



RESEARCH ARTICLE

# Aeroponic cultivation of chrysanthemum (*Chrysanthemum morifolium*): Influence of electrical conductivity on morphological, physiological and yield traits

Mangaiyarkarasi R\* & Baranidharan R

School of Agricultural Sciences, Dhanalakshmi Srinivasan University, Trichy 621 112, Tamil Nadu, India

\*Correspondence email - [mangaiyarkarasir.agri@dsuniversity.ac.in](mailto:mangaiyarkarasir.agri@dsuniversity.ac.in)

Received: 29 April 2025; Accepted: 09 July 2025; Available online: Version 1.0: 12 August 2025

**Cite this article:** Mangaiyarkarasi R, Baranidharan R. Aeroponic cultivation of chrysanthemum (*Chrysanthemum morifolium*): Influence of electrical conductivity on morphological, physiological and yield traits. Plant Science Today (Early Access). <https://doi.org/10.14719/pst.9200>

## Abstract

The present study investigates the influence of different electrical conductivity (EC) levels (0.5 EC and 1 EC) on the morphological, physiological and yield parameters of chrysanthemum grown under an aeroponic system. Significant differences were observed in plant height ( $V_2$  - 37.34 cm), stem diameter ( $V_1$  - 1.92 cm), number of leaves, internodal length, root length ( $V_2$  - 44.31 cm), root fresh and dry weight ( $V_5$  - 10.15 g), fresh and dry weight of the plant ( $V_2$  - 140.61 g), leaf area, transpiration rate, photosynthetic rate, stomatal conductance, total chlorophyll content and biochemical parameters such as soluble protein content ( $V_5$  - 67.29 mg g<sup>-1</sup>), catalase activity ( $V_5$  - 38.81  $\mu$ g H<sub>2</sub>O g<sup>-1</sup> min<sup>-1</sup>) and peroxidase activity. Flowering characteristics, including number of flowers per plant ( $V_4$  - 56.94 number), flower diameter ( $V_3$  - 6.62 cm), vase life and weight of cut stem ( $V_3$  - 5.53 g), were also significantly affected. The results indicate that the aeroponic system with optimized EC levels enhances growth and flowering performance in chrysanthemum.

**Keywords:** aeroponic system; chrysanthemum; electrical conductivity; flowering characteristics; morphological parameters; physiological parameters

## Introduction

Chrysanthemum (*Chrysanthemum morifolium*) is an economically important ornamental plant widely cultivated for its aesthetic and commercial value. Optimizing growth conditions, particularly nutrient management through electrical conductivity (EC) regulation, is crucial for enhancing plant performance. Aeroponic cultivation offers precise control over nutrient delivery, enabling better growth and flowering. However, limited research exists on the impact of different EC levels on chrysanthemum under aeroponic conditions.

The EC and pH are both good indicators. The EC should not be more than 2.0 mS/cm. Crop output responds positively in increasing concentrations until it reaches an optimal level, further increase in concentration often result in yield decrease (luxury use) (1). Yield may be reduced if concentrations are excessively high toxicity. The total nutrient solution ion concentration determines the plant's growth, development and productivity. Osmotic pressure is determined by the total quantity of ion in the nutritional solution (2). The quantity of nutrient concentration in nitrate fertilisers, such as calcium nitrate and potassium nitrate, increases the mean total number of mini tubers collected decreased, but treatments that utilised lesser nitrate fertilisers produced higher yield (3). This study aims to assess the morphological and physiological responses of chrysanthemum to varying EC levels under

aeroponic condition, providing insights into optimal growth conditions for improved productivity.

## Materials and Methods

### Experimental design

The study was conducted in a controlled aeroponic growing system with two EC levels (0.5 - E1 and 1 - E2) and was predicted using preliminary studies conducted. Five chrysanthemum varieties [ $V_1$  - Lorenzo (green colour),  $V_2$  - Prius Pink (peach colour),  $V_3$  - Furore (white colour),  $V_4$  - Merel Gold (white colour) and  $V_5$  - Lotte Orange (red colour)] were collected from local nursery, conoor, Tamil Nadu used in a factorial randomized block design with three replications.

### Details of polyhouse

The naturally ventilated polyhouse (NVP) was oriented in East-West direction with the central height of 5.7 m. The frame was constructed with the galvanized iron pipe. A rollable 150 g/m<sup>2</sup> (GSM) white colour polyethylene sheet, flap was provided on all the sides of the polyhouse to control the ventilation area and to cover the side vents during rainy season and to avoid the entry of rainwater. The temperature (25-30 °C) and relative humidity (70-85 %) inside the polyhouse was maintained by watering and overhead heating. 0.5 horsepower motor was used for pumping the water which was conveyed to the mainline/

laterals after filtering through screen filter. In the solution tank water and fertilizers are mixed, water was taken for spraying through laterals/mainline of low-density polyethylene (LDPE) material. Along the laterals, emitters/sprinklers with discharge rate of 7 L/hr at 4 bar pressure was assembled. Whereas misting interval was 2 min spray and 1 min off conditions given throughout the study.

### Preparation of nutrient solution

The nutrients used were calcium nitrate, potassium nitrate, mono-potassium phosphate, magnesium sulphate, manganese sulphate, zinc sulphate, copper sulphate, chelates of iron and boron (IAC Krishitech Private Limited).

### Crop growth stage and day length manipulation

Specific day length was imposed for different growth stages, such as vegetative stage occurred during long day conditions and reproductive stage was taken place at short day conditions. Day length was controlled first by determining the length of the prevailing natural day light conditions and then providing artificial light or dark condition for the required time.

In winter (December to March), natural day length of 9 hr was observed. For imposing long day conditions, artificial light was given for 4 hr (i.e., 9 + 4 = 13 h photoperiod), under tropical conditions of Madurai. Likewise for imposing short day, dark screening with UV stabilized black polythene sheet of 400 gauge was done and it was ensured that the light level was below 20 Watts.

### Growth parameters measured

Plant height, stem diameter, number of leaves, internodal length, root length, root fresh weight and root dry weight were recorded at 30, 60 and 90 days after transplanting (DAT) based on crop growth stages.

### Physiological and biochemical analysis

Leaf area, leaf area index, transpiration rate, photosynthetic rate (measured using LI-6400XT, LI-COR Inc., Nebraska, USA), stomatal conductance, total chlorophyll content and chlorophyll a and b were analyzed (4, 5). Soluble protein

content and catalase and peroxidase activity were analyzed using standard protocols (6, 7).

### Flowering parameters

Number of flowers per plant, flower diameter, vase life and weight of cut stem were measured to evaluate the impact of EC levels on flowering performance.

### Statistical analysis

Data were subjected to analysis of variance (ANOVA) and significant differences were analysed statistically by Agricultural Research Statistics (AGRES) software to interpret the results.

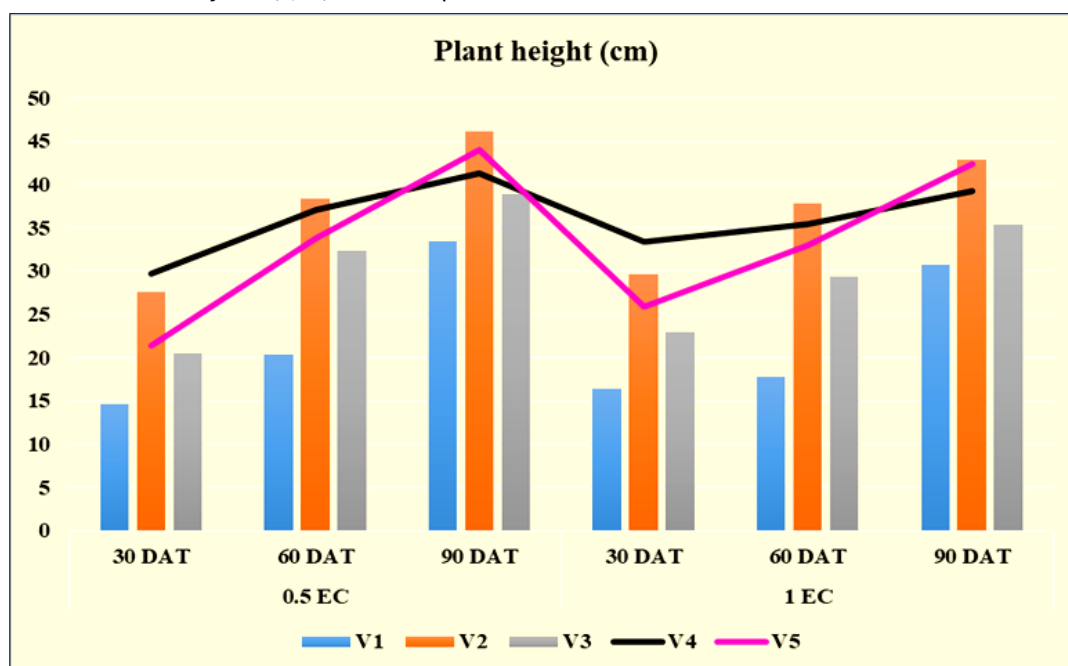
## Results and Discussions

### Plant height

Among the varieties, V<sub>2</sub> recorded the highest plant height (37.34 cm), while V<sub>1</sub> recorded the minimum plant height of 22.80 cm at the 0.5 EC level (Fig. 1). At the 1 EC level, V<sub>2</sub> recorded the utmost plant height (36.76 cm), while the lowest plant height was recorded in V<sub>1</sub> (21.60 cm). Among the interactions (V × E × D), V<sub>2</sub>E<sub>1</sub> recorded the maximum plant height at 90 DAT (46.09 cm), followed by V<sub>5</sub>E<sub>1</sub> (43.93 cm), while V<sub>1</sub>E<sub>2</sub> recorded the minimum plant height (30.72 cm). Similar findings were reported in potato (8). The findings of this study are consistent with those found on tomato plants, where plant height, leaf number and stomatal density were reduced as electrical conductivity increased (9). Reduced osmotic pressure of EC of the greenhouse tomato cultivars was the most important factor for growth and development (10). The electrical conductivity (EC) of the nutrient solution determines the success of aeroponics.

### Stem diameter

Among the varieties, V<sub>1</sub> recorded the highest stem diameter (1.92 cm), while V<sub>4</sub> recorded the lowest stem diameter (1.64 cm) at 0.5 EC level (Table 1). Maximum stem diameter was recorded in V<sub>1</sub> (1.79 cm) and the minimum stem diameter was observed V<sub>4</sub> (1.54 cm) at 1 EC level. Among the interactions (V × E × D), V<sub>1</sub>E<sub>1</sub> recorded the maximum stem diameter (2.19 cm), followed by



**Fig. 1.** Effect of electrical conductivity on plant height grown under aeroponic method of cultivation.

**Table 1.** Effect of electrical conductivity on stem diameter grown under aeroponic method of cultivation.

	Stem diameter (cm)							
	E <sub>1</sub> (0.5 EC)				E <sub>2</sub> (1 EC)			
	30 DAT	60 DAT	90 DAT	Mean	30 DAT	60 DAT	90 DAT	Mean
V <sub>1</sub>	1.65	1.93	2.19	1.92	1.15	1.83	1.97	1.79
V <sub>2</sub>	1.37	1.68	2.03	1.69	0.86	1.56	2.02	1.62
V <sub>3</sub>	1.42	1.70	1.87	1.66	1.36	1.62	1.85	1.61
V <sub>4</sub>	1.29	1.79	1.85	1.64	1.18	1.32	1.59	1.54
V <sub>5</sub>	1.35	1.88	1.93	1.72	1.32	1.77	1.84	1.64
Mean	1.42	1.80	1.97	1.73	1.35	1.69	1.89	1.64
Factors	Variety (V)	Electrical conductivity (E)	V × E	Days interval (D)	V × D	E × D	V × E × D	
Critical Difference	0.054	0.034	0.077	0.042	0.094	0.060	0.133	
Standard Deviation	0.027	0.017	0.038	0.021	0.047	0.030	0.067	

V<sub>1</sub>:Lorenzo (Green colour - Pompon type), V<sub>2</sub>:Prius Pink (Peach colour - Spray type), V<sub>3</sub>:Furore (White colour - Spray type), V<sub>4</sub>:Merel Gold (Yellow colour - Spray type), V<sub>5</sub>:Lotte Orange (Red colour - Spray type), E<sub>1</sub>:0.5 EC, E<sub>2</sub>:1 EC.

V<sub>2</sub>E<sub>1</sub> (2.03 cm), while V<sub>4</sub>E<sub>2</sub> observed the minimum stem diameter (1.59 cm) at 90 DAT. These findings suggest that V<sub>1</sub> is more tolerant or responsive to varying EC levels, maintaining higher stem thickness which is typically associated with better nutrient and water transport, potentially contributing to improved overall plant vigor.

### Number of leaves

Among the varieties, V<sub>4</sub> recorded a greater number of leaves (73.89), followed by V<sub>2</sub> (62.88) and V<sub>1</sub> recorded the minimum (34.58) at the 0.5 EC level (Table 2). At the 1 EC level, V<sub>4</sub> (54.21) recorded the highest number of leaves, V<sub>1</sub> recorded the lowest number of leaves (27.99). Among the interactions (V × E × D), V<sub>4</sub>E<sub>1</sub> recorded a greater number of leaves (105.28) recorded the least number of leaves at 90 DAT. Highest number of leaves, stem weight, flower diameter and stem diameter at lower EC concentration in rose (11). The result was different to the report in which root length; plant height was higher in higher concentration of nutrients in potato (3). It can be caused by osmotic stress condition in the root zone, resulting in decreased leaf turgor and decreased expansion of leaves (12).

### Root length

At the 0.5 EC level, the treatment V<sub>2</sub> had the longest root length (44.31 cm), followed by the treatment V<sub>4</sub>, which had the longest root length (35.94 cm) and the treatment V<sub>1</sub> which recorded

shortest root length (31.03 cm). At the 1 EC level, the treatment V<sub>2</sub> recorded the highest root length of 44.11 cm and the treatment V<sub>1</sub> recorded the minimum root length of 30.17 cm. Among the interactions, the treatment V<sub>2</sub>E<sub>1</sub> recorded supreme root length of 68.48 cm and V<sub>1</sub>E<sub>2</sub> recorded minimum root length of 35.19 cm at 90 DAT respectively (Fig. 2). Root length was higher under lowest EC and lower in the highest EC. The size of the root system was necessary to achieve maximum nitrogen uptake which is lowered at high nitrogen concentrations. This reduction in root size indicates a functional balance between root and shoot growth (13).

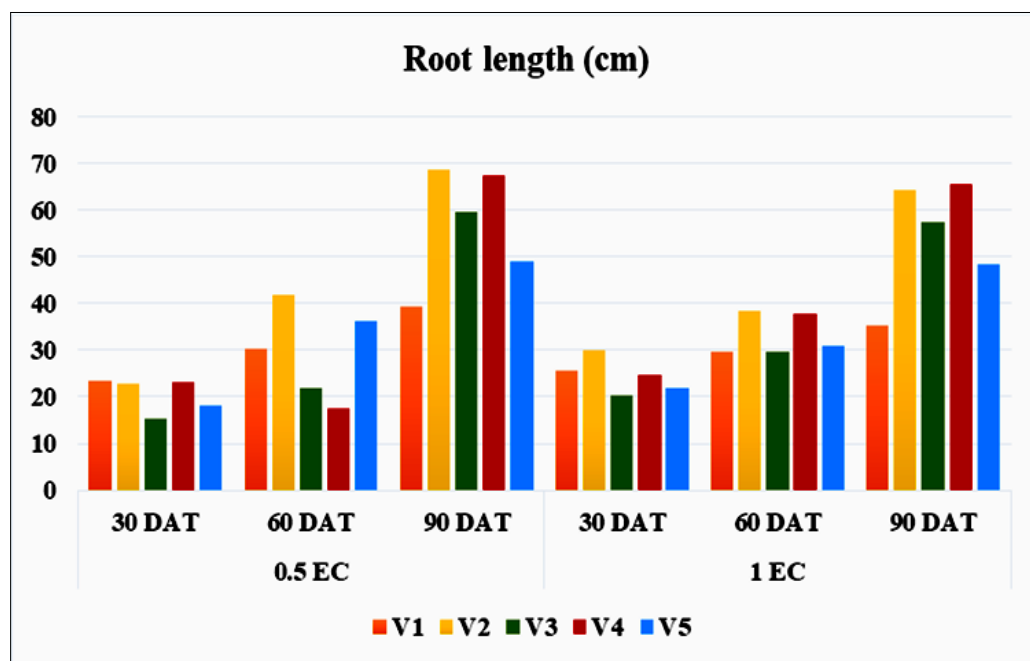
### Root fresh weight and root dry weight

The greatest root fresh weight was observed in V<sub>5</sub> (10.15 g), followed by V<sub>4</sub> (8.40 g), while the lowest root fresh weight was reported in V<sub>1</sub> (6.72 g). Among the interactions, the treatment V<sub>5</sub>E<sub>2</sub> had the highest root fresh weight of 10.36 g, followed by V<sub>5</sub>E<sub>1</sub> with a root fresh weight of 9.94 g and treatment V<sub>1</sub>E<sub>1</sub> recorded the lowest root fresh weight of 6.68 g. In respect to root dry weight, the maximum root dry weight was observed in V<sub>1</sub> (1.84 g), followed by V<sub>2</sub> (1.41 g) and the minimum root dry weight was reported in V<sub>4</sub> (1.21 g). Among the interactions, maximum root dry weight was recorded in V<sub>1</sub>E<sub>2</sub> (1.94 g), followed by V<sub>1</sub>E<sub>1</sub> (1.73 g) and V<sub>3</sub>E<sub>2</sub> (1.05 g) recorded minimum root dry weight (Table 3).

**Table 2.** Effect of electrical conductivity on number of leaves grown under aeroponic method of cultivation.

	Number of leaves (number)							
	E <sub>1</sub> (0.5 EC)				E <sub>2</sub> (1 EC)			
	30 DAT	60 DAT	90 DAT	Mean	30 DAT	60 DAT	90 DAT	Mean
V <sub>1</sub>	14.63	35.56	53.55	34.58	10.38	26.91	46.68	27.99
V <sub>2</sub>	27.68	68.34	92.63	62.88	26.64	53.17	65.31	48.37
V <sub>3</sub>	18.54	42.89	63.16	41.53	17.39	30.58	41.56	29.84
V <sub>4</sub>	26.23	90.17	105.28	73.89	23.45	65.34	73.84	54.21
V <sub>5</sub>	16.89	38.36	60.37	38.54	15.69	29.87	53.57	33.04
Mean	20.79	55.06	75.00	50.29	18.71	41.17	56.19	38.69
Factors	Variety (V)	Electrical conductivity (E)	V × E	Days interval (D)	V × D	E × D	V × E × D	
Critical Difference	0.881	0.557	1.246	0.682	1.526	0.965	2.158	
Standard Deviation	0.440	0.278	0.623	0.341	0.763	0.482	1.078	

V<sub>1</sub>:Lorenzo (Green colour - Pompon type), V<sub>2</sub>:Prius Pink (Peach colour - Spray type), V<sub>3</sub>:Furore (White colour - Spray type), V<sub>4</sub>:Merel Gold (Yellow colour - Spray type), V<sub>5</sub>: Lotte Orange (Red colour - Spray type), E<sub>1</sub>:0.5 EC, E<sub>2</sub>:1 EC.



**Fig. 2.** Effect of electrical conductivity on root length grown under aeroponic method of cultivation.

**Table 3.** Effect of electrical conductivity on root fresh weight and root dry weight grown under aeroponic method of cultivation.

	Root fresh weight (g)			Root dry weight (g)		
	E <sub>1</sub> (0.5 EC)	E <sub>2</sub> (1 EC)	Mean	E <sub>1</sub> (0.5 EC)	E <sub>2</sub> (1 EC)	Mean
V <sub>1</sub>	6.68	6.75	6.72	1.73	1.94	1.84
V <sub>2</sub>	7.93	8.07	8.00	1.30	1.51	1.41
V <sub>3</sub>	7.28	7.39	7.34	1.39	1.05	1.22
V <sub>4</sub>	8.17	8.62	8.40	1.19	1.23	1.21
V <sub>5</sub>	9.94	10.36	10.15	1.23	1.37	1.30
Mean	8.00	8.24	8.12	1.37	1.42	1.39

Factors	Root fresh weight		Root dry weight	
	Critical Difference	Standard Deviation	Critical Difference	Standard Deviation
Variety (V)	0.099	0.047	0.061	0.029
Electrical conductivity (E)	0.067	0.030	0.039	0.018
V × E	0.140	0.067	0.086	0.041

V<sub>1</sub>:Lorenzo (Green colour - Pompon type), V<sub>2</sub>:Prius Pink (Peach colour - Spray type), V<sub>3</sub>:Furore (White colour - Spray type), V<sub>4</sub>:Merel Gold (Yellow colour - Spray type), V<sub>5</sub>:Lotte Orange (Red colour - Spray type), E<sub>1</sub>:0.5 EC, E<sub>2</sub>:1 EC.

The observed variations in root fresh and dry weights among different treatments indicate significant genotypic and environmental influences on root development. The highest root fresh weight recorded in V<sub>5</sub> suggests that this variety possesses a robust root system, likely contributing to improved nutrient and water uptake, which are crucial for plant growth and productivity (14, 15). The relatively lower fresh weight in V<sub>1</sub> may point to a less developed root system or slower initial growth, potentially reducing the plant's ability to adapt to abiotic stress.

The treatment interaction results further support this, with V<sub>5</sub>E<sub>2</sub> showing the highest root fresh weight (10.36 g), suggesting that V<sub>5</sub> not only has strong genetic potential but also responds favorably to the environmental conditions of E<sub>2</sub>. In contrast, the minimum value in V<sub>1</sub>E<sub>1</sub> (6.68 g) reflects the compounded impact of genotype and environment on below-ground biomass accumulation (16).

Interestingly, the trend in root dry weight differed from fresh weight, with V<sub>1</sub> showing the highest dry weight (1.84 g) despite having the lowest fresh weight. This indicates a higher

root tissue density or lower water content, which may be an adaptive trait for water conservation under stress conditions (17). The high dry weight values observed in V<sub>1</sub>E<sub>2</sub> and V<sub>1</sub>E<sub>1</sub> emphasize this variety's ability to maintain biomass investment in root systems under varying environmental conditions.

On the other hand, the lower dry weights observed in V<sub>4</sub> and V<sub>3</sub>E<sub>2</sub> may reflect a reduced allocation of resources to root development or a response to environmental constraints that limit root biomass accumulation (18). These differences are significant, as root dry weight has a direct correlation with plant anchorage, storage capacity and sustained nutrient absorption (19).

Overall, the results suggest that V<sub>5</sub> may be more suitable for conditions favoring rapid early growth and water-rich environments, while V<sub>1</sub>'s denser root system may confer a competitive advantage under drought or nutrient-limited conditions. Such information is essential for breeding and selecting varieties for specific agroecological zones or stress-prone areas (20, 21).

### Fresh weight and dry weight of the plant

The fresh weight of the plant was recorded higher in  $V_2$  (140.61 g), while the least fresh weight of the plant was recorded in  $V_4$  (101.06 g) given in Table 4. Among the interactions, the fresh weight of the plant was recorded the greatest in  $V_2E_1$  (142.98 g) and the minimum was recorded in  $V_4E_2$  (98.27 g). In respect to dry weight of the plant, the highest dry weight of the plant was recorded in  $V_2$  (18.61 g) and the lowest was recorded in  $V_5$  (13.41 g). Among the interactions, maximum dry weight was recorded in  $V_2E_1$  (21.29 g), followed by the  $V_1E_1$  (19.53 g) and the minimum was recorded in  $V_5E_2$  (10.24 g).

The total ions in the nutritional solution are represented by electrical conductivity. The EC concentration has an impact on nutrient absorption, tuber productivity and tuber quality at different stages of plant growth in potato (22). EC is incompatible with plant growth, can be hazardous to plants (23). Because of the reduced osmotic potential of the nutrient solution, the availability of ions in the nutrient solution increases. Higher in nutrient solution, EC leads to water deficit in crop (24).

### Leaf area and leaf area index per plant

For leaf area of the plant, the maximum leaf area of the plant was recorded in  $V_3$  (284.11 cm<sup>2</sup>) and the minimum was recorded in  $V_4$  (225.01 cm<sup>2</sup>). Among the interactions, highest leaf area was recorded in  $V_3E_1$  (401.74 cm<sup>2</sup>) and the lowest was recorded in  $V_3E_2$  (166.47 cm<sup>2</sup>), respectively (Table 5).

In respect to leaf area index per plant, the higher leaf area index per plant was recorded in  $V_3$  (0.355) and the lower was recorded in  $V_4$  (0.281). Among the interactions, maximum leaf area index per plant was recorded in  $V_3E_1$  (0.502) followed by  $V_2E_1$  (0.405) and minimum was recorded in  $V_3E_2$  (0.208). These findings are in line with earlier studies that reported genotypic differences in leaf area expansion and LAI due to inherent genetic potential and their interaction with the environment (25). The superior performance of  $V_3$  under  $E_1$  could be attributed to better adaptation or physiological responses such as higher stomatal conductance and efficient nutrient utilization, which are known to support enhanced leaf development. On the other hand, the poor performance under  $E_2$  suggests that either abiotic stresses like drought or

**Table 4.** Effect of electrical conductivity on fresh weight of plant and dry weight of plant grown under aeroponic method of cultivation.

	Fresh weight of plant (g)			Dry weight of plant (g)		
	$E_1$ (0.5 EC)	$E_2$ (1 EC)	Mean	$E_1$ (0.5 EC)	$E_2$ (1 EC)	Mean
$V_1$	123.56	118.89	121.23	19.53	13.30	16.42
$V_2$	142.98	138.23	140.61	21.29	15.92	18.61
$V_3$	129.26	123.49	126.38	17.38	12.20	14.79
$V_4$	103.84	98.27	101.06	16.76	10.52	13.64
$V_5$	121.43	106.43	113.93	16.58	10.24	13.41
Mean	124.21	117.06	120.64	18.31	12.44	15.37

Factors	Fresh weight of plant		Dry weight of plant	
	Critical Difference	Standard Deviation	Critical Difference	Standard Deviation
Variety (V)	3.562	1.696	0.464	0.221
Electrical conductivity (E)	2.253	1.073	0.294	0.140
$V \times E$	5.038	2.398	0.657	0.313

$V_1$ :Lorenzo (Green colour - Pompon type),  $V_2$ :Prius Pink (Peach colour - Spray type),  $V_3$ :Furore (White colour - Spray type),  $V_4$ :Merel Gold (Yellow colour - Spray type),  $V_5$ :Lotte Orange (Red colour - Spray type),  $E_1$ :0.5 EC,  $E_2$ :1 EC.

**Table 5.** Effect of electrical conductivity on leaf area of plant and leaf area index per plant grown under aeroponic method of cultivation.

	Leaf area of plant (cm <sup>2</sup> )			Leaf area index per plant		
	$E_1$ (0.5 EC)	$E_2$ (1 EC)	Mean	$E_1$ (0.5 EC)	$E_2$ (1 EC)	Mean
$V_1$	304.31	182.40	243.36	0.380	0.228	0.304
$V_2$	323.93	205.67	264.80	0.405	0.257	0.331
$V_3$	401.74	166.47	284.11	0.502	0.208	0.355
$V_4$	282.70	167.32	225.01	0.353	0.209	0.281
$V_5$	274.67	189.73	232.20	0.343	0.237	0.29
Mean	317.47	182.32	249.89	0.40	0.23	0.31

Factors	Leaf area of plant		Leaf area index per plant	
	Critical Difference	Standard Deviation	Critical Difference	Standard Deviation
Variety (V)	6.630	3.156	0.011	0.005
Electrical conductivity (E)	4.193	1.996	0.007	0.003
$V \times E$	9.377	4.464	0.015	0.007

$V_1$ :Lorenzo (Green colour - Pompon type),  $V_2$ :Prius Pink (Peach colour - Spray type),  $V_3$ :Furore (White colour - Spray type),  $V_4$ :Merel Gold (Yellow colour - Spray type),  $V_5$ :Lotte Orange (Red colour - Spray type),  $E_1$ :0.5 EC,  $E_2$ :1 EC.



suboptimal nutrient availability might have adversely impacted the leaf development process (26).

Higher leaf area and LAI are associated with greater light interception and carbon assimilation, which are critical for plant growth and yield. Therefore, the superior leaf development observed in  $V_3$ , especially under  $E_1$ , could potentially translate into higher productivity. These results underscore the importance of selecting appropriate genotypes in conjunction with optimal environmental or management conditions to maximize growth and yield potential.

### Transpiration rate and photosynthetic rate

The transpiration rate was recorded higher in  $V_4$  ( $7.63 \text{ m mol H}_2\text{O m}^{-2} \text{ s}^{-1}$ ) followed by  $V_2$  ( $4.88 \text{ m mol H}_2\text{O m}^{-2} \text{ s}^{-1}$ ) and the lower transpiration rate was observed in  $V_3$  ( $2.08 \text{ m mol H}_2\text{O m}^{-2} \text{ s}^{-1}$ ). Among the interactions, maximum transpiration rate was recorded in  $V_4E_1$  ( $8.72 \text{ m mol H}_2\text{O m}^{-2} \text{ s}^{-1}$ ) and the minimum was observed in  $V_3E_2$  ( $1.29 \text{ m mol H}_2\text{O m}^{-2} \text{ s}^{-1}$ ), according to the interactions (Table 6). High transpiration in  $V_4$  could be indicative of greater stomatal conductance and higher water loss, potentially due to a less conservative water-use strategy, especially under favorable conditions like  $E_1$ .

In contrast,  $V_3$ 's lower transpiration rate, particularly under  $E_2$ , suggests a possible drought-avoidance or water-saving strategy, often seen in genotypes adapted to stress-prone environments. Such genotypes maintain tighter stomatal control to limit water loss and emphasize that reduced transpiration is a key adaptive trait under water-limited conditions (27).

In respect to photosynthetic rate,  $V_2$  ( $1.38 \mu \text{ mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ) had the maximum photosynthetic rate and  $V_1$  ( $0.13 \mu \text{ mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ) had the minimum. Among the interactions, the maximum photosynthetic rate was observed in  $V_2E_1$  ( $1.53 \mu \text{ mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ) and the minimum was observed in  $V_1E_2$  ( $0.09 \mu \text{ mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ). These differences in photosynthetic efficiency may be linked to variations in leaf morphology, chlorophyll content and stomatal behavior among the varieties (28). The decoupling between photosynthesis and transpiration, especially in varieties like  $V_2$  and  $V_3$ , highlights the complex regulation of water use and carbon gain. Notably, high transpiration does not always equate to high photosynthesis, which supports the idea that water use efficiency (WUE) should

also be assessed when evaluating plant performance under variable environments (29).

### Stomatal conductance and total chlorophyll content

$V_3$  ( $519.50 \text{ m mol H}_2\text{O m}^{-2} \text{ s}^{-1}$ ) had the highest stomatal conductance, followed by  $V_4$  ( $426 \text{ m mol H}_2\text{O m}^{-2} \text{ s}^{-1}$ ) and  $V_5$  ( $251.5 \text{ m mol H}_2\text{O m}^{-2} \text{ s}^{-1}$ ) with minimum stomatal conductance. Among the interactions, maximum stomatal conductance was observed in  $V_3E_1$  ( $521 \text{ m mol H}_2\text{O m}^{-2} \text{ s}^{-1}$ ) and minimum was reported in  $V_5E_2$  ( $227 \text{ m mol H}_2\text{O m}^{-2} \text{ s}^{-1}$ ) (Table 7).

In respect to total chlorophyll content of the plant,  $V_3$  ( $3.80 \text{ mg g}^{-1}$ ) recorded maximum total chlorophyll and  $V_5$  ( $2.43 \text{ mg g}^{-1}$ ) observed the minimum total chlorophyll. Among the interactions, highest total chlorophyll recorded in  $V_3E_1$  ( $3.86 \text{ mg g}^{-1}$ ), followed by  $V_2E_1$  ( $3.82 \text{ mg g}^{-1}$ ) and minimum total chlorophyll was observed in  $V_5E_2$  ( $2.26 \text{ mg g}^{-1}$ ). These results were similar in *Brassica campestris* (30). Stomatal closure or a decrease in total chlorophyll concentration in the leaves are due to high electrical conductivity (31).

### Soluble protein content and catalase activity

The highest soluble protein content of the plant was recorded in  $V_5$  ( $67.29 \text{ mg g}^{-1}$ ), followed by  $V_2$  ( $66.83 \text{ mg g}^{-1}$ ) and lowest was reported in  $V_3$  ( $61.71 \text{ mg g}^{-1}$ ). Among the interactions, maximum soluble protein content was recorded in  $V_5E_2$  ( $67.84 \text{ mg g}^{-1}$ ), followed by the treatment  $V_2E_2$  ( $67.38 \text{ mg g}^{-1}$ ), whereas minimum was observed in  $V_3E_1$  ( $61.15 \text{ mg g}^{-1}$ ) (Table 8). Soluble protein accumulation is often used as a biochemical marker of metabolic activity and stress response. The higher protein content in  $V_5$  and  $V_2$  under  $E_2$  suggests that these varieties have a robust capacity for maintaining protein synthesis under varied conditions, possibly due to enhanced enzymatic activity and stable cellular functions (32).

For catalase activity of the plant, the maximum was recorded in  $V_5$  ( $38.81 \mu \text{g H}_2\text{O g}^{-1} \text{ min}^{-1}$ ), followed by  $V_3$  ( $27.12 \mu \text{g H}_2\text{O g}^{-1} \text{ min}^{-1}$ ) and minimum was recorded in  $V_1$  ( $19.68 \mu \text{g H}_2\text{O g}^{-1} \text{ min}^{-1}$ ). Among the interactions, the highest catalase activity was recorded in  $V_5E_1$  ( $39.09 \mu \text{g H}_2\text{O g}^{-1} \text{ min}^{-1}$ ), followed by the treatment  $V_5E_2$  ( $38.53 \mu \text{g H}_2\text{O g}^{-1} \text{ min}^{-1}$ ) and lowest was recorded in  $V_1E_1$  ( $19.01 \mu \text{g H}_2\text{O g}^{-1} \text{ min}^{-1}$ ) (Table 8). Higher catalase activity typically signifies enhanced capacity to mitigate oxidative

**Table 6.** Effect of electrical conductivity on transpiration rate and photosynthetic rate grown under aeroponic method of cultivation.

	Transpiration rate ( $\text{m mol H}_2\text{O m}^{-2} \text{ s}^{-1}$ )			Photosynthetic rate ( $\mu \text{ mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ )		
	$E_1$ (0.5 EC)	$E_2$ (1 EC)	Mean	$E_1$ (0.5 EC)	$E_2$ (1 EC)	Mean
$V_1$	3.53	2.03	2.78	0.17	0.09	0.13
$V_2$	5.79	3.96	4.88	1.53	1.23	1.38
$V_3$	2.87	1.29	2.08	1.24	1.17	1.21
$V_4$	8.72	6.53	7.63	0.78	0.65	0.72
$V_5$	4.89	2.87	3.88	1.09	0.98	1.04
Mean	5.16	3.34	4.25	0.96	0.82	0.89

Factors	Transpiration rate		Photosynthetic rate	
	Critical Difference	Standard Deviation	Critical Difference	Standard Deviation
Variety (V)	0.134	0.064	0.029	0.014
Electrical conductivity (E)	0.085	0.040	0.018	0.009
$V \times E$	0.190	0.090	0.041	0.020

$V_1$ :Lorenzo (Green colour - Pompon type),  $V_2$ :Prius Pink (Peach colour - Spray type),  $V_3$ :Furore (White colour - Spray type),  $V_4$ :Merel Gold (Yellow colour - Spray type),  $V_5$ :Lotte Orange (Red colour - Spray type),  $E_1$ :0.5 EC,  $E_2$ :1 EC.

**Table 7.** Effect of electrical conductivity on stomatal conductance and total chlorophyll grown under aeroponic method of cultivation.

	Stomatal conductance (m mol H <sub>2</sub> O m <sup>-2</sup> s <sup>-1</sup> )			Total chlorophyll (mg g <sup>-1</sup> )		
	E <sub>1</sub> (0.5 EC)	E <sub>2</sub> (1 EC)	Mean	E <sub>1</sub> (0.5 EC)	E <sub>2</sub> (1 EC)	Mean
V <sub>1</sub>	281	263	272	3.18	3.07	3.13
V <sub>2</sub>	405	401	403	3.82	3.65	3.74
V <sub>3</sub>	521	518	519.50	3.86	3.73	3.80
V <sub>4</sub>	443	409	426	3.27	3.18	3.23
V <sub>5</sub>	276	227	251.5	2.59	2.26	2.43
Mean	385.2	363.6	374.4	3.34	3.18	3.26

Factors	Stomatal conductance		Total chlorophyll	
	Critical Difference	Standard Deviation	Critical Difference	Standard Deviation
Variety (V)	11.663	5.552	0.101	0.034
Electrical conductivity (E)	7.025	3.511	0.064	0.021
V × E	16.494	7.852	0.142	0.048

V<sub>1</sub>:Lorenzo (Green colour - Pompon type), V<sub>2</sub>:Prius Pink (Peach colour - Spray type), V<sub>3</sub>:Furore (White colour - Spray type), V<sub>4</sub>:Merel Gold (Yellow colour - Spray type), V<sub>5</sub>:Lotte Orange (Red colour - Spray type), E<sub>1</sub>:0.5 EC, E<sub>2</sub>:1 EC.

**Table 8.** Effect of electrical conductivity on soluble protein and catalase grown under aeroponic method of cultivation.

	Soluble protein (mg g <sup>-1</sup> )			Catalase (μg H <sub>2</sub> O g <sup>-1</sup> min <sup>-1</sup> )		
	E <sub>1</sub> (0.5 EC)	E <sub>2</sub> (1 EC)	Mean	E <sub>1</sub> (0.5 EC)	E <sub>2</sub> (1 EC)	Mean
V <sub>1</sub>	62.89	63.97	63.43	19.01	20.35	19.68
V <sub>2</sub>	66.28	67.38	66.83	22.63	23.77	23.20
V <sub>3</sub>	61.15	62.26	61.71	26.38	27.85	27.12
V <sub>4</sub>	61.98	63.09	62.54	23.49	25.68	24.59
V <sub>5</sub>	66.73	67.84	67.29	39.09	38.53	38.81
Mean	63.81	64.91	64.36	26.12	27.24	26.68

Factors	Soluble protein		Catalase	
	Critical Difference	Standard Deviation	Critical Difference	Standard Deviation
Variety (V)	1.894	0.902	0.928	0.442
Electrical conductivity (E)	0.125	0.570	0.491	0.279
V × E	2.679	1.275	1.313	0.625

V<sub>1</sub>:Lorenzo (Green colour - Pompon type), V<sub>2</sub>:Prius Pink (Peach colour - Spray type), V<sub>3</sub>:Furore (White colour - Spray type), V<sub>4</sub>:Merel Gold (Yellow colour - Spray type), V<sub>5</sub>:Lotte Orange (Red colour - Spray type), E<sub>1</sub>:0.5 EC, E<sub>2</sub>:1 EC.

stress by breaking down reactive oxygen species (ROS), particularly H<sub>2</sub>O<sub>2</sub>, which accumulates under various abiotic stresses like drought, salinity and high light intensity (33). Therefore, the higher catalase activity in V<sub>5</sub> suggests its superior stress resilience and better oxidative balance, which may contribute to its higher protein content and overall physiological performance.

In contrast, the low catalase activity in V<sub>1</sub>E<sub>1</sub> (19.01 μg H<sub>2</sub>O g<sup>-1</sup> min<sup>-1</sup>) indicates limited oxidative protection, which could lead to oxidative damage and compromised cellular function. These results align with previous studies that have linked catalase activity and protein accumulation to environmental adaptability and stress tolerance (34).

Altogether, V<sub>5</sub> emerges as a metabolically active and stress-tolerant variety with superior protein metabolism and antioxidative defense mechanisms, especially under E<sub>1</sub> and E<sub>2</sub> treatments. These traits make it a promising candidate for cultivation in environments where plants may encounter fluctuating or stressful conditions.

### Peroxidase activity and days to first flowering

For peroxidase activity of the plant, highest was recorded in V<sub>2</sub> (0.89 change in OD g<sup>-1</sup> min<sup>-1</sup>) and minimum peroxidase activity observed in V<sub>1</sub> (0.40 change in OD g<sup>-1</sup> min<sup>-1</sup>) (Table 9). Among the interactions, peroxidase activity was recorded the higher in V<sub>2</sub>E<sub>1</sub> (0.97 change in OD g<sup>-1</sup> min<sup>-1</sup>) and the minimum was observed in V<sub>1</sub>E<sub>1</sub> (0.39 Change in OD g<sup>-1</sup> min<sup>-1</sup>). Peroxidase enzymes are known to play a critical role in plant defense responses against biotic and abiotic stresses through the detoxification of ROS and involvement in lignin biosynthesis (35). The elevated peroxidase activity in V<sub>2</sub> suggests a better adaptive or defense mechanism in this variety under the given environmental conditions. Similar findings have been reported stress conditions such as drought and salinity often elevate peroxidase activity in plants as a protective mechanism (36).

In respect to days to first flowering, the minimum days to first flowering were recorded in V<sub>2</sub> (26.40 days), followed by V<sub>1</sub> (26.62 days), which was on par with V<sub>4</sub> and a greater number of days to first flowering was recorded in V<sub>3</sub> (35.26 days). Among

the interactions, minimum days to first flowering were recorded in  $V_2E_2$  (25.82 days), which was on par with  $V_4E_2$  and a greater number of days to first flowering was recorded in  $V_3E_1$  (35.87 days) (Table 9). Early flowering is often associated with early maturity, which can be advantageous under stress-prone environments or in regions with a short growing season. These results are consistent with genotypic variation in flowering time as an important selection criterion in breeding programs (37). Environmental cues such as temperature, light and water availability are known to influence floral induction and timing (38).

### Crop growth rate

The treatment  $V_3$  had the maximum crop growth rate of  $2.88 \text{ g m}^{-2} \text{ day}^{-1}$  followed by the treatment  $V_1$  with 2.85 and the treatment  $V_4$  with minimum crop growth rate of  $2.23 \text{ g m}^{-2} \text{ day}^{-1}$  at 0.5 EC. However, at the 1 EC level, the treatment  $V_2$  had the maximum crop growth rate of  $3.31 \text{ g m}^{-2} \text{ day}^{-1}$ , followed by the treatment  $V_1$  with  $3.00 \text{ g m}^{-2} \text{ day}^{-1}$  and treatment  $V_4$  with

minimum crop growth rate of  $1.56 \text{ g m}^{-2} \text{ day}^{-1}$  (Table 10). This shift in performance under varying EC levels suggests genotype-specific adaptability to salinity or ionic stress, where  $V_2$  may activate physiological or metabolic mechanisms to sustain or enhance growth even under higher osmotic stress. These findings align with previous research, which indicates that certain cultivars can maintain growth through improved osmotic adjustment, ion compartmentalization or increased antioxidant activity under salinity (39, 40).

Among the interactions, observations on crop growth rate were recorded during vegetative stage to bud appearance stage and bud appearance stage to flowering stage ( $V \times E \times S$ ), the treatment  $V_1E_2$  recorded maximum crop growth rate of  $3.87 \text{ g m}^{-2} \text{ day}^{-1}$  at vegetative stage to bud appearance stage and  $V_2E_2$  ( $2.98 \text{ g m}^{-2} \text{ day}^{-1}$ ) at bud appearance stage to flowering stage followed by  $V_2E_2$  which recorded a crop growth rate of  $3.64 \text{ g m}^{-2} \text{ day}^{-1}$  at vegetative stage to bud appearance stage and  $V_3E_1$  ( $2.76 \text{ g m}^{-2} \text{ day}^{-1}$ ) at bud appearance stage to flowering

**Table 9.** Effect of electrical conductivity on peroxidase and days to 1<sup>st</sup> flowering grown under aeroponic method of cultivation.

	Peroxidase (change in OD $\text{g}^{-1} \text{ min}^{-1}$ )			Days to 1 <sup>st</sup> flowering (days)		
	$E_1$ (0.5 EC)	$E_2$ (1 EC)	Mean	$E_1$ (0.5 EC)	$E_2$ (1 EC)	Mean
$V_1$	0.39	0.41	0.40	27.23	26.01	26.62
$V_2$	0.97	0.81	0.89	26.98	25.82	26.40
$V_3$	0.68	0.67	0.68	35.87	34.64	35.26
$V_4$	0.56	0.52	0.54	27.54	26.13	26.84
$V_5$	0.48	0.44	0.46	33.69	30.95	32.32
Mean	0.62	0.57	0.59	30.26	28.71	29.49

Factors	Peroxidase		Days to 1 <sup>st</sup> flowering	
	Critical Difference	Standard Deviation	Critical Difference	Standard Deviation
Variety (V)	0.017	0.008	0.900	0.428
Electrical conductivity (E)	0.011	0.005	NS	0.271
$V \times E$	0.025	0.012	1.273	0.606

$V_1$ :Lorenzo (Green colour - Pompon type),  $V_2$ :Prius Pink (Peach colour - Spray type),  $V_3$ :Furore (White colour - Spray type),  $V_4$ :Merel Gold (Yellow colour - Spray type),  $V_5$ :Lotte Orange (Red colour - Spray type),  $E_1$ :0.5 EC,  $E_2$ :1 EC.

**Table 10.** Effect of electrical conductivity on crop growth rate of plant grown under aeroponic method of cultivation ( $\text{g m}^{-2} \text{ day}^{-1}$ ).

	$E_1$ (0.5 EC)			$E_2$ (1 EC)		
	Vegetative to bud appearance stage	Bud appearance stage to flowering	Mean	Vegetative to bud appearance stage	Bud appearance stage to flowering	Mean
$V_1$	3.14	2.56	2.85	3.87	2.12	3.00
$V_2$	2.79	2.29	2.54	3.64	2.98	3.31
$V_3$	2.99	2.76	2.88	2.52	1.59	2.06
$V_4$	2.35	2.10	2.23	2.02	1.09	1.56
$V_5$	2.90	2.09	2.50	2.46	1.76	2.11
Mean	2.83	2.36	2.60	2.90	1.91	2.41

Factors	Critical Difference	Standard Deviation	Factors	Critical Difference	Standard Deviation
Variety (V)	0.059	0.029	$V \times S$	0.083	0.041
Electrical conductivity (E)	0.037	0.018	$E \times S$	0.051	0.026
$V \times E$	0.083	0.041	$V \times E \times S$	0.118	0.058
Stage (S)	0.037	0.018			

$V_1$ :Lorenzo (Green colour - Pompon type),  $V_2$ :Prius Pink (Peach colour - Spray type),  $V_3$ :Furore (White colour - Spray type),  $V_4$ :Merel Gold (Yellow colour - Spray type),  $V_5$ :Lotte Orange (Red colour - Spray type),  $E_1$ :0.5 EC,  $E_2$ :1 EC.



stage and the treatment  $V_4E_2$  recorded minimum crop growth rate of  $2.02 \text{ g m}^{-2} \text{ day}^{-1}$  at vegetative stage to bud appearance stage and  $V_4E_2$  ( $1.09 \text{ g m}^{-2} \text{ day}^{-1}$ ) at bud appearance stage to flowering stage. Growth rate differences between stages further reflect developmental priorities. The vegetative stage to bud appearance typically exhibits the highest CGR (crop growth rate) due to rapid canopy expansion and nutrient uptake (41). The slightly lower CGR during the bud to flowering stage may be attributed to a shift in resource allocation from vegetative growth to reproductive development.

These results underscore the importance of selecting genotypes like  $V_2$  and  $V_1$  for environments with higher salinity or variable EC levels, as they demonstrate both resilience and consistent biomass production. Moreover, the dynamic response of Crop Growth Rate across stages and interactions confirms the role of genotype  $\times$  environment  $\times$  growth stage interplay in determining crop productivity (42).

### Number of flowers per plant

In respect to number of flowers per plant, a greater number of flowers was recorded in  $V_4$  (56.94), followed by  $V_2$  (51.39) and minimum number of flowers was recorded in  $V_3$  (18.69). Among the interactions, a greater number of flowers was recorded in  $V_2E_1$  (67.58), followed by treatment  $V_4E_1$  (64.72 number) and minimum was recorded in  $V_1E_2$  (14.87 number) (Fig. 3). A high flower count is often an indicator of strong vegetative vigor and effective nutrient partitioning toward reproductive development (43). The superior floral productivity of  $V_4$  and  $V_2$  may be attributed to favorable sink-source dynamics and hormonal balance promoting floral differentiation and retention. Environmental condition  $E_1$  possibly enhanced flowering through better light or nutrient availability, a common driver for florogenesis (44).

### Weight of cut stem

The maximum weight of cut stem was recorded in  $V_3$  (5.53 g), followed by  $V_1$  (4.94 g) and lowest was observed in  $V_4$  (4.11 g). Among the interactions, the highest weight of cut stem was

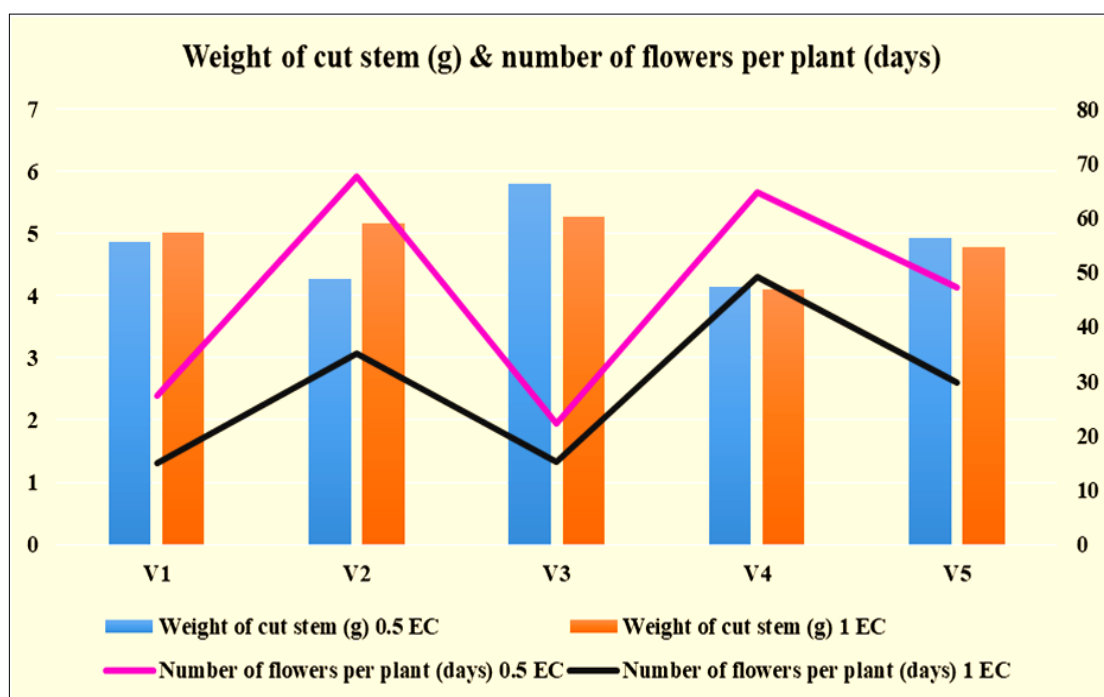
recorded in  $V_3E_1$  (5.80 g), followed by treatment  $V_3E_2$  (5.26 g), which was on par with  $V_2E_2$  and minimum weight of cut stem was observed in  $V_4E_2$  (4.09 g) (Fig. 3). Higher stem weight typically reflects greater structural strength and water-conducting capacity, both crucial for postharvest performance and mechanical handling (45). The consistent performance of  $V_3$  under both  $E_1$  and  $E_2$  implies resilience and strong growth dynamics across environments.

### Flower diameter and vase life

The highest flower diameter was recorded at  $V_3$  (6.62 cm), followed by  $V_2$  (6.12 cm) and the lowest was observed in  $V_1$  (5.20 cm). Among the interactions, the maximum diameter was recorded in  $V_3E_2$  (6.71 cm), followed by treatment  $V_3E_1$  (6.53 cm) and minimum was recorded in  $V_1E_2$  (5.19 cm) (Table 11). Larger flower diameter is a desirable ornamental trait and often results from optimal cell expansion and petal development influenced by both genetic and environmental factors (46). The consistent superior bloom size of  $V_3$ , especially under  $E_2$ , suggests its suitability for premium floral markets.

The maximum vase life was recorded in  $V_2$  (15.72 days), followed by  $V_5$  (11.37 days) and minimum was observed in  $V_1$  (9.30 days) (Table 11). Among the interactions, maximum vase life was recorded in  $V_2E_1$  (16.98 days), followed by  $V_2E_2$  (14.46 days) and minimum vase life was recorded in  $V_4E_2$  (9.25 days). Extended vase life in  $V_2$  may be attributed to reduced ethylene sensitivity, higher antioxidant activity and better water uptake capacity, traits commonly associated with floral longevity (47). The drastic reduction in vase life under  $E_2$  for  $V_4$  further reflects the importance of genotype-environment interaction in postharvest performance.

Cut flower yield was also decreased with increasing EC level and this result was like the reported in cucumber (48). EC value increased, potato seed production decreased, when grown aeroponically in the lowlands with root zone cooling (4). High EC concentrations lowered food and water uptake, salt and chloride toxicity in stem cells and plant photosynthetic



**Fig. 3.** Effect of electrical conductivity on weight of cut stem and number of flowers per plant grown under aeroponic method of cultivation.

**Table 11.** Effect of electrical conductivity on flower diameter and vase life of plant grown under aeroponic method of cultivation.

	Flower diameter (cm)			Vase life (days)		
	E <sub>1</sub> (0.5 EC)	E <sub>2</sub> (1 EC)	Mean	E <sub>1</sub> (0.5 EC)	E <sub>2</sub> (1 EC)	Mean
V <sub>1</sub>	5.21	5.19	5.20	9.29	9.31	9.3
V <sub>2</sub>	6.08	6.15	6.12	16.98	14.46	15.72
V <sub>3</sub>	6.53	6.71	6.62	10.47	9.62	10.045
V <sub>4</sub>	5.49	5.48	5.49	9.89	9.25	9.57
V <sub>5</sub>	5.23	5.35	5.29	11.93	10.81	11.37
Mean	5.71	5.78	5.74	11.71	10.69	11.20

Factors	Flower diameter		Vase life (days)	
	Critical Difference	Standard Deviation	Critical Difference	Standard Deviation
Variety (V)	0.189	0.090	0.362	0.172
Electrical conductivity (E)	0.115	0.057	0.229	0.109
V × E	0.268	0.128	0.512	0.244

V<sub>1</sub>:Lorenzo (Green colour - Pompon type), V<sub>2</sub>:Prius Pink (Peach colour - Spray type), V<sub>3</sub>:Furore (White colour - Spray type), V<sub>4</sub>:Merel Gold (Yellow colour - Spray type), V<sub>5</sub>:Lotte Orange (Red colour - Spray type), E<sub>1</sub>:0.5 EC, E<sub>2</sub>:1 EC.

ability (49). The result was same as that where the total number of tubers was higher in lower concentration of nutrients in potato (3). Rapid seed multiplication technique, in aeroponics, are currently being used in underdeveloped nations to obtain high-quality mini tubers (3).

This study comprehensively evaluated the impact of varying EC levels on the growth, physiological and biochemical traits of different plant varieties. Results demonstrated significant varietal differences in response to EC levels, with V<sub>2</sub> and V<sub>5</sub> emerging as the most adaptable and vigorous genotypes under varying environmental conditions. V<sub>2</sub> consistently exhibited superior performance across multiple parameters, including plant height, root length, fresh and dry weight, photosynthetic rate and peroxidase activity, especially under the E<sub>1</sub> environment. On the other hand, V<sub>5</sub> showed enhanced root biomass, higher protein content and strong antioxidant enzyme activity, indicating its stress-resilient nature.

In contrast, V<sub>1</sub> generally recorded lower values for many growth and physiological traits, yet showed high root dry weight, suggesting a conservative growth strategy potentially suited for stress conditions. V<sub>3</sub> showed notable performance in leaf area and stomatal conductance, while V<sub>4</sub> displayed higher transpiration but comparatively lower growth efficiency, possibly due to suboptimal water-use strategy.

## Conclusion

The findings underscore the importance of genotype × environment × nutrient interaction in determining plant performance under aeroponic growing system. Identifying varieties like V<sub>2</sub> and V<sub>5</sub>, which maintain growth and physiological balance under stress, is vital for developing resilient crop systems suited to fluctuating or suboptimal growing conditions. As well as 0.5 EC was best for aeroponic system since it is spraying continuously with less interval. These insights are essential for agronomic management strategies in controlled-environment or stress-prone field conditions.

## Acknowledgements

The authors thank the Department of Floriculture and Landscape Architecture, Tamil Nadu Agricultural University, Coimbatore and IAC Krishitech Private Limited for providing financial assistance to carry out the research work.

## Authors' contributions

MR and BR carried out the research work in the field & lab, done statistical analysis and drafted the manuscript. All authors read and approved the final version of the manuscript.

## Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interests to declare.

**Ethical issues:** None

## References

- Gorbe E, Calatayud A. Optimization of nutrition in soilless systems: A review. *Adv Bot Res.* 2010;53:193-245. [https://doi.org/10.1016/S0065-2296\(10\)53006-4](https://doi.org/10.1016/S0065-2296(10)53006-4)
- Landowne D. *Cell Physiology*: Lange Medical Books/McGraw-Hill. 2006.
- Tessema L, Chindi A, Gebremedhin WG, Solomon A, Shunka E, Seid E. Determination of nutrient solutions for potato (*Solanum tuberosum* L.) seed production under aeroponics production system. *Open Agri.* 2017;2(1):155-59. <https://doi.org/10.1515/opag-2017-0015>
- Williams R. The physiology of plant growth with special reference to the concept of net assimilation rate. *Ann Bot.* 1946;10(37):41-72.
- Yoshida S, Forno DA, Cock JH. Laboratory manual for physiological studies of rice. 1971. <https://doi.org/10.5555/19721703488>
- Lowry O, Rosebrough N, Farr AL, Randall R. Protein measurement with the Folin phenol reagent. *J Biol Chem.* 1951;193(1):265-75. <https://doi.org/10.5555/19511404458>

7. Hammerschmidt R, Nuckles E, Kuć J. Association of enhanced peroxidase activity with induced systemic resistance of cucumber to *Colletotrichum lagenarium*. *Physiol Plant Pathol*. 1982;20(1):73-82. [https://doi.org/10.1016/0048-4059\(82\)90025-X](https://doi.org/10.1016/0048-4059(82)90025-X)
8. Sumarni E, Suhardiyanto H, Seminar KB, Saptomo SK. Temperature distribution in aeroponics system with root zone cooling for the production of potato seed in tropical lowland. *Int J Sci Eng Res*. 2013;4(6):799-804.
9. Romero-Aranda R, Soria T, Cuartero J. Tomato plant-water uptake and plant-water relationships under saline growth conditions. *Plant Sci*. 2001;160(2):265-72. [https://doi.org/10.1016/S0168-9452\(00\)00388-5](https://doi.org/10.1016/S0168-9452(00)00388-5)
10. Reina-Sánchez A, Romero-Aranda R, Cuartero J. Plant water uptake and water use efficiency of greenhouse tomato cultivars irrigated with saline water. *Agric Water Manag*. 2005;78(1-2):54-66. <https://doi.org/10.1016/j.agwat.2005.04.021>
11. Kim HJ, Cho YS, Kwon OK, Cho MW, Hwang JB, Bae SD, et al. Effect of pH and EC of hydroponic solution on the growth of greenhouse rose. *Asian J Plant Sci*. 2005.
12. Huang J, Redman RE. Salt tolerance of *Hordeum* and *Brassica* species during germination and early seedling growth. *Can J Plant Sci*. 1995;75:815-19. <https://doi.org/10.4141/cjps95-137>
13. Szaniawski R. Adaptation and functional balance between shoot and root activity of sunflower plants grown at different root temperatures. *Ann Bot*. 1983;51(4):453-59. <https://doi.org/10.1093/oxfordjournals.aob.a086490>
14. Lynch JP. Root architecture and plant productivity. *Plant Physiol*. 1995;109(1):7-13. <https://doi.org/10.1104/pp.109.1.7>
15. Comas LH, Becker SR, Von Mark VC, Byrne PF, Dierig DA. Root traits contributing to plant productivity under drought. *Front Plant Sci*. 2013;4:442. <https://doi.org/10.3389/fpls.2013.00442>
16. Fageria NK, Moreira A. The role of mineral nutrition on root growth of crop plants. *Adv Agron*. 2011;110:251-331. <https://doi.org/10.1016/B978-0-12-385531-2.00004-9>
17. Sharp RE, Poroyko V, Hejlek LG, Spollen WG, Springer GK, Bohnert HJ, et al. Root growth maintenance during water deficits: Physiology to functional genomics. *J Exp Bot*. 2004;55(407):2343-51. <https://doi.org/10.1093/jxb/erh276>
18. Rich SM, Watt M. Soil conditions and cereal root system architecture: Review and considerations for linking Darwin and Weaver. *J Exp Bot*. 2013;64(5):1193-208. <https://doi.org/10.1093/jxb/ert043>
19. Smith FA. Growth, activity and interaction with soils. *Plant Roots*. 2007. <https://doi.org/10.1093/aob/mcm099>
20. Passioura JB. Environmental biology and crop improvement. *Funct Plant Biol*. 2002;29(5):537-46. <https://doi.org/10.1071/FP02020>
21. Reynolds MP, Mujeeb-Kazi A, Sawkins M. Prospects for utilizing plant-adaptive mechanisms to improve wheat and other crops in drought- and salinity-prone environments. *Anal Appl Biol*. 2005;146(2):239-59. <https://doi.org/10.1111/j.1744-7348.2005.040058.x>
22. Chang DC, Park CS, Kim SY, Kim SJ, Lee YB. Physiological growth responses by nutrient interruption in aeroponically grown potatoes. *Am J Potato Res*. 2008;85(5):315.
23. Teixeira J, Pereira S. High salinity and drought act on an organ-dependent manner on potato glutamine synthetase expression and accumulation. *Environ Exp Bot*. 2007;60(1):121-26. <https://doi.org/10.1016/j.envexpbot.2006.09.003>
24. Greenway H, Munns R. Mechanisms of salt tolerance in nonhalophytes. *Ann Rev Plant Physiol*. 1980;31(1):149-90. <https://doi.org/10.1146/annurev.pp.31.060180.001053>
25. Slafer GA, Rawson HM. Sensitivity of wheat phasic development to major environmental factors: A re-examination of some assumptions made by physiologists and modelers. *Aust J Plant Physiol*. 1994;21(4): 393-426. <https://doi.org/10.1071/PP9940393>
26. Farooq M, Wahid A, Kobayashi N, Fujita D, Basra SMA. Plant drought stress: Effects, mechanisms and management. *Agron Sustain Dev*. 2009;29(1):185-212.
27. Blum A. Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. *Field Crops Res*. 2009;112(2-3):119-23. <https://doi.org/10.1016/j.fcr.2009.03.009>
28. Flexas J, Barbour MM, Brendel O, Cabrera HM, Carriqui M, Diaz-Espejo A, et al. Mesophyll diffusion conductance to CO<sub>2</sub>: An unappreciated central player in photosynthesis. *Plant Sci*. 2012;193-194:70-84. <https://doi.org/10.1016/j.plantsci.2012.05.009>
29. Condon AG, Richards RA, Rebetzke GJ, Farquhar GD. Breeding for high water-use efficiency. *J Expl Bot*. 2004;55(407):2447-60. <https://doi.org/10.1093/jxb/erh277>
30. Ding X, Jiang Y, Zhao H, Guo D, He L, Liu F, et al. Electrical conductivity of nutrient solution influenced photosynthesis, quality and antioxidant enzyme activity of pakchoi (*Brassica campestris* L. ssp. *chinensis*) in a hydroponic system. *PLoS One*. 2018;13(8):e0202090. <https://doi.org/10.1371/journal.pone.0202090>
31. Romero-Aranda R, Syvertsen JP. The influence of foliar applied urea nitrogen and saline solutions on net gas exchange of citrus leaves. *J Am Soc Hortic Sci*. 1996;121(3):501-506.
32. Hayat S, Hayat Q, Alyemeni MN, Wani AS, Pichtel J, Ahmad A. Role of proline under changing environments: A review. *Plant Signal Behav*. 2012;7(11):1456-66. <https://doi.org/10.4161/psb.21949>
33. Gill SS, Tuteja N. Reactive oxygen species and antioxidant machinery in abiotic stress tolerance in crop plants. *Plant Physiol Biochem*. 2010;48(12):909-30. <https://doi.org/10.1016/j.plaphy.2010.08.016>
34. Miller G, Suzuki N, Ciftci-Yilmaz S, Mittler R. Reactive oxygen species homeostasis and signalling during drought and salinity stresses. *Plant Cell Environ*. 2010;33(4):453-67. <https://doi.org/10.1111/j.1365-3040.2009.02041.x>
35. Sharma P, Jha AB, Dubey RS, Pessarakli M. Reactive oxygen species, oxidative damage and antioxidative defense mechanism in plants under stressful conditions. *J Bot*. 2012;1-26. <https://doi.org/10.1155/2012/217037>
36. Jaleel CA, Gopi R, Manivannan P, Panneerselvam R. Responses of antioxidant defense system of *Catharanthus roseus* (L.) to paclobutrazol treatment under salinity. *Acta Physiol Plant*. 2009;31(3):361-66.
37. Kumar A, Singh D, Singh M. Genetic variability and character association in French bean (*Phaseolus vulgaris* L.). *Legume Res*. 2015;38(3):353-56.
38. Blümel M, Dally N, Jung C. Flowering time regulation in crops-What did we learn from *Arabidopsis*? *Curr Opin Biotech*. 2015;32:121-29. <https://doi.org/10.1016/j.copbio.2014.11.023>
39. Munns R, Tester M. Mechanisms of salinity tolerance. *Ann Rev Plant Biol*. 2008;59:651-81. <https://doi.org/10.1146/annurev.arplant.59.032607.092911>
40. Ashraf M, Harris PJC. Photosynthesis under stressful environments: An overview. *Photosynthetica*. 2013;51(2):163-90. <https://doi.org/10.1007/s11099-013-0021-6>
41. Watson DJ. The physiological basis of variation in yield. *Adv Agron*. 1952;4:101-45. [https://doi.org/10.1016/S0065-2113\(08\)60307-7](https://doi.org/10.1016/S0065-2113(08)60307-7)
42. Lobell DB, Hammer GL, McLean G, Messina C, Roberts MJ, Schlenker W. The critical role of extreme heat for maize production in the United States. *Nat Clim Change*. 2014;3(5):497-501. <https://doi.org/10.1038/nclimate1832>
43. Arora JS, Khanna K. Introductory ornamental horticulture. Kalyani publishers. 2010.

44. Singh AK, Patil VK, Sharma RR. Flower induction in ornamental plants: Physiology and practices. *J Appl Nat Sci*. 2017;9(3):1720–30.
45. Hertogh AD, Nard ML. The physiology of flower bulbs. A comprehensive treatise on the physiology and utilization of ornamental flowering bulbous and tuberous plants. 1993.
46. Halevy AH, Mayak S. Senescence and postharvest physiology of cut flowers-Part 2. *Hortic Rev* 1981;3:59–143. <https://doi.org/10.1002/9781118060766#page=69>
47. Nowak J, Rudnicki RM. Postharvest handling and storage of cut flowers, florist greens and potted plants. Timber Press. 1990.
48. Roh M, Lee Y, Kim H, Lee K, Bae J. Development of nutrient solution suitable for closed system in substrate culture of cucumber. *J Biol Prod Facil Environ Control* (Korea Republic). 1997.
49. Amel A, Nir Gavish, Liang Zhu, Dario R. Dekel, Michael A Hickner, Ein-Eli Y. Bicarbonate and chloride anion transport in anion exchange membranes. *J Mem Sci*. 2016;514:125-34. <https://doi.org/10.1016/j.memsci.2016.04.027>

#### Additional information

**Peer review:** Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

**Reprints & permissions information** is available at [https://horizonpublishing.com/journals/index.php/PST/open\\_access\\_policy](https://horizonpublishing.com/journals/index.php/PST/open_access_policy)

**Publisher's Note:** Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

**Indexing:** Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc

See [https://horizonpublishing.com/journals/index.php/PST/indexing\\_abstracting](https://horizonpublishing.com/journals/index.php/PST/indexing_abstracting)

**Copyright:** © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (<https://creativecommons.org/licenses/by/4.0/>)

**Publisher information:** Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.