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Research Article

Effect of nutrient solution electrical conductivity on cucumber growth and yield in controlled pot soil cultivation

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Abstract

This study investigated the influence of different electrical conductivity (EC) levels on cucumber growth and yield in pot soil under controlled conditions. Four EC treatments were tested: control, T1 (0.5 $dS·m^{-1}$), T2 (1.5 $dS·m^{-1}$), and T3 (2.5 $dS·m^{-1}$), over a 53-day period. Irrigation and drainage dynamics were monitored alongside plant growth, fruit production, and leaf gas exchange. Plants in T2 and T3 required higher irrigation volumes but showed lower drainage rates (16.4%-17.2%), whereas the control and T1 required less irrigation but had higher drainage (24.8%-29.0%). Nutrient leaching was most pronounced in T3 at 51 days after treatment (DAT). Growth and yield parameters were significantly influenced by EC treatments: the highest plant height, leaf area, and fruit fresh weight were observed in T2 and T3 at 53 DAT, while T3 reduced fruit number and quality. Photosynthetic rate peaked in T3 (12.7 $\mu mol\ m^{-2}\ s^{-1}$) but was associated with lower drainage pH and higher electrolyte leakage. In contrast, T2 improved overall growth and yield performance. Water use efficiency (WUE) was highest in T2 (2.82 $g\ L^{-1}$) and lowest in T1 (2.22 $g\ L^{-1}$). The highest Fertilizer use efficiency (FUE) was observed in T1 and the lowest in T3. Principal component analysis revealed that traits such as fruit fresh weight, fruit dry weight, leaf length, leaf width, leaf fresh weight, and leaf dry weight were strongly associated with T2. These findings demonstrate that a moderate EC level of 1.5 $dS·m^{-1}$ optimizes cucumber productivity in controlled pot soil cultivation.

Keywords: electrolyte leakage; drainage rate; irrigation volume; photosynthesis rate; water use efficiency

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Introduction

Cucumber (*Cucumis sativus* L.) is one of the most widely consumed vegetables worldwide, valued for its crisp texture and refreshing taste (Ejaz and Bahadur, 2024). It plays a vital role in both traditional and modern cuisine, often included in dishes such as kimchi, salads, and soups (Surya and Lee, 2022). In Korea, total

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cucumber production in 2023 reached 288,253 tons over 4,078 hectares, with greenhouse-grown cucumbers yielding the highest outputs (KOSIS, 2024). Greenhouse allows for year-round cultivation, which minimizes the impact of external weather conditions and reduces the risk of pests and diseases (Singh *et al.*, 2024).

However, continuous greenhouse cultivation presents significant challenges, particularly in nutrient management. Maintaining an optimal nutrient balance is crucial for sustaining plant health and maximizing yields under controlled conditions (Li *et al.*, 2022). Insufficient nutrient availability adversely affects plant growth and agricultural productivity. Nutrient deficiencies can cause substantial yield losses, decline in produce quality, and, in severe cases, plant death (Grzebisz *et al.*, 2022). Therefore, effective nutrient management is essential for enhancing the sustainability and productivity of greenhouse-grown cucumbers.

Cucumber plants require a balanced supply of macronutrients and micronutrients to support vegetative growth, flowering, and fruit development. An imbalance in nutrient supply can lead to physiological disorders such as fruit malformation, leaf chlorosis, and reduced fruit set (Campos *et al.*, 2021). Furthermore, the interaction between nutrient availability and environmental factors such as temperature, humidity, and light intensity adds complexity to nutrient uptake. Therefore, precise control over nutrient delivery is critical for improving cucumber yield and quality in controlled growing systems.

Fertigation involves applying water-soluble fertilizers through irrigation systems, making it an efficient method for enhancing nutrient delivery. This technique allows for precise and uniform distribution of nutrients directly to the plant root zone, which improves nutrient use efficiency and minimizes environmental losses (Incrocci *et al.*, 2017). A critical parameter in fertigation management is the electrical conductivity (EC) of the nutrient solution. EC reflects the concentration of dissolved salts, which directly affects the plant's ability to absorb water and nutrients (Lu *et al.*, 2022). Maintaining an appropriate EC level is crucial for optimal plant growth, as both low and high EC values can disrupt osmotic balance (Hung *et al.*, 2025). This disruption may lead to nutrient deficiencies or toxicities (Dewir and Alsadon, 2022). Krauss *et al.* (2006) reported that tomatoes grown under high EC levels showed reduced yield and higher concentrations of sugars, organic acids, and carotenoids. Amalfitano *et al.* (2017) also reported that moderate EC levels in hydroponically grown peppers resulted in improved fruit quality, particularly higher levels of ascorbic acid and carotenoids. Méndez-Cifuentes *et al.* (2023) observed that increasing EC to 2.0 $dS{\cdot}m^{-1}$ in sub-irrigated tomato improved overall fruit yield and quality, although excessive salt accumulation later in the growing period negatively impacted production. In the cultivation of potted cucumbers, fertigation enables the accurate adjustment of nutrient levels to align with the plant's growth stages, supporting a more responsive and dynamic approach to nutrient management (Kim *et al.*, 2022).

Despite the benefits of fertigation, limited research has examined the effects of different EC levels in soil-based systems, particularly for cucumbers. Soil-based cultivation introduces additional complexity due to factors such as soil texture, organic matter content, and microbial activity, which affect nutrient availability and uptake (Kim *et al.*, 2024; Kim *et al.*, 2025). Unlike hydroponic systems, where nutrient availability is tightly controlled, soil-based systems present challenges in managing nutrient retention and leaching (Al-Shammary *et al.*, 2024). This can potentially lead to imbalances in the root zone. Therefore, understanding the relationship between EC levels and nutrient dynamics in fertigated soil is essential for optimizing cucumber growth and ensuring consistent fruit quality.

While EC effects in hydroponics are well documented, limited studies have addressed its role in soil-based fertigation systems for cucumbers. This study aims to evaluate how varying nutrient solution EC levels affect cucumber growth, nutrient uptake, and fruit quality in fertigated pot soil under controlled conditions. The findings from this study will provide valuable insights into fertilizer management strategies for soil-based cucumber production, contributing to enhanced yield and improved production efficiency in controlled environments.

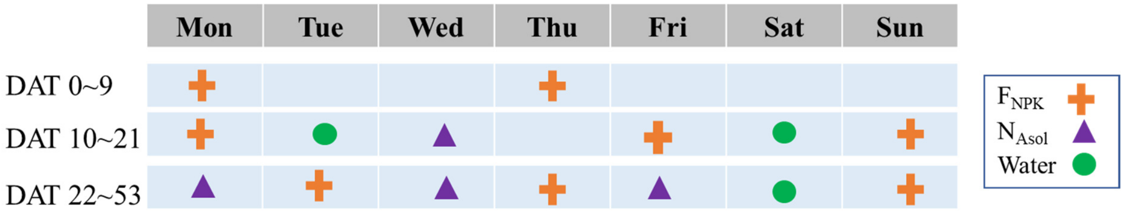
Materials and Methods

Plant material and growing conditions

This experiment was conducted in a controlled environment room (457 cm × 318 cm) for 85 days. Seeds of cucumber cultivar 'Backdadagi' (Asia Seed Co., Seoul, Korea) were sown in a 50-hole tray and grown for 24 days in controlled environmental conditions. Uniform-sized seedlings (an average plant height of 3.76 cm and a stem diameter of 1 mm) were transplanted into 2 L plastic pots containing sandy soil mixed with organic fertilizer and placed on cultivation shelves (W40 cm × L120 cm × H180 cm) for 60 days. The organic fertilizer used in this study was Gisaengto (Taeheung F&G, Korea), which was mixed with sandy soil at a ratio of approximately 1:32. Prior to transplanting, the EC and pH of the soil were measured following 1:5 soil-water extracts using a portable EC/pH meter (HI 9814, HANNA Instruments, Inc., USA). The controlled environment room was maintained at 24 °C (22~27 °C), 59% (46~68%) RH on average (data not shown), a 12/12-hour photoperiod, and a light intensity of 500 μmol m^{-2} s^{-1} at the shoot tips of cucumber plants. The sandy soil used in this study had a pH of 8.87 and an electrical conductivity (EC) of 0.23 dS·m^{-1}. The organic matter content was 1.97 g kg^{-1}, while the concentrations of NH_4, Available phosphorus (P_2O_5), K^+, Ca^{2+}, Mg^{2+}, and Na^+ were 2.86 ppm, 21.24 mg kg^{-1}, 0.08 cmol kg^{-1}, 5.75 cmol kg^{-1}, 0.36 cmol kg^{-1}, and 0.07 cmol kg^{-1}, respectively. Available P_2O_5 was determined using the Lancaster method by measuring absorbance at 720 nm with an inductively coupled plasma optical emission spectrometer (ICP-OES, GBC, Australia). Organic matter content was assessed using the Tyurin method, while exchangeable cations were quantified using the 1 M ammonium acetate extraction method (CH_3COONH_4) (pH = 7.0) and analyzed with ICP-OES (GBC, Australia).

Experimental design and treatments

The experiment consisted of four EC (dS·m^{-1}) levels: T1 (EC 0.5), T2 (EC 1.5), T3 (EC 2.5), and a control. These EC levels were applied to irrigation water and established using an NPK fertilizer (19-6-20) (Yaraterra Crystallon Blue, Yara, Norway). The NPK nutrient solution with different EC levels was supplied to cucumber plants by overhead irrigation 8 days after transplanting. In addition, all treatments were irrigated with water as well as nutrient solution A regularly (N-K-Ca-Fe were 160.7, 161.5, 123.4 and 3.0 ppm, respectively) at EC 1.0 dS·m^{-1}. Nutrient solution A was developed by the Korean Horticultural Experiment Station for cucumber cultivation and was applied separately as a supplement because the NPK fertilizer lacked calcium and iron both essential elements for cucumber growth. The experimental groups were randomly assigned, with each treatment replicated 10 times to ensure reliable results. The irrigation schedule for T1, T2, and T3 is shown in Figure 1. The EC levels of the NPK fertilizer were adjusted based on the differences between the treatments. During the treatment period, irrigation was performed twice per week from day 0 to 9 and then daily. The daily irrigation volume per plant was gradually increased from 100 to 500 mL based on plant growth.



	Mon	Tue	Wed	Thu	Fri	Sat	Sun
DAT 0~9	✚			✚			
DAT 10~21	✚	●	▲		✚	●	✚
DAT 22~53	▲	✚	▲	✚	▲	●	✚

F_{NPK} ✚
N_{Asol} ▲
Water ●

Figure 1. Irrigation schedule of T1, T2, and T3 treatments
Where F_{NPK} and $N_{Asol,}$ represents NPK fertilizer and nutrient solution A, respectively

The control group supplied NPK solution with an EC of 0.5 twice a week for the first 9 days. Afterward, NPK with EC 1.0 was applied once a week, along with Solution A applied 1 to 3 times weekly. On the remaining days, plants were irrigated water.

Irrigation and drainage ions analysis

The supplied nutrient solutions and the resulting drainage ion contents were analyzed to assess ion uptake or loss. Drainage samples were collected at 37, 40, 51, and 52 DAT. At each sampling point, irrigated solutions and drainage samples were obtained in clean and washed bottles. Both samples were filtered two times, initially, using Whatman 6 filter paper with a pore size of 3 μm under vacuum conditions to eliminate larger debris. The filtrates were then passed through a 0.45 μm syringe filter to remove fine particulates and prepare the samples for analysis. Prior to analysis, pre-filtered samples were diluted tenfold with ultrapure deionized water to bring ion concentrations within the optimal detection range. Then, anions were determined using ion chromatography (DX-100, Dionex Corp., USA) equipped with an AS14 analytical column. Cations were analyzed using inductively coupled plasma optical emission spectrometry (ICP-OES; Thermo Scientific iCAP 6300 Duo, UK). The system was calibrated using certified standards, and no further chemical treatment was applied to the samples prior to analysis. The ion content of irrigation solutions is shown in Table 1. Nutrient solution A was not included in the total ion content; it was analyzed separately. The net ions were calculated using the following formula;

$$\text{Net ion contents (ppm)} \\ = (\text{Irrigation volume} * \text{irrigation ions}) - (\text{drainage volume} * \text{drainage ions})$$

Table 1. Analysis results of ion contents in irrigated solutions.

Irrigated solutions	**Irrigation concentrations (ppm)**			
	NO_3	**PO_4**	**K**	**Ca**
NPK 2.5 $dS{\cdot}m^{-1}$	328.8	136.2	354.4	7.3
NPK 1.5 $dS{\cdot}m^{-1}$	189.4	98.3	223.1	7.9
NPK 1.0 $dS{\cdot}m^{-1}$	125.7	57.7	143.2	7.5
NKP 0.5 $dS{\cdot}m^{-1}$	58.8	48.9	65.4	7.6
Solution A (1.0 $dS{\cdot}m\text{-}^{1}$)	160.7	15.8	161.5	123.4
Water	3.8	0.3	ND	8.3

ND: not detected

Irrigation and drainage parameters

Irrigation and drainage volumes were measured using a measuring cylinder every day. Drainage EC and pH were determined using a portable EC/pH meter. The retained volume was calculated by subtracting the drainage volume collected from each plant from the irrigation amount supplied to that plant. Drainage rate (%), retained amount (L per plant), water use efficiency (WUE, $g{\cdot}L^{-1}{\cdot}plant^{-1}$), and Fertilizer Use Efficiency (FUE, g DW.g fertilizer) were calculated as followed equations.

$$\text{Drainage rate} = \frac{\text{Drainage amount}}{\text{Irrigation amount}} \times 100$$

$$\text{Retained amount} = \text{Irrigation amount} - \text{Drainage amount}$$

$$\text{WUE} = \frac{\text{Shoot dry weight} + \text{Fruit dry weight}}{\text{Irrigation amount} - \text{drainage amount}}$$

$$\text{FUE} = \frac{\text{Shoot dry weight} + \text{Fruit dry weight}}{\text{Fertilizer amount used}}$$

Growth and fruit quality parameters

Growth parameters including plant height, leaf length and width, leaf area, stem diameter, leaf fresh and dry weight (FW and DW), and stem FW and DW were measured at 24 and 53 DAT. The stem diameter was measured 1 cm above the soil surface using a digital caliper (CD-20CPX; Mitutoyo Corp., Kawasaki, Japan). Leaf area was measured using a leaf area meter (LI-3100, Li-Cor Inc., Nebraska, USA). Dry mass rate was calculated with FW and DW. Regarding productivity parameters, fruit length of individual fruit was measured from 1 to 15 days after flowering (DAF). Fruit FW and DW, and fruit number were measured at 53 DAT. In this study, ten plants were initially grown per treatment. Of these, four plants were used for the first destructive analysis at 24 DAT, and the remaining six plants were used for the second destructive analysis at 53 DAT.

Electrolyte leakage measurement

Electrolyte leakage was measured using an EC meter following the method described by Khan *et al.* (2013) at 51 DAT. This time point was chosen because it coincided with the onset of severe stress symptoms. For each biological replicate, a 1 g fresh weight sample of leaves was collected by pooling leaf material from multiple plants within the same treatment group to reduce variation. The pooled samples were then cut into small pieces (approximately 1 cm^2) and immersed in 25 mL of distilled water at 4 °C for 24 hours. After incubation, the EC of the solution was measured using an EC meter (DS-71G, HORIBA Ltd., Japan).

Leaf gas exchange and relative chlorophyll content

Leaf gas exchange parameters, including photosynthetic rate, transpiration rate, stomatal conductance, and intercellular CO_2 concentration, were measured using a portable photosynthesis system (LI-6800; LI-COR Inc., Nebraska, USA) from the 5th leaf from the top at 24 DAT. Conditions of the chamber were temperature 20 °C, CO_2 concentration 400 $\mu mol \cdot mol^{-1}$, and light intensity 1,000 $\mu mol\ m^{-2}\ s^{-1}$ within a 6 m^2 area. Relative chlorophyll content was measured at 9:00 AM during different developmental stages using a SPAD meter (SPAD-502, Konica Minolta, Tokyo, Japan). Measurements were taken on the fifth fully expanded leaf from the top of each plant. For each sample, SPAD readings were recorded from four different points on the same leaf, and the average value was used. Both gas exchange and relative chlorophyll content were measured with three replications per treatment.

Statistical analysis

All collected data were subjected to statistical analysis to identify significant differences and relationships among the measured variables and treatments. Data normality was assessed using the Shapiro-Wilk test, while the homogeneity of the variances was evaluated using Levene's test. Analysis of variance (ANOVA) and mean separation were conducted using SPSS software version 26 (IBM Corp., Armonk, NY, USA). Duncan's multiple range test (DMRT) was used to compare means at $p < 0.05$. Pearson's correlation analysis and principal component analysis (PCA) were performed using MetaboAnalyst R (version 6).

Results and Discussion

Growth performance and biomass accumulation under different electrical conductivity (EC) levels

The growth performance of cucumber plants was significantly influenced by different EC levels in the nutrient solution (Table 2). At 24 DAT, the highest EC treatment (T3) promoted significantly higher plant height compared to the control. In support of the numerical values in Table 2, Figure 2 visually confirms that higher EC levels stimulated plant height growth during the early stages. Additionally, leaf size and area increased with EC, with T3 showed the largest leaf area at this stage. Similarly, stem thickness was highest in T3 at 24 DAT, suggesting that high EC levels at early stages enhance structural development and water retention capacity (Yang *et al.*, 2024). Biomass accumulation also reflected this trend: T3 resulted in the highest leaf fresh weight and stem biomass, indicating improved water uptake and early vigor. However, the dry mass rate decreased under higher EC conditions, reflecting a higher water content in tissues and a lower proportion of dry matter (Nguyen *et al.*, 2021). These results suggest that, in the early growth phase, T3 promote vegetative growth primarily through osmotic adjustment mechanisms that increase cellular water content.

Table 2. The effects of different concentration of EC on cucumber plant growth and biomass related parameters

DAT	Treatment	Plant height (cm)	Leaf length (cm)	Leaf width (cm)	Total leaf area (cm²)	Leaf		Stem diameter	Stem		Dry Biomass rate (%)
						Fresh weight (g)	Dry weight (g)		Fresh weight (g)	Dry weight (g)	
24	Control	90.1b^z	11.5b	14.3a	1619.3c	34.5c	6.3c	7.1b	21.4d	1.7c	14.3a
	T1	90.1b	11.7ab	14.7a	1853.6c	40.6c	7.0bc	7.4b	29.9c	1.2bc	12.8b
	T2	98.8b	12.8ab	15.1a	3215.9b	70.3b	8.1b	7.9b	39.3b	2.4b	9.5c
	T3	110.3a	13.1a	15.5a	4150.8a	92.3a	10.9a	8.9a	52.1a	3.5a	10.0c
53	Control	223.1b	18.3ab	21.8b	4570.3b	93.7b	10.7b	8.5c	77.6b	6.1b	9.8a
	T1	228.2b	16.7bc	22.6b	5168.1b	106.3b	12.4b	8.7bc	89.7b	7.4b	10.1a
	T2	260.2a	20.3a	26.7a	7768.8a	187.0a	18.3a	9.6ab	157.3a	11.6a	8.7b
	T3	248.6a	20.6a	26.9a	8302.8a	173.0a	16.4a	9.7a	155.8a	10.8a	8.2b

Means followed by different letters within each column are significantly different according to Duncan's Multiple Range Test (DMRT) at $p < 0.05$. Where; Control (EC0.5 + water), T1 (EC 0.5), T2 (1.5) and T3 (EC 2.5)

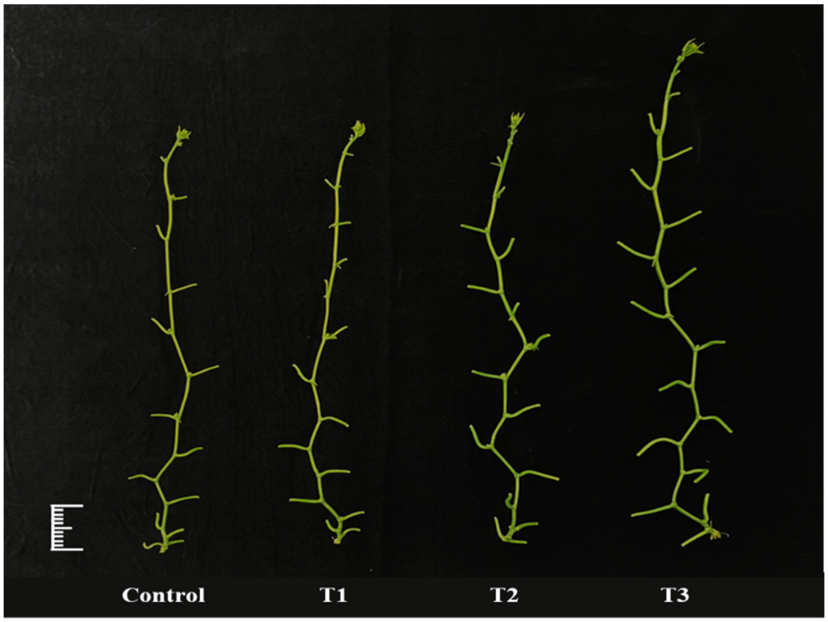


Figure 2. Effect of different EC levels on cucumber plant height captured at the early growth stage (24 DAT)

Control = EC 0.5 + water, T1 = EC 0.5, T2 = EC 1.5, and T3 = EC 2.5

At 53 DAT, growth patterns began to diverge. Plant height was highest in the T2 treatment, with a slight decline in T3, suggesting that while an EC of 1.5 continues to support elongation, higher levels (2.5 dS·m^{-1}) may impose osmotic stress, thereby reducing growth efficiency. Leaf area remained largest in T3; however, the marginal decline compared to T2 indicates possible limitations in leaf expansion due to osmotic effects.

Stem thickness continued to follow the earlier pattern, with T3 still producing the thickest stems, reinforcing the notion that high EC contributes to stronger structural development. Biomass trends at 53 DAT further highlight this distinction: leaf fresh weight and stem biomass were both highest in T2, indicating a shift from T3's early advantage, although the differences were not statistically significant. The continued decrease in dry mass rate under higher EC levels further reflects excessive water accumulation, which although beneficial for fresh biomass, compromises dry matter accumulation. This suggests a trade-off between biomass volume and tissue density. The increase in fresh biomass at higher EC can be attributed to greater water influx driven by osmotic adjustment, as cells accumulate compatible solutes to maintain turgor. However, this may reduce photosynthate translocation efficiency, leading to lower dry matter content (Chen and Jiang, 2010).

These findings indicate that an EC of 1.5 dS·m^{-1} (T2) provides an optimal balance between promoting growth and avoiding osmotic stress, making it ideal for maximizing cucumber biomass and structural development across growth stages. In contrast, an EC of 2.5 dS·m^{-1} (T3) may initially enhance growth through osmotic-driven water uptake but can hinder later-stage development due to osmotic stress effects. The reduced plant height at lower EC levels during later stages may be due to insufficient nutrient availability, limiting cell elongation and vegetative growth (Choi *et al.*, 2024). On the other hand, growth reduction at higher EC levels is likely the result of solute accumulation, which imposes osmotic stress (Hao *et al.*, 2021). Similar trends were observed in leaf traits: T3 produced the largest leaves at 24 DAT and the highest total leaf area at 53 DAT, but osmotic limitations likely restricted further expansion at later stages.

Irrigation and drainage characteristics under different EC levels

The irrigation amount (IA), drainage rate (DR), drainage EC (DE), and drainage pH (DP) differed among treatments over the experimental period (Figure 3). The study was conducted using three replications per treatment (n = 3) to ensure the reliability and statistical validity of the results. The IA ranged from 100 to 500 mL per pot and was adjusted according to the growth stage of the plants. Initially, all treatments received the same amount of irrigation, as there was no difference in growth (Figure 3A).

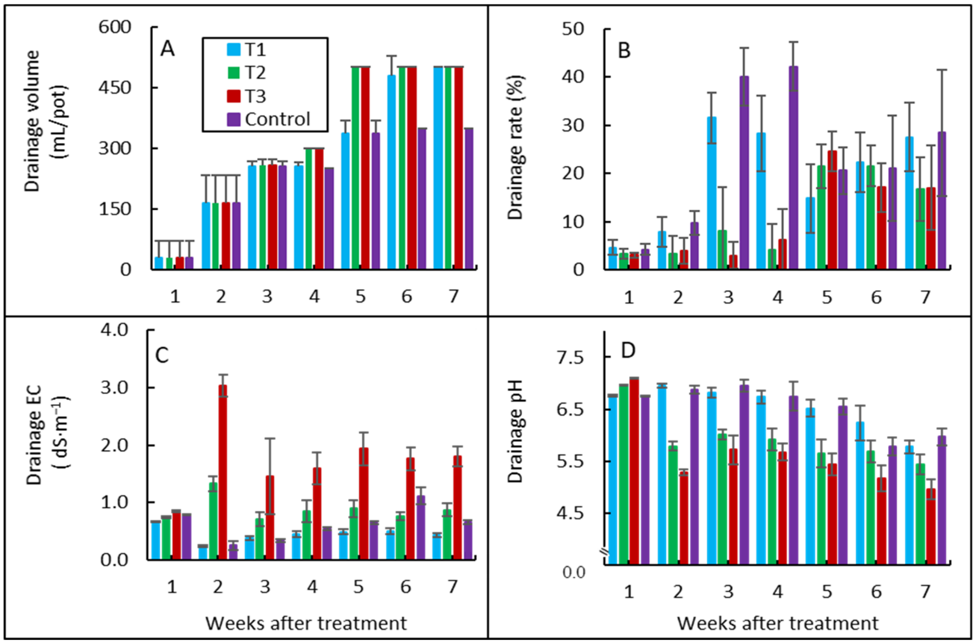


Figure 3. Graphs showing the drainage volume, drainage rate, drainage EC, and drainage pH at different nutrient solution EC levels measured over weeks after treatment

Treatments include Control (EC 0.5 + water), T1 (EC 0.5), T2 (EC 1.5), and T3 (EC 2.5) Error bars represent the standard deviation (n = 3)

However, as the plants developed, variations in growth led to noticeable differences in water requirements. The increased growth in T2 and T3 resulted in higher irrigation demand, indicating greater transpiration and biomass accumulation. In contrast, the control group, which had the least growth, received the lowest amount of irrigation, while T1, with moderate growth, received a medium irrigation volume.

DR also varied among treatments, reflecting differences in plant water uptake and growth dynamics (Figure 3B). The control and T1 treatments displayed the greatest fluctuations in drainage rates, especially during the initial and final weeks of the experiment. This might be due to less water absorption by the plants as a result of the low growth rate. On the other hand, T2 and T3 showed lower drainage rates at the beginning and end of the experiment, which may be attributed to more efficient water uptake driven by their enhanced growth. These two treatments experienced an increase in drainage rate during the third week, followed by a gradual decline after the fourth week, corresponding with changes in plant water use efficiency and possible root system development over time (Çakir *et al.*, 2017). DE patterns varied across treatments (Figure 3C). T3 recorded the highest values, reflecting increased ion accumulation due to nutrient leaching, specifically at 51 DAT. T2 exhibited moderate EC levels, while T1 and the control recorded the lowest values, indicating reduced ion accumulation from a lower nutrient supply. At week six, the control showed 0.5 dS m^{-1}, which declined by week seven. Although it was lower than in T2 and T3, it remained higher than in T1 at the seventh week.

DP tended to decrease as EC and the time of the treatments increased (Figure 3D). The control and T1 generally maintained the highest pH, except at week five, suggesting minimal acidification due to the lower nutrient concentration. T2 had a lower pH than T1 and the Control, but it remained within the optimal range for plant growth. T3 exhibited the lowest pH, potentially due to its higher EC levels (Al-Shammary *et al.*, 2024). Furthermore, the study conducted by Shanmugavel *et al.* (2023) also reported that the use of a high amount of nutrient solution leads to nutrient imbalances and soil acidifications. The observed decline in pH can be attributed to root exudate-driven acidification, which is influenced by the plant's need to maintain ionic balance during nutrient uptake. Under high EC conditions, plants absorb excess cations such as ammonium (NH_4^+) or potassium (K^+) (Coleto *et al.*, 2023). To maintain charge balance, roots release protons (H^+) into the rhizosphere, resulting in acidification. This proton extrusion is facilitated by plasma membrane H^+-ATPases, whose activity is upregulated under high nutrient concentrations, thereby intensifying rhizosphere acidification (Yan *et al.*, 2002).

The total irrigation and drainage characteristics for 53 DAT are shown in Table 3. T2 and T3 had significantly higher irrigation volumes (17.1 L $plant^{-1}$) compared to T1 (15.6 L $plant^{-1}$) and the control (13.2 L $plant^{-1}$). The increased irrigation volume in T2 and T3 reflects the higher growth rates of cucumbers under these treatments. Total drainage volume was significantly lower in T2 and T3 compared to T1 and the control. Consequently, the DR was also significantly lower in T2 (17.2%) and T3 (16.4%) than in T1 (24.8%) and the control (29.0%). The DE increased with increasing nutrient solution EC, being significantly highest in T3, followed by T2, control, and T1. The DP was highest in T1 and the control, but decreased significantly in T3 with increasing nutrient EC levels. Total retained amount (RA) ranged from 9.3 to 14.1 where the significantly highest value was observed in T2 and T3 whereas the lowest amount was recorded for the control.

The higher DR in the control resulted from lower ionic strength, which reduced soil water retention; as a result, it restricts plant growth. On the other hand, the reduced DR in T2 and T3 indicates that higher EC concentrations increased osmotic potential, leading to better water retention and plant growth. The stable DE in T1 and the control suggests that lower nutrient concentrations lead to reduced ion accumulation and consistent water movement. The lower DP in T2 and T3 implies that higher EC levels enhance ion exchange and root exudation, resulting in greater acidification and potential osmotic stress. These findings emphasize the need to optimize nutrient solution EC to balance water movement, nutrient availability, and soil salinity for improved plant health.

Table 3. Effect of different EC levels of nutrient solution on irrigation and drainage characteristics for 53 DAT

Treatment	IA (L plant $^{-1}$)	DA (L plant^{-1})	RA (L plant^{-1})	DR (%)	DE (dS·m^{-1})	DP
T1	15.6 ± 0.01b^{z}	3.9 ± 0.15a	11.7 ± 0.07b	24.8 ± 0.39a	0.46 ± 0.08d	6.5 ± 0.05a
T2	17.1 ± 0.08a	2.9 ± 0.39b	14.1 ± 0.26a	17.2 ± 1.01b	0.81 ± 0.06b	5.8 ± 0.04b
T3	17.1 ± 0.08a	2.7 ± 0.24b	14.1 ± 0.05a	16.4 ± 0.53b	1.70 ± 0.08a	5.5 ± 0.06c
Control	13.2 ± 0.11c	3.8 ± 0.24a	9.3 ± 0.05c	29.0 ± 0.53a	0.64 ± 0.07c	6.4 ± 0.02a

Data is presented as mean ± standard error; means followed by different letters within each column are significantly different according to Duncan's Multiple Range Test (DMRT) at $p < 0.05$ (n=46); IA, DA, RA, DR, DE, and DP represents irrigation amount, drainage amount, retained amount, drainage rate, drainage EC and drainage pH, respectively

Net uptake and loss ions concentration at different EC levels

Net ion uptake or loss by cucumber plants are summarized in Figure 4. In this work, net uptake or loss refers to the difference between the total amount of a given ion supplied through irrigation and the amount recovered in the drainage solution. Significant differences among treatments were observed in ion uptake and loss. At 37 DAT, the highest nutrient uptake occurred in T3, where NO_3^-, PO_4^{3-}, and K^+ concentrations reached 139.1, 64.7, and 155.5 ppm, respectively (Figure 4). In contrast, calcium uptake was negative across all treatments involving NPK fertilization. The control group (water-only irrigation) exhibited minimal nutrient uptake, suggesting potential nutrient deficiencies. At 40 DAT under Solution A irrigation, ion uptake improved across all treatments. T1 and T2 showed enhanced uptake of NO_3^-, K^+, and Ca^{2+} compared to the control, with T2 exhibiting the highest calcium absorption (53.2 ppm), while T1 showed the highest uptake of NO_3^- (73.3 ppm) and K^+ (77.2 ppm) (Figure 4). The differential uptake of K^+ and Ca^{2+} observed in T1 and T2 suggests distinct cation interaction dynamics at the root membrane. K^+ and Ca^{2+} often compete for uptake due to shared transport pathways and membrane binding sites, particularly at high concentrations (Horie *et al.*, 2011). In T1, the elevated uptake of K^+ may have partially inhibited Ca^{2+} absorption due to antagonistic interactions, a common phenomenon where excess K^+ reduces Ca^{2+} influx by occupying transport channels or altering membrane potential. Conversely, T2 showed the highest Ca^{2+} uptake, possibly due to reduced K^+ competition or improved expression of calcium-specific transporters under this treatment.

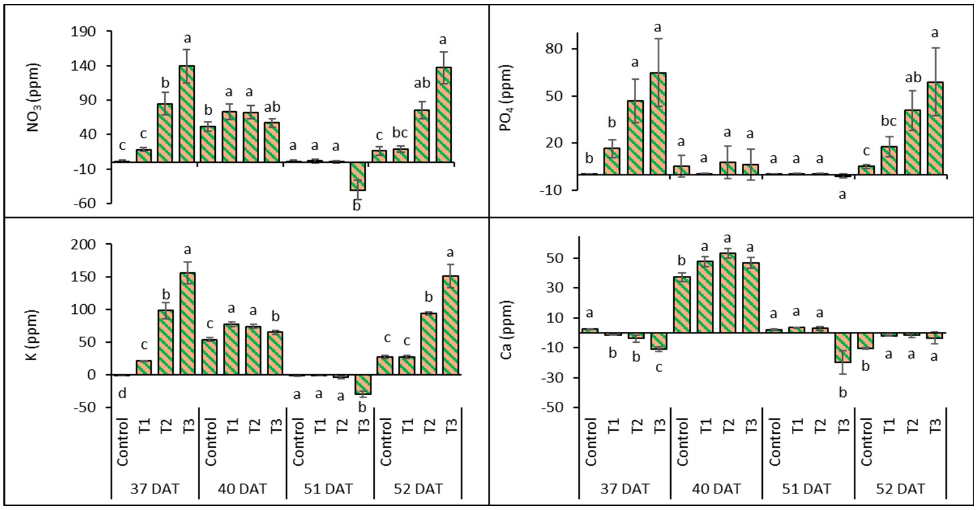


Figure 4. Net ion uptake and loss in cucumber plants at different DAT under varying EC levels

Different lowercase letters on the bars indicate statistically significant differences at $p < 0.05$ according to Duncan's Multiple Range Test (DMRT). Error bars represent the standard deviation (n = 3). Applied Irrigation types were as follows: NPK solution at 37 DAT and 52 DAT, Solution A at 40 DAT, and water at 51 DAT

By 51 DAT under continued water-only irrigation, significant ion losses were detected in the high EC group (T3), with net reductions of - 40.5 ppm NO_3^-, - 29.6 ppm K^+, and -19.9 ppm Ca^{2+}, relative to the control, which maintained more stable ion levels (Figure 4). These losses suggest a decline in root ion uptake efficiency due to prolonged high EC exposure, likely caused by osmotic stress impairing membrane integrity and transport processes (Yuan *et al*., 2021). At 52 DAT under NPK irrigation, T3 again showed the highest nutrient uptake across all measured ions, with NO_3^-, PO_4^{3-}, and K^+ concentrations remaining highest, while calcium values remained negative, though less pronounced than under water-only conditions (Figure 4). This net calcium loss may be attributed to competitive interactions at the root surface with other cations present in high concentrations. In this study, increasing the EC of the nutrient solution generally enhanced the uptake of macronutrients such as NO_3^-, PO_4^{3-}, and K^+. However, the positive effects of high EC were highly dependent on the presence of adequate nutrient supply. Under water-only conditions, high EC (T3) led to severe ion losses, potentially due to osmotic stress and nutrient imbalances. In contrast, under nutrient-enriched irrigation (Solution A or NPK), high EC levels promoted increased nutrient uptake efficiency. These findings align with those of Samarakoon *et al*. (2017), who reported that high EC levels enhanced macronutrient uptake in lettuce but no influence on yield above 1.8 mS cm^{-1}. Similarly, in the present study, despite the increased uptake of key nutrients under high EC conditions, there was no significant improvement in fruit development in cucumber plants.

Yield related parameters under different EC levels

Table 4 shows the effects of different EC levels on cucumber fruit yield at 53 DAT. The control group had the highest total fruit count compared to T3, although the difference was not statistically significant, suggesting that high EC levels may reduce total fruit production. These results indicate that while higher EC levels may lead to the formation of smaller fruits, they do not necessarily enhance overall fruit yield per plant (He *et al*., 2024). The number of fruits >10 cm was highest in the control and lowest in T1, but the differences among all treatments were not statistically significant. Fruits <10 cm were more frequent in T1 and T2 than in the control (1.0) and T3 (0.8).

Table 4. Fruit number per plant, fruit fresh weight (TFW), and fruit dry weight of cucumbers grown under different nutrient solution EC levels at 53 DAT

Treatment	Fruit number per plant			FFW (g plant^{-1})	FDW (g plant^{-1})
	10cm >	10cm <	Total		
Control	9.0 a^z	1.0 b	10.0 a	135.4 b	4.93 b
T1	6.7 ab	2.2 a	8.8 a	230.0 a	6.22 ab
T2	6.8 ab	2.0 a	8.8 a	331.1 a	10.03 a
T3	7.2 ab	0.8 b	8.0 ab	196.3 ab	8.90 a

Means followed by different letters within each column are significantly different according to Duncan's Multiple Range Test (DMRT) at $p < 0.05$ (n = 5). Where; Control= EC 0.5 and water, T1= an EC 0.5; T2 = an EC 1.5, and T3 = an EC 2.5

Although T2 had fewer fruits than the control, its total yield was higher. Fruit fresh weight (FFW) increased with moderate EC, with T2 showing the highest value, followed by T1 and T3, while the control had the lowest. This suggests that moderate EC (T2) enhances fruit growth, while the highest EC (T3) reduces biomass. Similarly, fruit dry weight (FDW) was highest in T2, significantly greater than in the control, highlighting improved dry matter accumulation at moderate EC. High EC (T3) reduced fruit number and biomass, likely due to osmotic stress affecting flower development and fruit set. Furthermore, in cucumber cultivation, an imbalance in nutrient supply can lead to significant physiological disorders, including fruit malformation, leaf chlorosis, and a reduction in fruit set. The reduction in fruit number in T3 may be due to osmotic stress, which can hinder flower development and fruit set (He *et al.*, 2024). These findings highlight the importance of optimizing EC levels for improved cucumber yield and quality.

In this work, moderate EC levels may enhance sink strength in cucumber fruits by promoting stronger hormonal signaling and vascular development. Increased sink strength in the T2 treatment facilitates greater assimilate partitioning to the developing fruits, resulting in larger fruit size and higher fresh and dry weights. Improved nutrient availability at moderate EC supports enhanced photosynthetic activity, boosting source capacity and ensuring a continuous supply of assimilates to the fruits (Li *et al.*, 2024). This efficient source-sink relationship under moderate EC allows for optimal carbohydrate allocation, favoring fruit growth over vegetative expansion.

To further explore how EC affects fruit growth dynamics, fruit elongation was monitored post-anthesis. Figure 5 shows that cucumber fruit length was significantly influenced by EC levels across all measurement periods. At 1 DAF, fruit length was shortest in T1 and longest in T2 but there was no significant difference among the treatments. By 3 DAF, T3 showed the greatest elongation, but by 6 DAF, T2 recorded the longest length. At 9 DAF, T2 remained the longest, followed by T3. At 12 DAF, T2 was nearly double than that of the control, while T3 showed moderate growth. By 15 DAF, T2 fruits were 69.93% longer than the control. These results suggest that moderate EC (T2) enhances early and overall fruit elongation. High EC (T3) showed positive but reduced effects, likely due to osmotic stress limiting cell expansion. Similar conclusions were drawn by Watabe *et al.* (2022), who found that higher EC levels significantly impact tomato growth and fruit quality. Low EC levels in the control limited fruit growth, while T1 outperformed the control at later stages, indicating improved nutrient availability. In this finding, an EC level of 1.5 (T2) appears optimal for maximizing cucumber fruit length. These findings are consistent with previous research indicating that moderate EC can enhance plant growth, whereas higher EC leads to stress conditions that negatively affect physiological processes in crops (Lam *et al.*, 2020).

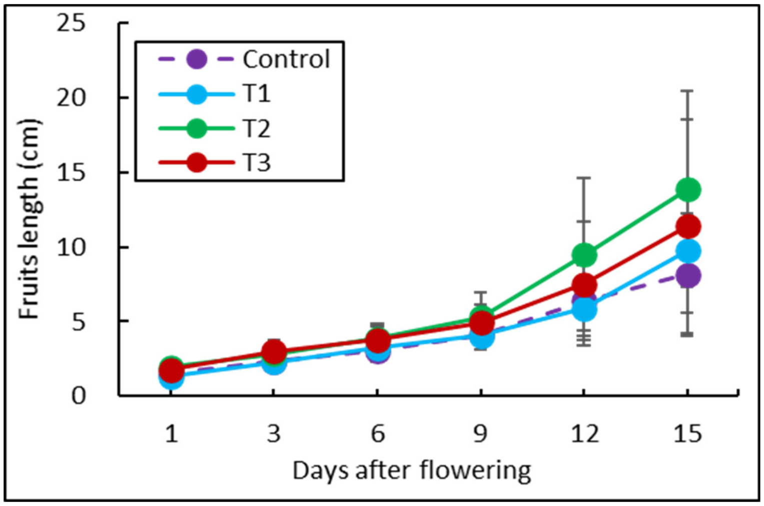


Figure 5. Effect of different EC levels on cucumber fruit length measured every three days after flowering
Where; Control = EC 0.5 + water, T1 = EC 0.5, T2 = EC 1.5, and T3 = EC 2.5. The error bars indicate the standard deviation

Electrolyte leakage (EL) of cucumber leaf under different EC levels

Electrolyte leakage (EL) reflects cell membrane stability and stress tolerance in plants. Elevated EC levels generally increase membrane damage (Turan *et al.*, 2022). This study assessed EL of cucumber leaves at 51 DAT under different EC treatments using a conductivity-based assay (Khan *et al.*, 2013). A significantly lower EL value was recorded in T2 (0.10), while the highest was observed in T3 (0.14) at $p < 0.05$, indicating membrane damage-induced stress (Figure 6). In this finding, T1 and control recorded EL values of 0.12 and

0.11, respectively, with no significant difference (Figure 6). Reduced EL in T2 suggests moderate EC levels enhance membrane stability through osmotic adjustment, while higher EC (T3) disrupts membrane integrity. In addition, findings align with previous studies showing moderate EC improves stress tolerance, whereas high EC damages membranes (Yang *et al.*, 2024). Osmotic adjustment enhances membrane stability by maintaining cell turgor pressure and regulating intracellular osmotic potential. This is achieved through the accumulation of compatible solutes and selective ion uptake, which helps preserve membrane structure and function by minimizing dehydration-induced stress (Xu *et al.*, 2025). Additionally, enhanced antioxidant activity plays a crucial role by scavenging excess reactive oxygen species (ROS) produced under EC stress, thereby preventing lipid peroxidation and oxidative damage to membrane components (Rao *et al.*, 2025). Together, osmotic adjustment and antioxidant defense mechanisms contribute to improved membrane integrity and overall cellular stability under moderate EC levels.

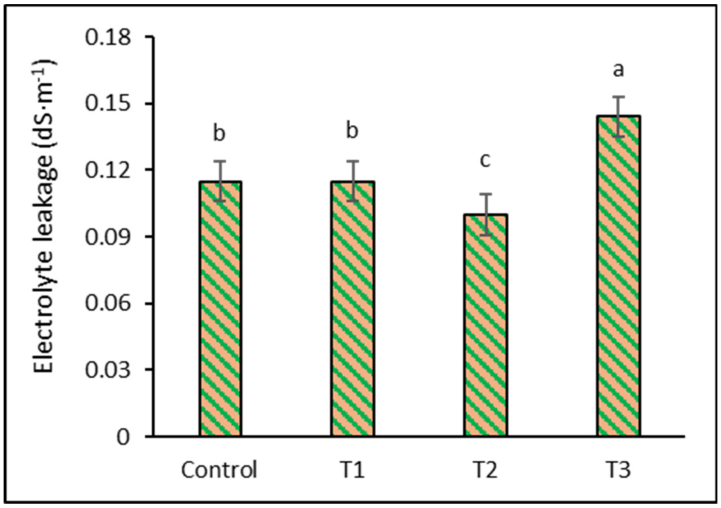


Figure 6. Electrolyte leakage in cucumber leaves under different EC levels, measured at 51 DAT
Different letters on the bars indicate significant differences at $p < 0.05$ according to DMRT, and error bars represent the standard deviation (n = 4)

Leaf gas exchange parameters and relative chlorophyll content under different EC levels

The photosynthesis rate (Pn) of cucumber plants was significantly different between the control and EC treated plants. The control treatment had the lowest Pn, while T1, T2, and T3 showed significantly higher Pn (Table 5). This suggests that EC levels may enhance chlorophyll synthesis, thereby improving photosynthetic efficiency (He *et al.*, 2024). However, the diminishing increase between T2 and T3 indicates a saturation point where further increases in EC do not provide additional benefits. Similarly, the transpiration rate (Tr) increased with EC levels, with the control showing the lowest Tr, while T1, T2, and T3 recorded the highest (Table 5). This rise suggests improved water movement through enhanced stomatal opening (Lv *et al.*, 2024), but excessive Tr at high EC levels may increase water loss, which could be detrimental under drought conditions (Shin and Son, 2015). The intercellular CO_2 concentration (Ci) also increased with EC levels, from 159.07 μmol mol^{-1} in the control to 279.43, 304.33, and 319.63 μmol mol^{-1} in T1, T2, and T3, respectively, indicating improved CO_2 diffusion and photosynthetic efficiency (Table 5). The rise in Ci may be an adaptive response to maintain carbon assimilation efficiency under higher EC conditions, thus preventing photosynthetic downregulation (Ruiz-Vera *et al.*, 2021). Stomatal conductance (Gs) followed a similar trend, it showed an increasing order as of EC increased, reflecting enhanced stomatal regulation and water-use efficiency (Table 5). Gs is crucial for maintaining the plant's water-use efficiency (Bertolino *et al.*, 2019), and the observed increase with EC treatments suggests that cucumber plants can tolerate moderate EC-induced osmotic stress by adjusting their stomatal behavior. Moderate EC levels can trigger osmotic adjustment in cucumber plants by promoting the accumulation of compatible solutes such as proline and soluble sugars, which help maintain cell turgor under osmotic stress (He *et al.*, 2024). Moderate EC also influences ion homeostasis by enhancing selective ion uptake mechanisms, allowing plants to maintain a favorable K^+/Na^+ ratio and avoid ionic toxicity (Malakar and Chattopadhyay, 2021). Furthermore, elevated EC may alter hormonal balances, such as increasing abscisic acid (ABA) levels, which regulate stomatal closure and improve water-use efficiency (Bharath *et al.*, 2021). In this work, T2 positively influences photosynthesis, transpiration, and gas exchange by optimizing stomatal function, but T3 may lead to a plateau where further increases offer limited benefits.

Table 5. Effect of different EC levels of nutrient solution on leaf gas exchange parameters at 24 DAT

Treatments	**Pn (μmolm^{-2} s^{-1})**	**Tr (mmol m^{-2} s^{-1})**	**Ci (μmol mol^{-1})**	**Gs (mol m^{-2} s^{-1})**
Control	9.3 ± 0.26b^z	0.8 ± 0.11b	159.1 ± 2.00a	0.07 ± 0.18b
T_1	11.3 ± 0.45a	2.0 ± 0.03a	279.4 ± 4.22a	0.17 ± 0.11a
T_2	12.4 ± 0.06a	2.7 ± 0.06a	304.3 ± 5.57a	0.27 ± 0.09a
T_3	12.7 ± 0.27a	3.3 ± 0.15a	319.6 ± 7.30a	0.37 ± 0.18a

Data is presented as mean ± standard error; means followed by different letters within each column are significantly different according to Duncan's Multiple Range Test (DMRT) at $p < 0.05$ (n=5). Where; Control= EC0.5 and water, T1= an EC 0.5; T2 = an EC 1.5, and T3 = an EC 2.5. Pn=photosynthesis rate, Tr= transpiration rate, Ci=intercellular CO_2 concentration and Gs=stomata conductance.

The SPAD values (relative chlorophyll content) varied among treatments and growth stages in response to different EC levels (Table 6). At 24 DAT, there were no significant differences in SPAD readings between treatments, indicating that early growth was not influenced by EC levels. Similarly, nutrient uptake such as nitrate (NO_3^-) did not differ significantly across treatments during this stage (data not shown). By 38 DAT, the effects of varying EC levels on SPAD values became more evident. The control and T1 treatments showed similar values, while T3 exhibited significantly higher values. In this finding T2 showed significantly higher value than control and T1. This result is in line with the findings presented in Table 4 at 37 DAT, which is one day before the SPAD measurement. At this time point, the control and T1 treatments showed significantly lower nitrate values, whereas T2 and T3 showed the highest values. This indicates that T2 and T3 improved chlorophyll synthesis, likely due to better nitrogen uptake efficiency (Table 3). At 53 DAT, a significant increase in SPAD values was observed across treatments. The control and T1 values remained relatively low, while T3 showed substantial increases, suggesting that higher EC levels positively influenced chlorophyll content and photosynthetic efficiency. There was no significant difference between T2 and the other treatments. This improvement can be attributed to enhanced availability of key nutrients such as nitrogen and potassium as presented in Table 4.

Table 6. Impact of different EC levels on the relative chlorophyll content (SPAD) at various DAT

Treatment	**24 DAT**	**38 DAT**	**53 DAT**
Control	33.8 ± 1.70a	37.3 ± 0.93c	53.3 ± 2.70b
T1	33.2 ± 2.63a	37.6 ± 2.13c	52.5 ± 2.15b
T2	34.8 ± 1.20a	44.6 ± 1.25b	56.3 ± 2.32ab
T3	37.1 ± 4.47a	47.9 ± 1.75a	60.1 ± 2.45a

Data is presented as mean ± standard deviation Means followed by different letters within each column are significantly different according to Duncan's Multiple Range Test (DMRT) at $p < 0.05$ (n=5). Where; Control= EC0.5 and water, T1= an EC 0.5; T2 = an EC 1.5, and T3 = an EC 2.5

Water use efficiency and fertilizer use efficiency under different EC levels

Figure 7 shows the effects of varying EC levels on water use efficiency (WUE) and fertilizer use efficiency (FUE) in cucumber plants. WUE values ranged from 2.22 to 2.82 g L^{-1}/plant, with the highest efficiency observed in treatment T2 (2.82 g L^{-1} /plant), which was significantly greater than those recorded in the control and T1 treatments. However, exposure to the highest EC level (T3) resulted in a slight reduction in WUE. Apparent FUE declined with increasing EC, likely due to ion accumulation and reduced partitioning into harvestable biomass. FUE values ranged from 1.4 to 7.5 g DW g^{-1} fertilizer, with the highest value observed in treatment T1 (7.5 g DW g^{-1} fertilizer). The control and T2 treatments had FUE values of 2.8 and 2.6 g DW g-$^{-1}$ fertilizer, respectively. As EC levels increased, FUE progressively declined, reaching its lowest value under T3 conditions. These results suggest that moderate EC levels, as in T2, enhance WUE, while excessive salinity impairs both water and nutrient uptake, likely due to osmotic stress and ion toxicity. Elevated EC levels may disrupt osmotic balance, reduce nutrient uptake efficiency, and induce toxicity, ultimately inhibiting plant growth (do Carmo *et al.*, 2024). Although WUE peaked under moderate EC (T2), the concurrent decline in FUE suggests that cucumber plants may prioritize water acquisition over nutrient assimilation under such conditions. This response may be attributed to enhanced stomatal regulation or increased aquaporin activity, which facilitate water uptake under moderate osmotic stress. Simultaneously, the reduced FUE may result from downregulation or impaired activity of root nutrient transporters, suggesting a shift in resource allocation favoring water acquisition over nutrient assimilation (Gonzalez-Dugo *et al.*, 2012). Conversely, the higher FUE observed in T1 and the control treatments implies a more balanced nutrient uptake (He *et al.*, 2024). While T3 treatment was associated with increased total nutrient uptake, its corresponding FUE was markedly reduced, reinforcing the detrimental effects of high EC levels on nutrient use efficiency and overall plant performance.

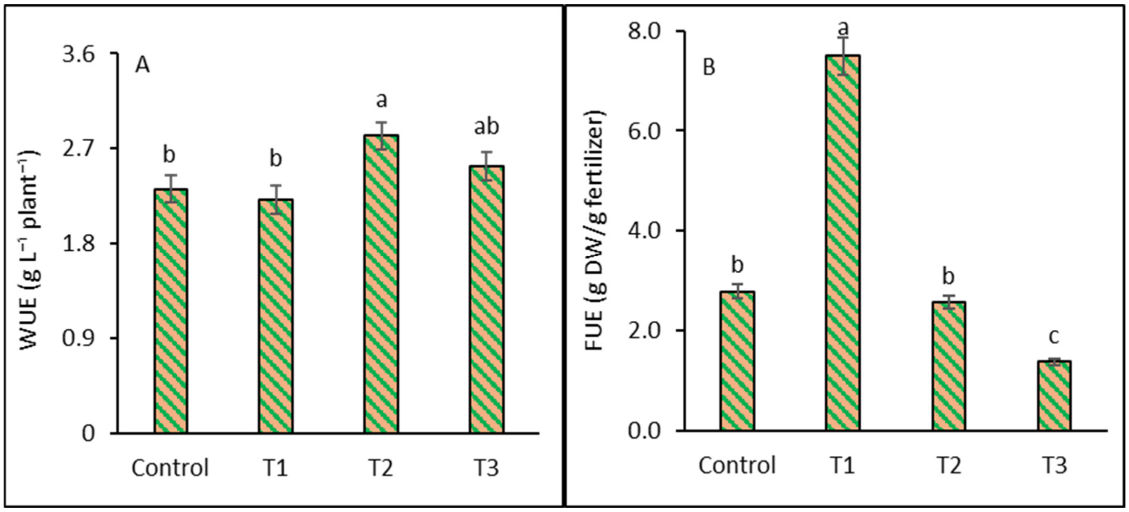


Figure 7. Impact of varying EC levels on water use efficiency (WUE) and fertilizer use efficiency (FUE) Treatments include Control (EC 0.5 + water), T1 (EC 0.5), T2 (EC 1.5), and T3 (EC 2.5); Different letters on the bars indicates the significant different at $p < 0.05$ (n = 3) among the treatments and the error bars indicates the standard deviation

The findings on WUE and FUE provide insights into their relationship with cucumber fruit yield and quality under different EC levels. Treatment T2, which showed the highest WUE, also produced the greatest fruit fresh and dry weights, suggesting a positive link between efficient water use and improved fruit biomass. However, despite this high WUE, T2 had a relatively low FUE, indicating a possible imbalance between water and nutrient utilization at moderate EC levels. In contrast, T1 showed higher FUE but lower WUE and fruit biomass, suggesting that efficient nutrient use alone did not lead to improved yield. The lowest FUE recorded under T3 conditions further highlights that excessive EC negatively affects nutrient efficiency, likely due to osmotic stress and ion toxicity (He *et al.*, 2024).

Correlation analysis of growth, physiological, and stress responses traits in cucumber

Correlation analysis revealed several statistically significant relationships among irrigation, drainage, and various morphological, physiological, and fruit quality traits of cucumbers grown under different EC levels (Figure 8 and Table A1).

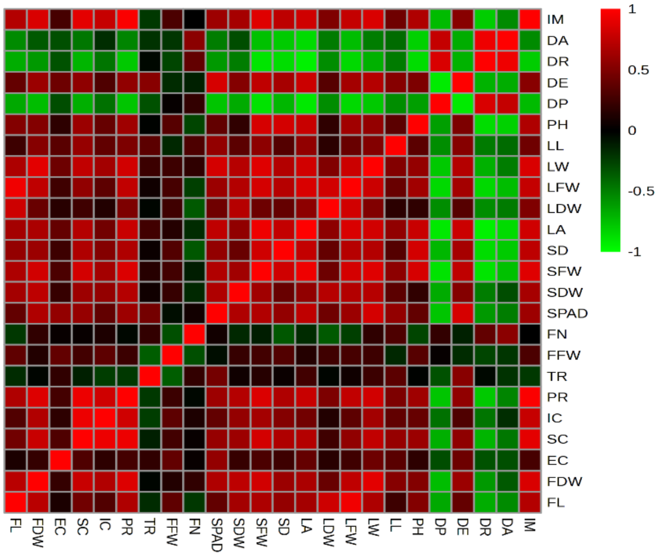


Figure 8. Heatmap illustrating the correlations among the evaluated parameters
The color gradient ranges from green, indicating negative correlations, to red, representing positive correlations; Where, IM = irrigation amount, DA = drainage amount, DR = Drainage rate, DE = drainage EC, DP = Drainage pH, PH = Plant height, LL = Leaf length, LW = leaf width, LFW = leaf fresh weight, LDW = leaf dry weight, LA = leaf area, SD = stem diameter, SFW = stem fresh weight, SDW = stem dry weight, SPAD = relative chlorophyll content, FN = fruit number, FFW = fruit fresh weight, TR = transpiration rate, PR = photosynthesis rate, IC = Intercellular CO_2 concentration, SC = Stomatal conductance, EC = electrolyte leakage, FDW = Fruit dry weight and FL = Fruit length

Among the most noteworthy findings, stem fresh weight (SFW) exhibited a very strong positive correlation with leaf area (LA) ($r = 0.96, p < 0.001$), suggesting that plants with larger leaf areas accumulate more stem biomass. This indicates that vigorous vegetative growth, particularly leaf expansion, plays a crucial role in supporting stem development (Kalve *et al.*, 2014). Similarly, the photosynthetic rate (PR) was strongly and positively associated with irrigation amount (IM) ($r = 0.93, p < 0.001$), highlighting the critical role of water availability in enhancing photosynthetic efficiency. Adequate irrigation appears to directly promote gas exchange and photosynthate production, which are essential for optimal plant growth and productivity (Kabir *et al.*, 2021). Another significant relationship was observed between fruit length (FL) and leaf fresh weight (LFW) ($r = 0.92, p < 0.001$). Higher leaf fresh weight is directly related to leaf size. Larger leaves contribute to increased fruit elongation by enhancing the supply of assimilates (Li *et al.*, 2022). Fruit dry weight (FDW) also showed a strong positive correlation with leaf width (LW) ($r = 0.91, p < 0.001$), emphasizing the contribution of leaf morphology to fruit development and final yield. Furthermore, intercellular CO_2 concentration (IC) correlated strongly with photosynthetic rate ($r = 0.90, p < 0.001$), reflecting the close physiological link between internal CO_2 availability and photosynthetic activity (Shin *et al.*, 2025). In contrast, drainage rate

(DR) showed strong negative correlations with key growth parameters. Leaf area (LA) was negatively correlated with DR (r = -0.93, $p < 0.001$), indicating that excessive drainage may limit leaf expansion due to reduced water retention in the root zone. Similarly, stem fresh weight (SFW) had a strong negative relationship with DR (r = -0.91, $p < 0.001$), suggesting that high drainage rates can inhibit overall plant biomass accumulation. Stomatal conductance (SC) also decreased with increasing DR (r = -0.87, $p < 0.001$), implying that water loss through excessive drainage leads to partial stomatal closure, restricting gas exchange and potentially reducing photosynthetic capacity. Furthermore, a strong positive correlation was observed between stem dry weight (SDW) and leaf dry weight (LDW) (r = 0.87, p < 0.001), indicating coordinated growth between the two organs. Moreover, stem fresh weight (SFW) and plant height (PH) were positively associated (r = 0.86, $p < 0.001$), strengthening the idea that taller plants tend to develop greater biomass. Collectively, these results indicate that water management practices, particularly irrigation and drainage, have a significant impact on both vegetative and reproductive growth parameters under varying levels EC. Optimizing irrigation while minimizing excessive drainage is essential for improving physiological performance and maximizing yield in cucumbers grown under different EC levels in controlled pot soil conditions.

Identification of relationships between treatments and parameters using principal component analysis

Principal component analysis (PCA) was performed to explore the relationships between the evaluated parameters and treatment groups. For PCA analysis, we used three replications per treatment for each parameter. The first five principal components (PCs) accounted for a cumulative variance of 91.1%, with PC1 and PC2 contributing 48.29% and 23.69% of the total variance, respectively (Table 7). PC1, which explained the largest portion of the variability, was primarily associated with irrigation, drainage, vegetative growth, and physiological efficiency traits. The ten most contributor variables in PC1, based on their high absolute loading values, were stomata conductance (SC), shoot fresh weight (SFW), leaf area (LA), drainage rate (DR), leaf fresh weight (LFW), intercellular CO_2 concentration (IC), irrigation amount (IM), photosynthetic rate (PR), drainage EC (DE), and drainage pH (DP) (Table 7). PC2, which explained 23.69% of the total variance, was mainly driven by traits related to fruit development and physiological characteristics. The ten most contributing variables to PC2 were transpiration rate (TR), fruit fresh weight (FFW), leaf length (LL), fruit number (FN), SPAD, DE, electrolyte leakage (EC), Fruit length (FL), plant height (PH), and Leaf dry weight (LDW) (Table 7). These variables indicate that PC2 explains variation related to water relations, fruit load, and photosynthetic pigment content.

In the PCA biplot, the control group was distinctly positioned in the left quadrant, closely associated with parameters such as DA and DR, suggesting that plants under standard conditions maintained stable drainage characteristics (Figure 9). T1 is positioned near the center, showing moderate effects on plant physiological traits. T2 and T3 treatments are positioned further along PC1 and PC2, demonstrating significant differentiation from the control (Figure 9). Particularly, T3 is associated with increased SC, TR, and DE, indicating a physiological response to elevated EC effects (Figure 9). Higher EC levels typically induce osmotic stress, leading to enhanced transpiration and changes in stomatal behavior as the plant attempts to regulate water loss. Traits such as FFW, fruit dry weight (FDW), LL, LDW and LFW are more aligned with T2, suggesting that moderate EC level might have a stimulatory effect on fruit and vegetative growth, possibly through osmotic adjustments or stress-induced metabolic changes. However, high electrolyte leakage might negatively impact biomass accumulation, as evidenced by the grouping of electrolyte leakages with T3, indicating higher cellular damage due to EC induced oxidative stress. The findings suggest that while T2 might promote certain growth parameters, T3 induces physiological stress, disrupting plant water relations, increasing membrane damage, and reducing overall biomass production. These results align with previous studies indicating that highest EC levels affect plant metabolism, particularly by altering ion homeostasis and water uptake, leading to differential impacts on plant growth depending on the severity of stress (Lam *et al*., 2020).

Table 7. Loadings of five principal components (PC1 to PC5) with eigenvalues greater than 1, illustrating the contributions of various irrigation, drainage, morphological, physiological, and yield-related variables in cucumbers grown under different EC levels

Variables	PC1	PC2	PC3	PC4	PC5
IM	**0.91**	-0.19	0.11	0.27	0.06
DA	-0.83	-0.06	0.45	0.25	0.07
DR	**-0.94**	0.11	0.30	-0.03	0.00
DE	**0.84**	**0.31**	-0.31	0.02	-0.17
DP	**-0.87**	-0.19	0.07	0.12	0.31
PH	0.69	**-0.22**	-0.45	0.36	0.12
LL	0.55	**0.60**	-0.03	0.20	0.16
LW	0.86	0.15	0.35	-0.03	0.23
LFW	**0.93**	-0.18	0.22	-0.09	-0.06
LDW	0.74	**-0.29**	0.39	-0.40	-0.09
LA	**0.94**	0.12	-0.14	-0.01	0.05
SD	0.77	-0.21	-0.36	-0.04	-0.06
SFW	**0.94**	0.05	-0.11	0.09	-0.01
SDW	0.68	-0.01	0.47	-0.48	-0.18
SPAD	0.71	**0.47**	0.13	-0.28	0.15
FN	-0.26	**0.54**	0.50	0.47	0.35
FFW	0.08	**-0.72**	-0.09	-0.28	0.58
TR	-0.11	**0.84**	-0.16	-0.40	-0.08
PR	**0.91**	-0.08	0.12	0.20	-0.07
IC	**0.93**	-0.12	-0.01	0.23	0.05
SC	**0.94**	0.15	-0.17	0.21	0.05
EC	0.37	**0.25**	-0.14	-0.35	0.74
FDW	0.80	0.14	0.51	0.21	-0.05
FL	0.79	**-0.40**	0.41	0.02	-0.04
Eigenvalues	9.44	6.42	2.24	1.99	1.31
Variance	48.29	23.69	8.36	6.29	5.47

Where, IM = irrigation amount, DA = drainage amount, DR = Drainage rate, DE = drainage EC, DP = Drainage pH, PH = Plant height, LL = Leaf length, LW = leaf width, LFW = leaf fresh weight, LDW = leaf dry weight, LA = leaf area, SD = stem diameter, SFW = stem fresh weight, SDW = stem dry weight, SPAD = relative chlorophyll content, FN = fruit number, FFW = fruit fresh weight, TR = Transpiration rate, PR = photosynthesis rate, IC = Intercellular CO$_2$ concentration, SC = Stomatal conductance, EC = electrolyte leakage, FDW = Fruit dry weight and FL = Fruit length; Bolded values in PC1 and PC2 represent the top ten variables with the highest contributions

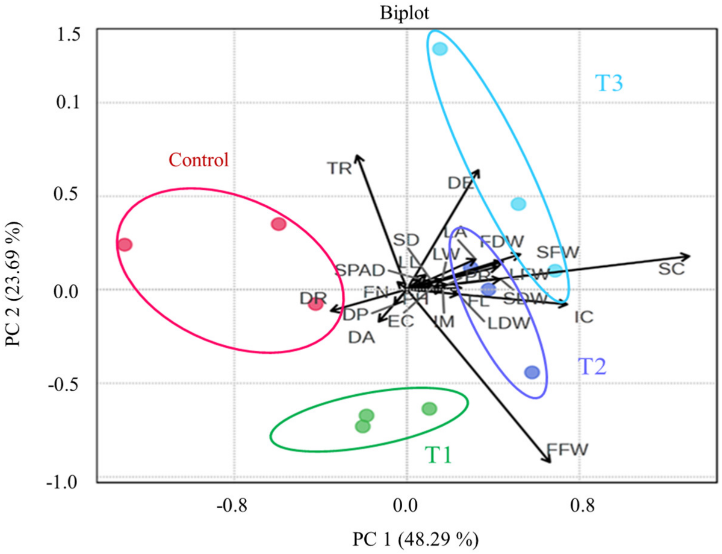


Figure 9. Principal component analysis biplot showing the distribution of different treatments and their associations with physiological and morphological traits under varying electrical conductivity (EC) levels. The first two principal components, PC1 and PC2, explain 48.29% and 23.69% of the total variance, respectively

Where, IM = irrigation amount, DA = drainage amount, DR = Drainage rate, DE = drainage EC, DP = Drainage pH, PH = Plant height, LL = Leaf length, LW = leaf width, LFW = leaf fresh weight, LDW = leaf dry weight, LA = leaf area, SD = stem diameter, SFW = stem fresh weight, SDW = stem dry weight, SPAD = relative chlorophyll content, FN = fruit number, FFW = fruit fresh weight, TR = Transpiration rate, PR = photosynthesis rate, IC = Intercellular CO_2 concentration, SC = Stomatal conductance, EC = electrolyte leakage, FDW = Fruit dry weight and FL = Fruit length

Conclusion

This study evaluated the effects of different EC levels on cucumber growth performance in pot soil under a controlled environment. Significant differences were observed in irrigation dynamics, growth traits, biomass accumulation, and fruit quality parameters among the treatments. Cucumber plants grown under treatment T1 and the control exhibited higher drainage rates and lower irrigation volume, along with lower drainage EC and higher drainage pH. These plants also demonstrated reduced growth performance, fruit yield, and biomass accumulation, coupled with increased electrolyte leakage, suggesting potential physiological stress. In contrast, plants in treatment T3 showed higher irrigation volume and lower drainage rates, EC, and pH. Despite showing improvements in certain growth-related parameters, these plants exhibited reduced fruit number and fruit fresh weight, indicating a possible compromise between vegetative growth and reproductive output. In this work, T2 yielded the most balanced results, with optimal growth performance and fruit-related parameters, suggesting that a moderate EC level (1.5 $dS \cdot m^{-1}$) may promote both vegetative and reproductive growth, possibly through osmotic adjustments or stress-induced metabolic adaptations. Although gas exchange parameters were enhanced by EC treatments compared to the control, the differences among T1, T2, and T3 were not statistically significant. However, strong positive correlations were observed among key growth-related traits, including plant height, leaf size, shoot biomass, and fruit yield. Principal component analysis further supported that fruit fresh weight, fruit dry weight, and leaf-related traits were more aligned with T2, showing the potential benefits of a moderate EC level. Future research should focus on refining EC management strategies tailored to each developmental stage of cucumbers while considering environmental variables and economic feasibility.

Authors' Contributions

Conceptualization KYC, MK and GR; Data curation MK and GR; Formal analysis MZ and MK; Funding acquisition KYC; Investigation MK and MGR; Methodology KYC, MK and MGR; Project administration KYC; Resources KYC; Software KYC; Supervision KYC; Validation KYC; Visualization KYC; Writing – MZ, MK and MGR; Writing - review and editing MZ and KYC.

All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

Not applicable.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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Appendix

Table A1. Correlation among evaluated irrigation, drainage, morphological, and physiological parameters

r	IM	DA	DR	DE	DP	PH	LL	LW	LFW	LDW	LA	SD	SFW	SDW	SPAD	FN	FFW	TR	PR	IC	SC	EC	FDW	FL
IM	1																							
DA	-0.38	1																						
DR	-0.81**	0.79**	1																					
DE	0.35	-0.68*	-0.57	1																				
DP	-0.32	0.75**	0.59*	-0.63*	1																			
PH	0.62*	-0.68*	-0.83***	0.42	-0.53	1																		
LL	0.33	-0.24	-0.5	0.26	-0.3	0.39	1																	
LW	0.81**	-0.35	-0.70*	0.52	-0.33	0.54	0.56	1																
LFW	0.75**	-0.62*	-0.82**	0.49	-0.64*	0.59*	0.41	0.80**	1															
LDW	0.5	-0.38	-0.48	0.15	-0.38	0.1	0.12	0.5	0.81**	1														
LA	0.75**	-0.79**	-0.93***	0.65*	-0.63*	0.79**	0.55	0.78**	0.82**	0.46	1													
SD	0.69*	-0.59*	-0.79**	0.76**	-0.43	0.65*	0.35	0.77**	0.70*	0.35	0.72**	1												
SFW	0.78**	-0.69*	-0.91***	0.60*	-0.64*	0.86***	0.57	0.82**	0.84***	0.41	0.96***	0.77**	1											
SDW	0.61*	-0.23	-0.46	0.23	-0.4	0.14	0.33	0.72**	0.80**	0.87***	0.51	0.45	0.54	1										
SPAD	0.55	-0.49	-0.59*	0.70*	-0.38	0.38	0.52	0.83***	0.60*	0.38	0.72**	0.70*	0.66*	0.59*	1									
FN	-0.04	0.52	0.29	-0.19	0.48	-0.21	0.39	0.25	-0.21	-0.31	-0.1	-0.2	-0.07	-0.08	0.12	1								
FFW	0.4	-0.06	-0.38	0.14	0.01	0.45	-0.01	0.35	0.31	0.13	0.27	0.49	0.34	0.16	0.18	-0.26	1							
TR	-0.55	-0.2	0.2	0.45	-0.23	-0.21	0.25	-0.13	-0.16	-0.22	0.01	-0.03	-0.06	-0.15	0.19	0.15	-0.39	1						
PR	0.93***	-0.33	-0.76**	0.46	-0.38	0.47	0.48	0.80**	0.72**	0.5	0.72**	0.70*	0.75**	0.69*	0.62*	0	0.3	-0.33	1					
IC	0.83***	-0.13	-0.64*	0.28	-0.13	0.5	0.49	0.72**	0.51	0.23	0.58*	0.67*	0.68*	0.51	0.49	0.12	0.42	-0.35	0.90***	1				
SC	0.81**	-0.54	-0.87***	0.62*	-0.43	0.69*	0.68*	0.80**	0.64*	0.25	0.85***	0.80**	0.85***	0.44	0.76**	0.04	0.32	-0.1	0.86***	0.82**	1			
EC	0.23	-0.2	-0.32	0.47	-0.09	0.16	0.32	0.41	0.23	0.11	0.41	0.36	0.29	0.18	0.59*	0.04	0.57	0.18	0.31	0.24	0.46	1		
FDW	0.73**	-0.17	-0.56	0.39	-0.38	0.41	0.58*	0.91***	0.76**	0.49	0.59*	0.64*	0.69*	0.73**	0.69*	0.28	0.22	-0.18	0.76**	0.64*	0.68*	0.21	1	
FL	0.68*	-0.37	-0.62*	0.24	-0.52	0.46	0.22	0.68*	0.92***	0.80**	0.57	0.53	0.64*	0.77**	0.36	-0.19	0.32	-0.37	0.59*	0.38	0.4	0.02	0.75**	1

Where, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$, IM = irrigation amount, DA = drainage amount, DR = Drainage rate, DE = drainage EC, DP = Drainage pH, PH = Plant height, LL = Leaf length, LW = leaf width, LFW = leaf fresh weight, LDW = leaf dry weight, LA = leaf area, SD = stem diameter, SFW = stem fresh weight, SDW = stem dry weight, SPAD = relative chlorophyll content, FN = fruit number, FFW = fruit fresh weight, TR = transpiration rate, PR = photosynthesis rate, IC = Intercellular CO_2 concentration, SC = Stomatal conductance, EC = electrolyte leakage, FDW = Fruit dry weight and FL = Fruit length