (cm), stem thickness (cm), yield (kg).
Abbreviations: EWT, electronic water treatment; HSTWW, high-salinity treated wastewater; ICC, intraclass correlation; LSGW, low-salinity groundwater.

The ANOVA test did not produce statistical results indicating that stem thickness was a significant addition to the model. In fact, adding this factor variable increased the model BIC's by a significant proportion which indicates the model robustness decreased by the addition of this variable. The results of the models themselves confirm these results (Table 4).

We found that cucumbers irrigated with EWT–treated HSTWW (Max Grow) had higher plant length and yield than those under LSGW, with statistically significant effects in the mixed-effects models (Table 4). According to the mixed-effects model, plant length was higher by approximately 13 cm on average and yield by approximately 0.42 kg per plant under EWT–treated HSTWW (Table 4). The mixed-effects estimates indicate statistically significant, but modest effects under EWT–treated HSTWW: plant length + 13.0 cm on average (95% CI 7.9–18.1 cm) and yield + 0.42 kg plant^{-1} (95% CI 0.21–0.62 kg), with no significant effect on stem thickness (Table 4). Importantly, our study targeted comparability rather than superiority: weekly trajectories for HSTWW + EWT and LSGW largely tracked each other and converged by the final assessment (Figures 4 and 5), indicating that EWT–treated HSTWW can deliver LSGW–like performance at greenhouse scale. In addition, we do not have sufficient evidence of a difference between treatments for stem thickness, as the estimated effect was small and imprecise. Week-by-week readings from both treatments generally tracked each other, and by the final assessment the group means for plant length and stem thickness were closely aligned (Figures 4 and 5), indicating practical comparability. Taken together, the results show that using EWT–treated HSTWW can deliver nearly the same measurements as LSGW, while still yielding on-average gains in length and yield. While we did not directly quantify root-zone ions or leachate EC, the observed pattern is consistent with the intended function of the Max Grow unit in mitigating salinity-related growth penalties.

The statistical results indicate that cucumbers irrigated with EWT–treated HSTWW achieved growth outcomes comparable to those irrigated with LSGW. In other words, the findings support growth comparability between the two treatments rather than advocating for one irrigation approach over the other. Practically, this means that after inline EWT Jordan Valley farmers using KAC/KTD water can expect plant performance on par with LSGW, assuming the same cultivar, fertigation, schedule, and greenhouse management.

3.2 | Feasibility Within the Jordan Valley

The adoption of EWT systems like Max Grow is particularly well-suited to the geographical and economic realities of the Jordan Valley. Many of the methods for addressing water salinization face high barriers. Nature-based solutions for addressing salinization may be effective, but they are not widely used in the Jordan Valley and may even require specialized management of new cropping patterns or fertilizer applications which many farmers do not have extensive experience with. Conventional RO desalination systems are energy-intensive, expensive, and require regular maintenance along with technical expertise. A small-scale RO unit suitable for this size of an operation in the Jordan Valley (10–15 m^3/day capacity) typically costs between $16,000 and $25,000 USD in addition to regular filter replacements and skilled maintenance. RO systems have high operational costs due to energy requirements and membrane fouling which contributes to long-term expenses. Purchasing freshwater is similarly cost prohibitive for many farmers. During our experiment, the cost of high-quality freshwater was $1050 USD for 430 m^3 equating to $\$2.44/m^3$.

In contrast, EWT operates without membranes, chemicals, or high-pressure pumps. Its low capital cost, zero consumable parts, and minimal electricity usage make it a practical and innovative solution even for small- and medium-scale farmers in the Jordan Valley. The Max Grow device costs approximately $2600 USD with no maintenance costs, no replaceable parts, and negligible electricity consumption. These cost savings do not come at the expense of crop productivity: statistical results confirm that both sets of crops grow at similar rates allowing farmers to benefit from this new treatment without incurring any loss in crop growth. When used over multiple seasons, the EWT device demonstrates a strong return on investment, particularly when the avoided costs of desalinated water or freshwater purchases are considered. This economic advantage is a key factor that can drive the broader adoption of EWT devices in water-scarce agricultural regions like the Jordan Valley.

3.3 | Implications for Data Quality and Food Safety (Scope-Appropriate Monitoring)

This trial targeted growth responses and water-quality changes (EC, pH) over a single short cucumber cycle. For fruiting cucurbits like cucumber, edible-tissue accumulation of Na^+/Cl^- over one short season is generally limited relative to leaf tissues, because salt stress is expressed primarily as osmotic effects and ion toxicity in vegetative organs, with management typically focused on root-zone/leachate EC control in soilless systems. Accordingly, the primary food-safety concern for short-cycle cucumbers under saline/TWW irrigation is root-zone salt management rather than large salt residues in fruit; systematic leachate EC monitoring and periodic ion panels are the industry-

standard QA tools [59–61]. That said, when TWW is used, a simple end-of-cycle fruit ion check (Na^+, Cl^-; and NO_3^- if nitrate fertilization is high) is a low-cost addition to confirm residue equivalence by treatment [62].

4 | Conclusion

Our experimental evaluation of the Max Grow EWT device shows that applying EWT to HSTWW can mitigate salinity-related growth penalties: cucumbers irrigated with EWT–treated HSTWW achieved growth and yield comparable to, and in some measures higher than, those obtained under LSGW. These findings have important implications for Jordan's agricultural sector, where water scarcity and salinity in the Jordan Valley make affordable and efficient options essential.

Rather than removing salts via desalination, EWT applies RF energy in-line to influence ion aggregation and scaling behavior, integrating into existing irrigation networks without filters or major redesign. This is particularly relevant in the Jordan Valley, where HSTWW and brackish groundwater are available resources amid LSGW scarcity. The device's low operating complexity and modest power requirements make EWT a practical option for risk-averse farmers who cannot absorb the capital and running costs of desalination systems. Lowering these financial and technical barriers could support wider adoption, offering a realistic pathway for salinity mitigation in low-resource greenhouse systems and opening opportunities for sustainable production on marginal water.

By lowering the salinity burden at the point of irrigation, EWT can help limit salt build-up in the root zone, thereby supporting soil health and reducing the risk of long-term declines in soil fertility. Repeated use of saline water is a known driver of soil salinization in the Jordan Valley, and ongoing efforts to expand the safe reuse of TWW for agriculture mean salinity pressure will continue. Preserving soil quality is, therefore, critical for sustaining productivity. In this context, wider adoption of EWT could enable farmers to utilize HSTWW while mitigating salinity-related risks to soils.

The EWT approach addresses key economic, operational, and environmental constraints of saline irrigation in the Jordan Valley: it is relatively affordable, simple to integrate into existing systems, and—in our experiment—delivered crop performance comparable to LSGW. By lowering technical and cost barriers to using HSTWW, EWT devices such as Max Grow can help farmers maintain productivity, avoid higher desalination costs, and contribute to more sustainable water use in Jordan's greenhouse systems.

Although evaluated in a Mediterranean-arid greenhouse in the Jordan Valley, the approach is directly transferable to regions that (i) rely on brackish groundwater or TWW for irrigation (roughly TDS ~1000–3000 mg/L; EC ~1–3 dS/m), (ii) use pressurized drip systems at modest submain flows (~1–5 m^3 h^{-1}), and (iii) have stable low-voltage power and basic pump/filtration infrastructure. In such settings, inline EWT can be adopted with minimal plumbing changes and no brine handling, offering a lower-cost alternative to small-scale desalination where the objective is noninferior crop performance rather than salt removal. Adoption should include routine monitoring of irrigation/leachate EC and periodic soil/tissue assays to manage salinity and food-safety risk and may require blending and leaching fractions for sources above approximately 3–5 dS m^{-1} or for highly salt-sensitive crops. With these guardrails, the EWT pathway is applicable across arid and semiarid greenhouse hubs that face LSGW scarcity but have access to HSTWW or brackish supplies, providing a practical route to maintain yields while containing capital and operating costs.

Nomenclature

EWT:	Electronic water treatment
RO:	Reverse osmosis
ED:	Electrodialysis
KAC:	King Abdullah Canal
KTD:	King Talal Dam
MIRRA:	Methods for irrigation and agriculture
EC:	Electroconductivity
ANOVA:	Analysis of variance
AIC:	Akaike information criterion
BIC:	Bayesian information criterion
Chi-squ:	Chi-squared test.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon request.

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