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Original Article

Evaluation of growth and physio-biochemical characteristics of Chinese chives (*Allium tuberosum*) in an aeroponic system under varied EC concentrations

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Abstract

Electrical conductivity (EC) of the nutrient solution is an important factor governing nutrient availability, osmotic conditions, plant growth, and quality in soilless cultivation. This study evaluated the effects of four nutrient-solution EC levels (0.8, 1.2, 1.6, and 2.0 dS m^{-1}) on the growth, biomass accumulation, phenolic and flavonoid contents, radical-scavenging activity, and nutrient-solution dynamics of Chinese chive (*Allium tuberosum* Rottler ex Spreng) grown in an aeroponic system. Growth measurements were obtained at 5-day intervals over a 15-day treatment period. Moderate EC levels, particularly 1.2 and 1.6 dS m^{-1}, generally supported greater plant height, leaf production, root development, and shoot and root biomass than the lowest EC. However, responses of total polyphenol content (TPC), total flavonoid content (TFC), and radical-scavenging activity were tissue- and assay-dependent rather than uniformly enhanced by a particular EC. Nutrient-solution analyses indicated temporal changes in macro- and micronutrient concentrations, although these observations should be interpreted cautiously because nutrient analyses were based on a single analytical sample and therefore were not suitable for inferential statistical comparison. Overall, the results indicate that an EC range of approximately 1.2–1.6 dS m^{-1} may provide a suitable starting range for aeroponic production of the tested Chinese chive cultivar under the experimental conditions. Further experiments with independent nutrient-solution replicates, longer production periods, and repeated harvests are required to validate this recommendation.

Keywords: Antioxidant activity, Electrical conductivity, Polyphenol content, Radical scavenging, Total flavonoid content, Aeroponics

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Introduction

Chinese chives (*Allium tuberosum* Rottler ex Spreng) are a perennial vegetable that has long been used for culinary and medicinal purposes, particularly in East Asia. They contain vitamins, minerals, dietary fiber, and antioxidant compounds and are characterized by a distinctive flavor and aroma (Shahrajabian et al., 2021; Moon et al., 2003; Devi et al., 2025). Their reported antioxidant and pharmacological properties have increased interest in their production and quality improvement (Lim et al., 2006; Kim, 2021). Previous studies have reported considerable radical-scavenging activity and appreciable concentrations of phenolic and flavonoid compounds in Chinese chives (Devi et al., 2025).

In Korea, Chinese chive cultivation is mainly carried out in open fields and soil-based greenhouse systems. Conventional fertilization can lead to inefficient nutrient use and salt accumulation when nutrients are supplied excessively or imbalanced. Because Chinese chives are repeatedly harvested, nutrient demand may also vary with plant's developmental stage, making precise nutrient management particularly important. Wang et al. (2021) reported that modified fertilization strategies could improve several growth and quality characteristics of Chinese chives compared with conventional fertilization.

Soilless cultivation systems provide greater control over nutrient concentration, water availability, and root-zone conditions than conventional soil-based production. Aeroponic systems are particularly attractive because nutrient solution is delivered directly to the root zone, potentially improving root aeration and nutrient-use efficiency. However, the response of a crop to nutrient-solution EC is crop- and cultivar-dependent, and increasing EC does not necessarily result in greater nutrient uptake or biomass production. Recent studies have emphasized that EC should be considered together with nutrient composition, crop developmental stage, and the characteristics of the production system rather than as a stand-alone indicator of nutrient availability.

Previous studies on hydroponic cultivation of Chinese chives have examined nutrient-solution concentration, substrate selection, and quality-related responses (Oh, 2001; Huang et al., 2007; Son, 2013; Xie et al., 2023). Physiological and metabolic studies have also shown that Chinese chives can respond positively to mild nutrient or salinity stress, although excessive stress can adversely affect growth and nutrient balance. For example, hydroponically grown Chinese chives have revealed physiological and metabolic responses to mild salinity, demonstrating that moderate ionic stress can alter growth, nutrition, and quality-related characteristics.

Recent hydroponic research further indicates that nutrient concentrations in recirculating systems can change substantially during crop growth even when EC remains relatively stable. Therefore, monitoring individual nutrients, in addition to EC, can provide information that cannot be obtained from EC measurements alone.

Despite these advances, information remains limited on the responses of Chinese chives to different nutrient-solution EC levels specifically under aeroponic cultivation. Therefore, the present study evaluated the effects of four EC levels on growth, biomass, phenolic and flavonoid contents, radical-scavenging activity, and nutrient-solution dynamics of Chinese chives. The study was designed to identify an EC range that supports favorable vegetative growth while maintaining biochemical quality under the tested aeroponic conditions.

Material and Methods

Growth characteristics of aeroponic chives under varied nutrient-solution EC levels

The chive variety used in the experiment was 'Speed Green' (*Allium tuberosum* 'Speed Green'), which is commercially available from World seed Co., Korea. The nutrient solution was formulated according to the Japanese Enshi-type solution for onion plants and contained NO_3^--N 16, NH_4^+-N 2.0, PO_4-P 2.0, K 14.0, Ca 2.0, Mg 2.0, and SO_4-S 2.0 me L^{-1}.

On November 13, 2024, 128-cell seedling trays were filled with potting soil, and eight chive seeds were sown per cell. Seedlings were grown in a growth chamber at 20 °C and 60% relative humidity. The prepared nutrient solution was diluted to an EC of 0.8 dS m^{-1} and supplied by bottom watering.

On January 3, 2025, seedlings were removed from the potting soil, and their roots were washed. The seedlings were bundled in five groups and trimmed to 3 cm from the base. The trimmed seedlings were then transplanted into aeroponic pots containing perlite (2–4 mm diameter; SJ PLANT Co., Korea). Plants were initially maintained using nutrient solution at an EC of 0.8 dS m^{-1}. On February 5, 2025, the plants were

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exposed to four nutrient-solution EC treatments: 0.8, 1.2, 1.6, and 2.0 dS m^{-1}.

The experiment consisted of three independent experimental units per EC treatment. Growth characteristics were assessed at 5, 10, and 15 days after treatment initiation. Because measurements were obtained repeatedly from the experimental units over time, the time-point observations were treated as repeated measurements rather than independent observations. The measured variables included number of leaves, number of roots, plant height, root length, shoot fresh weight, root fresh weight, shoot dry weight, and root dry weight. The nutrient solution was replaced after each growth observation.

For improved reproducibility, the manuscript should report the dimensions and number of plants accommodated by each aeroponic unit, spray/nozzle specifications, spray frequency or duration, nutrient-solution volume per unit, solution temperature, light conditions, and pH management. These variables can influence nutrient delivery and root-zone conditions in aeroponic cultivation and should therefore be clearly documented.

Analysis of nutrient solution in the aeroponic system

After each growth observation, the nutrient solution was replenished to compensate for the volume consumed. EC and pH were measured using a portable electrical conductivity meter (HI 9811-5, Hanna Instruments, USA). Samples of the nutrient solution were submitted to the Agricultural Soil Analysis Center at Sunchon National University for the determination of ammonia nitrogen, nitrate nitrogen, sulfate, copper, manganese, boron, zinc, iron, potassium, calcium, magnesium, and total phosphorus.

Because only one analytical sample was available for each treatment-time combination, nutrient-solution measurements were treated as descriptive observations. No inferential statistical tests were applied to these data, and differences among treatments should not be interpreted as statistically confirmed treatment effects. The nutrient-solution results are therefore presented to illustrate temporal and treatment-associated trends rather than to provide definitive estimates of nutrient uptake.

The equipment used for elemental analysis is presented in Table 1.

Table-1. Analytical instruments and methods used for nutrient analysis.

Element	Analysis Equipment
NH_4-N, NH_3-N, Sulfur ion	Dionex Aquion Ion Chromatography System, Thermo Fisher Scientific, US
Copper, Manganese, Boron, Zinc, Iron	PerkinElmer NexION 350X ICP-MS, PerkinElmer, Inc., US
Potassium, Calcium, Magnesium	PerkinElmer Avio 200 ICP-OES, PerkinElmer, Inc., US
Total Phosphorus	Biochrom Libra S22 UV-Vis Spectrophotometer, Biochrom Ltd., GB

Extraction of chive samples

Chives cultivated under all EC treatments were harvested, washed, and freeze-dried for 72 h. The dried samples were ground using a blender. Extraction was performed using a slightly modified method of Jang et al. (2020). Briefly, 100 mL of 70% ethanol was added to 1 g of powdered sample, followed by ultrasonic extraction (Powersonic 410, HWASHIN TECHNOLOGY Co., Korea) for 30 min. The extracts were filtered through filter paper using a filtration flask and vacuum pump. The resulting 70% ethanol extracts were used for antioxidant analyses.

Total polyphenol content and total flavonoid content

Total polyphenol content (TPC) was determined using a modified Folin–Ciocalteu method (Velioglu et al., 1998). Briefly, 2 mL of 2% sodium carbonate was

added to 0.1 mL of extract and allowed to react for 3 min, followed by the addition of 0.1 mL of 50% Folin–Ciocalteu reagent. The reaction mixture was maintained for 30 min, and absorbance was measured at 750 nm using a UV/visible spectrophotometer. TPC was expressed as tannic acid equivalents (TAE) per gram of sample based on a tannic acid standard curve. Total flavonoid content (TFC) was determined using the diethylene glycol colorimetric method (Lee et al., 2022). A 0.2-mL sample was mixed with 2 mL diethylene glycol and 0.2 mL 1 N NaOH and incubated for 1 h at 37 ± 2 °C. Absorbance was measured at 420 nm. TFC was expressed as naringin equivalents (NE) per gram of sample based on a naringin standard curve.

ABTS and DPPH radical-scavenging activity

ABTS radical-scavenging activity was determined using a modified method of Re et al. (1999). A 7.4 mM ABTS solution was mixed with 2.6 mM potassium persulfate and maintained in darkness for 24 h. The resulting solution was diluted until an absorbance of 0.70 ± 0.03 at 732 nm was obtained. Aliquots of diluted ABTS solution (0.95 mL) were mixed with 0.05 mL sample extract and incubated in darkness for 10 min. Absorbance was measured at 732 nm.

DPPH radical-scavenging activity was determined using a modified method of Blois (1958). A 0.8 mL aliquot of diluted DPPH solution was mixed with 0.2 mL sample extract and incubated in darkness for 30 min. Absorbance was measured at 517 nm.

For both assays, radical-scavenging activity was expressed as RC_{50}, defined as the extract concentration required to reduce the initial radical signal by 50%. Because RC_{50} is an inverse measure of antioxidant potency, lower RC_{50} values indicate stronger radical-scavenging activity.

Statistical analysis

Growth and biochemical data were analyzed using SAS 9.4 (SAS Institute Inc., Cary, NC, USA). For growth measurements collected repeatedly from the same experimental units at 5, 10, and 15 days, a repeated-measures linear mixed-effects model was used, with EC, time, and EC × time as fixed effects and experimental unit as the repeated/random factor. Appropriate covariance structure was selected based on model-fit criteria. When significant treatment effects were detected, Tukey-adjusted pairwise comparisons were performed at $p < 0.05$.

Biochemical measurements obtained from independent experimental samples were analyzed using one-way ANOVA where the assumptions of the model were satisfied, followed by Tukey's honestly significant difference test at $p < 0.05$. The numbers of biological replicates and technical measurements were reported separately. Nutrient-solution measurements, which were based on a single analytical sample per treatment-time combination, were summarized descriptively and were not subjected to inferential statistical analysis.

Results

Growth characteristics of chives cultivated under different EC levels

Growth responses differed according to EC level and sampling time, with significant effects of treatment, time, and/or their interaction detected by the repeated-measures analysis. The comparative phenotypes of Chinese chives after 15 days are presented in Figure 1. Plant height increased throughout the experimental period and reached the highest value of 25.33 cm at EC 1.6 dS m^{-1}, compared with 23.36 cm at EC 0.8 dS m^{-1} after 15 days. The response indicates that increasing EC from 0.8 to moderate levels was generally favorable for vegetative growth, whereas the response at 2.0 dS m^{-1} did not provide a consistent additional benefit.

The number of leaves also varied with EC and time. After 15 days, the highest value was recorded at EC 1.2 dS m^{-1} (28 leaves $cell^{-1}$), whereas lower values were recorded at 0.8 and 2.0 dS m^{-1}. The decline in leaf production at the highest EC compared with the moderate EC treatments suggests that increasing nutrient concentration beyond the favorable range did not proportionally improve vegetative development. Root length and number of roots showed broadly similar treatment-dependent responses (Table 2; Figure 2).

Shoot fresh weight also varied among EC treatments. At the final observation, values of approximately 2.79 and 3.03 g $cell^{-1}$ were recorded at EC 1.6 and 2.0 dS m^{-1}, respectively. However, because the responses varied across sampling dates, the data do not support a simple linear relationship between EC and biomass. Similar treatment-dependent patterns were observed for shoot dry weight, root fresh weight, and root dry weight (Table 2; Figure 2).

Overall, the repeated-measures analysis indicates that moderate EC treatments, particularly 1.2 and 1.6 dS m^{-1}, generally supported favorable vegetative growth

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under the conditions tested. However, these results should not be interpreted as evidence that 1.2 dS m^{-1} is universally optimal, because cultivar, aeroponic system design, nutrient formulation, environmental conditions, and crop developmental stage may all modify the response.



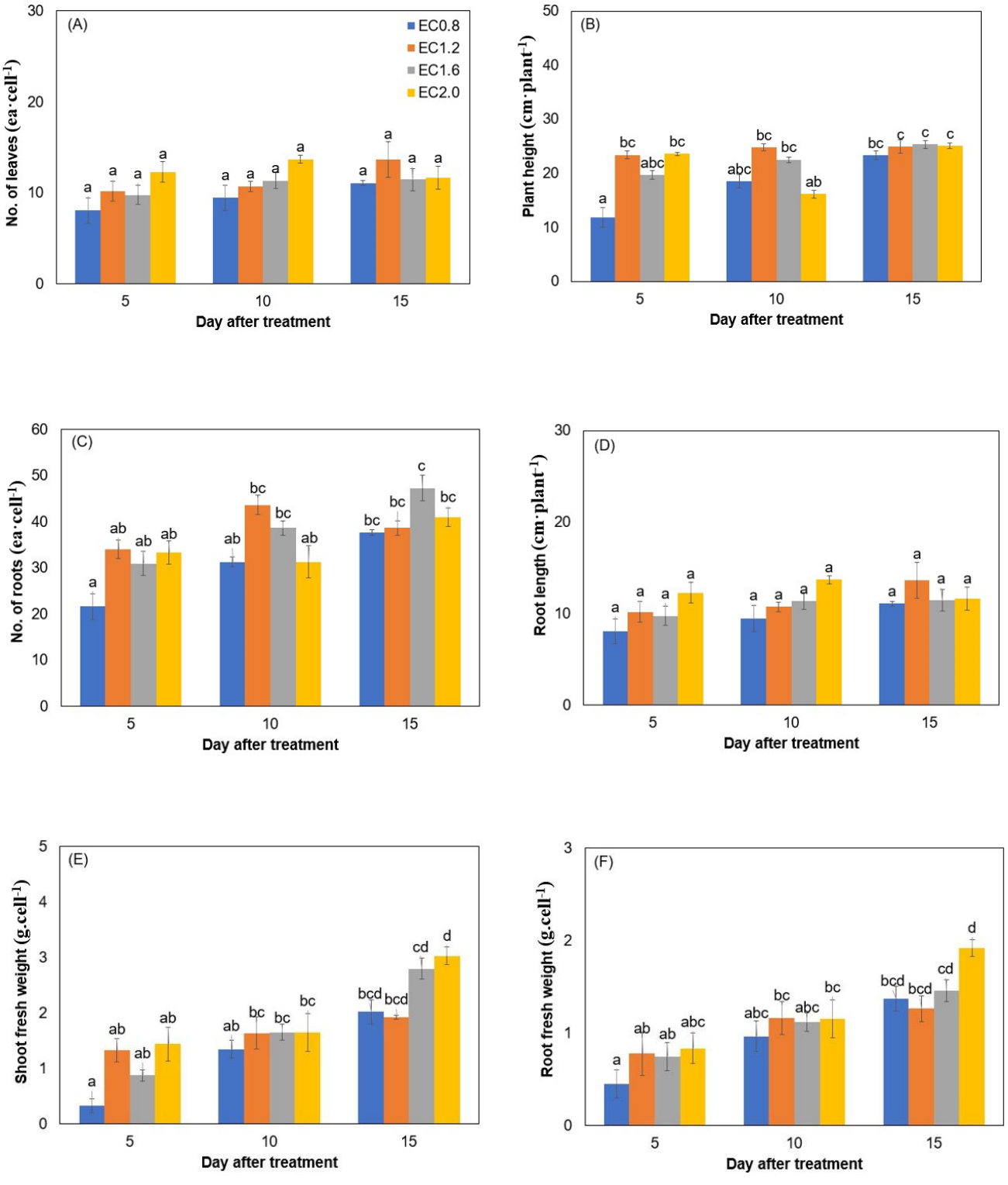
Figure-1. Comparative phenotypes of Chinese chive plants after 15 days experiment. The ECs, 1.2 $dS.m^{-1}$ and 1.6 $dS.m^{-1}$ showed better morphology than other EC treatments. There are three replications for each EC treatment.

Table-2. Growth characteristics of Chinese chive at 15 days of treatment as affected by nutrient solution concentration strength in aeroponic system.

Nutrient solution strength	Plant height ($cm \cdot plant^{-1}$)	No. of leaves ($ea \cdot cell^{-1}$)	Shoot fresh weight ($g \cdot cell^{-1}$)	Shoot dry weight ($g \cdot cell^{-1}$)	No. of roots ($ea \cdot cell^{-1}$)	Root length ($cm \cdot plant^{-1}$)	Root fresh weight ($g \cdot cell^{-1}$)	Root dry weight ($g \cdot cell^{-1}$)	Leaf area ($cm^2 \cdot cell^{-1}$)
EC 0.8	23.36 ± 0.81bc	25.66 ± 0.57def	2.0 ± 0.21bcd	0.18 ± 0.005cd	37.66±0.57bc	11.1 ± 0.26a	1.3 ± 0.13bcd	0.13 ± 0.008cde	46.35±0.76c
EC 1.2	24.96 ± 1.20c	28 ± 0f	1.92 ± 0.03bcd	0.17 ± 0.007bcd	38.66 ±1.52bc	13.66 ± 1.93a	1.26 ± 0.13bcd	0.13 ± 0.01bcd	60.51 ± 2.34bc
EC 1.6	25.33 ± 0.70c	27 ± 1ef	2.79 ± 0.18cd	0.27 ± 0.02d	47.33 ± 2.7c	11.46 ± 1.18a	1.45 ± 0.120cd	0.18 ± 0.009cd	57.2 ± 2.45cd
EC 2.0	25.06 ± 0.49c	23 ± 0abcde	3.03 ± 0.15d	0.27 ± 0.01d	41 ± 2bc	11.66 ± 1.28a	1.91 ± 0.09d	0.22 ± 0.02d	47.51 ± 1.56c
Anova	F = 6.233	F = 10.316	F = 9.556	F = 11.223	F = 6.864	F = 0.777	F = 8.658	F = 8.735	F = 6.432
	Df = 11,1	Df = 11,1	Df = 11,1	Df = 11,1	Df = 11,1	Df = 11,1	Df = 11,1	Df = 11,1	Df = 11,1
	P = 0.000	P = 0.000	P = 0.000	P = 0.000	P = 0.000	P = 0.659	P = 0.000	P = 0.000	P = 0.000

Values (± SD) are means of 3 replicates (n = 3). Different letters indicate significant differences among the means written in every column according to Tukey's HSD following one-way ANOVA ($\alpha<0.05$).

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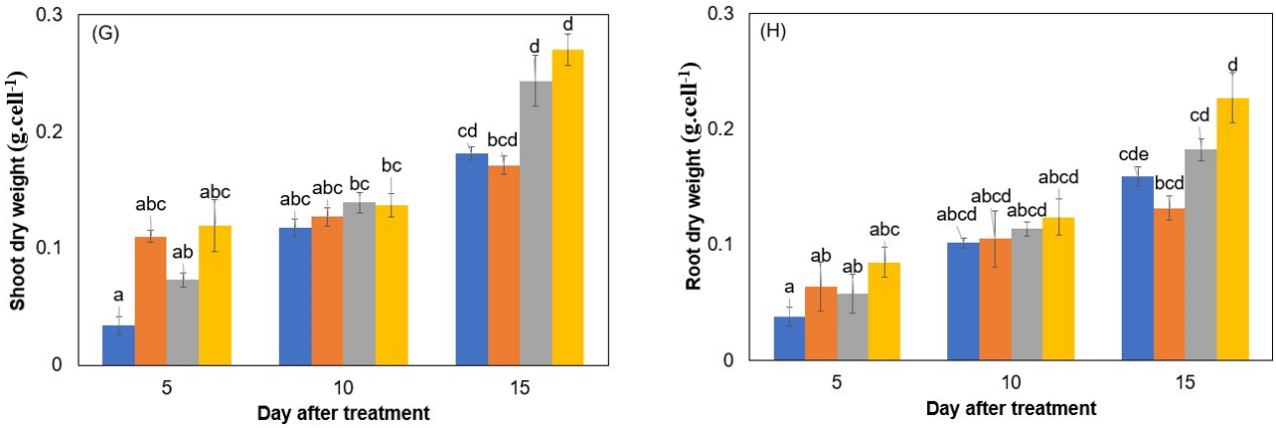


Figure-2. The observation of changes in growth characteristics during the time interval e.g. 5, 10 and 15 days. No. of leaves (A), Plant height (B), No. of roots (C), and Root length (D), Shoot fresh weight (E), Root fresh weight (F), Shoot dry weight (G), Root dry weight (H).

Vertical bars show mean and ± SD (n = 3). Different letters indicate significant differences among the means according to Tukey's HSD following one-way ANOVA ($\alpha<0.05$).

Antioxidant compound contents in aeroponically grown chives

TPC and TFC showed distinct responses according to tissue type and EC treatment (Figure 3). Shoot TPC was highest at approximately 8.76 mg GAE g^{-1} at EC 2.0 dS m^{-1} and lowest at approximately 7.40 mg GAE g^{-1} at EC 1.6 dS m^{-1}. In roots, TPC was highest at EC 1.6 dS m^{-1} (9.89 mg GAE g^{-1}) and lowest at EC 1.2 dS m^{-1} (8.54 mg GAE g^{-1}).

Shoot TFC was highest at EC 0.8 dS m^{-1} (34.5 mg NE g^{-1}) and lowest at EC 1.6 dS m^{-1} (30.38 mg NE g^{-1}). Root TFC was highest at EC 1.2 dS m^{-1} (3.71 mg NE g^{-1}) and lowest at EC 2.0 dS m^{-1} (3.03 mg NE g^{-1}). The substantially higher TFC values in shoots than roots indicate strong tissue-specific differences in flavonoid accumulation. Importantly, the biochemical data do not demonstrate a uniform increase in TPC or TFC with increasing EC.

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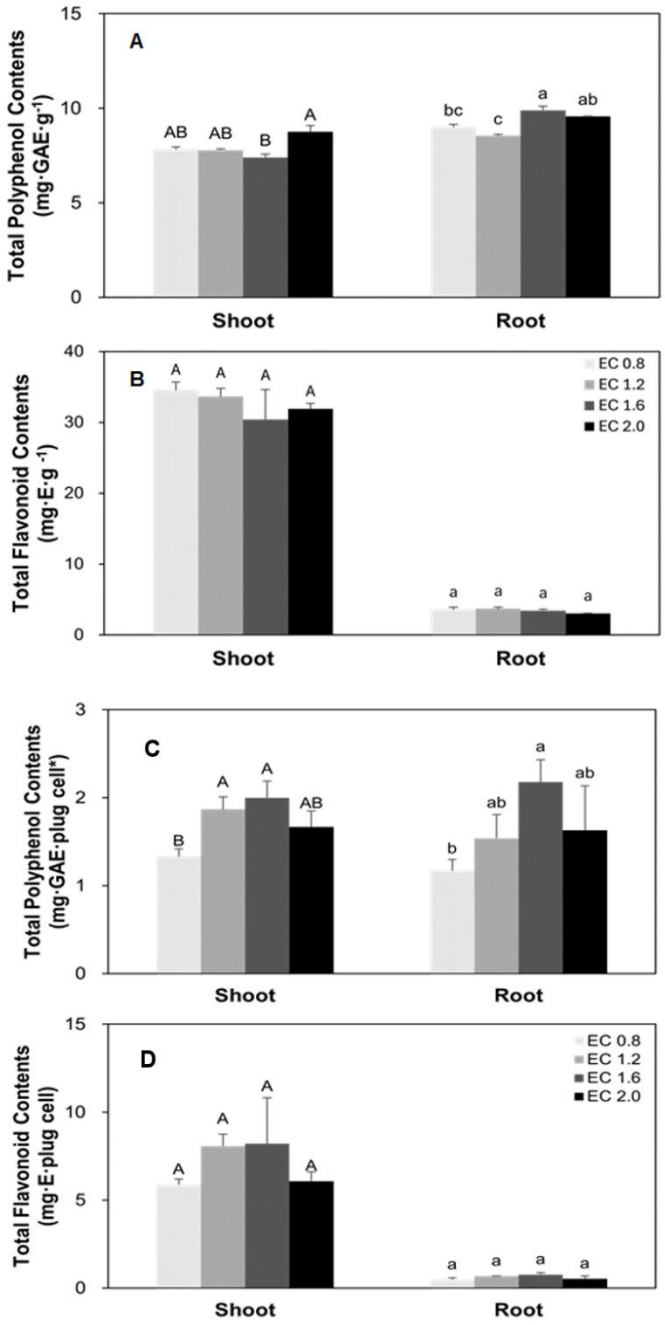


Figure-3. The total antioxidant compounds of Chinese chive were calculated by the following methods (1) per gram for each treatment (2) multiplying the antioxidant content per gram for each treatment by the dry weight per cell. Total Polyphenol Contents (A and C), and Total Flavonoid Contents (B and D).

Vertical bars show mean and ± SD (n = 3). Different letters indicate significant differences among the means according to Tukey's HSD following one-way ANOVA ($\alpha<0.05$). *cell means 5 plants in a plug cell.

ABTS and DPPH radical-scavenging activity

Radical-scavenging responses varied according to tissue and assay (Figure 4). Because lower RC_{50} values indicate stronger radical-scavenging activity, the results should be interpreted based on the lowest RC_{50} rather than the highest numerical value.

For DPPH, shoot RC_{50} values ranged from approximately 11.16 to 15.87 mg mL^{-1}, with the

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lowest value observed at EC 2.0 dS m^{-1} and the highest at EC 1.2 dS m^{-1}. In roots, the lowest RC50 was approximately 5.62 mg mL^{-1} at EC 1.6 dS m^{-1}, indicating comparatively stronger DPPH-scavenging activity at this treatment.

For ABTS, the lowest shoot RC_{50} was approximately 4.43 mg mL^{-1} at EC 1.2 dS m^{-1}, whereas the highest value was approximately 6.79 mg mL^{-1} at EC 1.6 dS m^{-1}. In roots, the lowest RC_{50} was approximately 3.91 mg mL^{-1} at EC 0.8 dS m^{-1} and the highest was approximately 4.84 mg mL^{-1} at EC 1.2 dS m^{-1}.

These findings demonstrate that antioxidant capacity was both assay- and tissue-dependent. Accordingly, the results do not support the generalized conclusion that moderate EC consistently increases antioxidant activity. Differences among DPPH, ABTS, TPC, and TFC responses may reflect the distinct chemical principles and classes of antioxidant compounds detected by these assays.

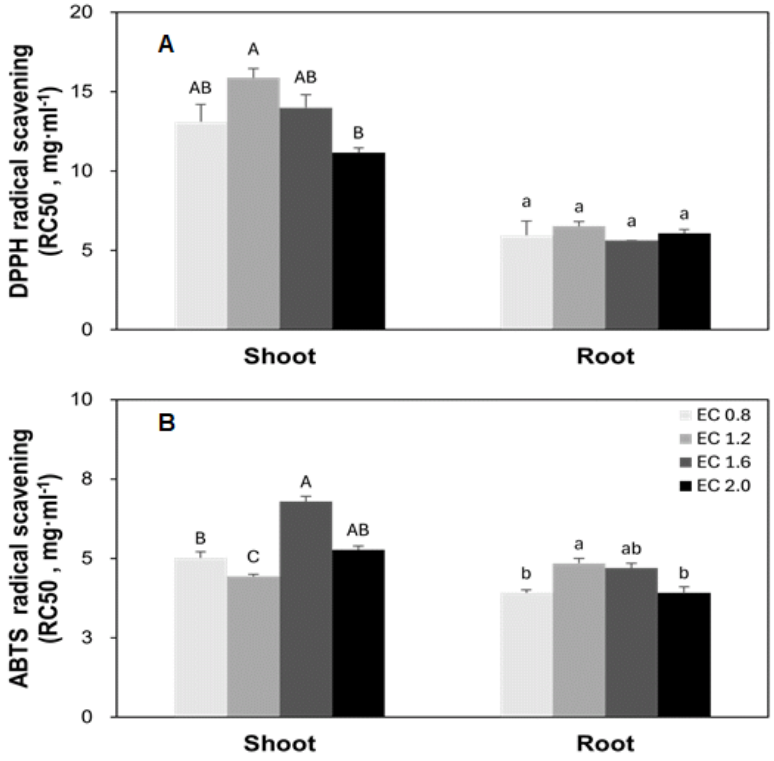


Figure-4. Free radical scavenging activities in the shoot and root of Chinese chive depending on nutrient solution strength. It is important to note that the smaller the RC50 value, the greater the antioxidant activity. Uppercase letters indicate the shoot, and lowercase letters indicate the root. DPPH (A) and ABTS (B).

Vertical bars show mean and ± SD (n = 3). Different letters indicate significant differences among the means according to Tukey's HSD following one-way ANOVA ($\alpha<0.05$).

Nutrient-solution concentration dynamics

The concentrations of macronutrients in the nutrient solution changed during cultivation (Figure 5). Mg, NH_4^+-N, Ca, and P showed relatively limited variation compared with some other nutrients. K showed greater apparent depletion at EC 1.6 and 2.0 dS m^{-1} during the earlier growth period, whereas smaller changes were observed at EC 0.8 and 1.2 dS m^{-1}. However, because nutrient-solution analyses were not replicated, these patterns should be regarded as descriptive observations rather than statistically confirmed differences in nutrient uptake.

S showed greater apparent depletion during later growth periods, whereas NO_3^--N showed relatively limited depletion early in the experiment and more pronounced depletion at later stages. These temporal changes may indicate changes in nutrient demand as plants developed, but they cannot be distinguished from other processes affecting nutrient-solution concentrations without replicated measurements and a complete mass-balance assessment.

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Among micronutrients, Mn exhibited relatively pronounced changes across treatments, whereas Fe showed comparatively smaller changes. Cu and Zn also displayed treatment- and time-dependent residual concentrations. The observed residual nutrient concentrations suggest that EC alone may not accurately describe the availability or utilization of individual nutrients. This interpretation is consistent with recent hydroponic research showing that individual nutrient concentrations can diverge substantially during cultivation despite relatively stable EC values.

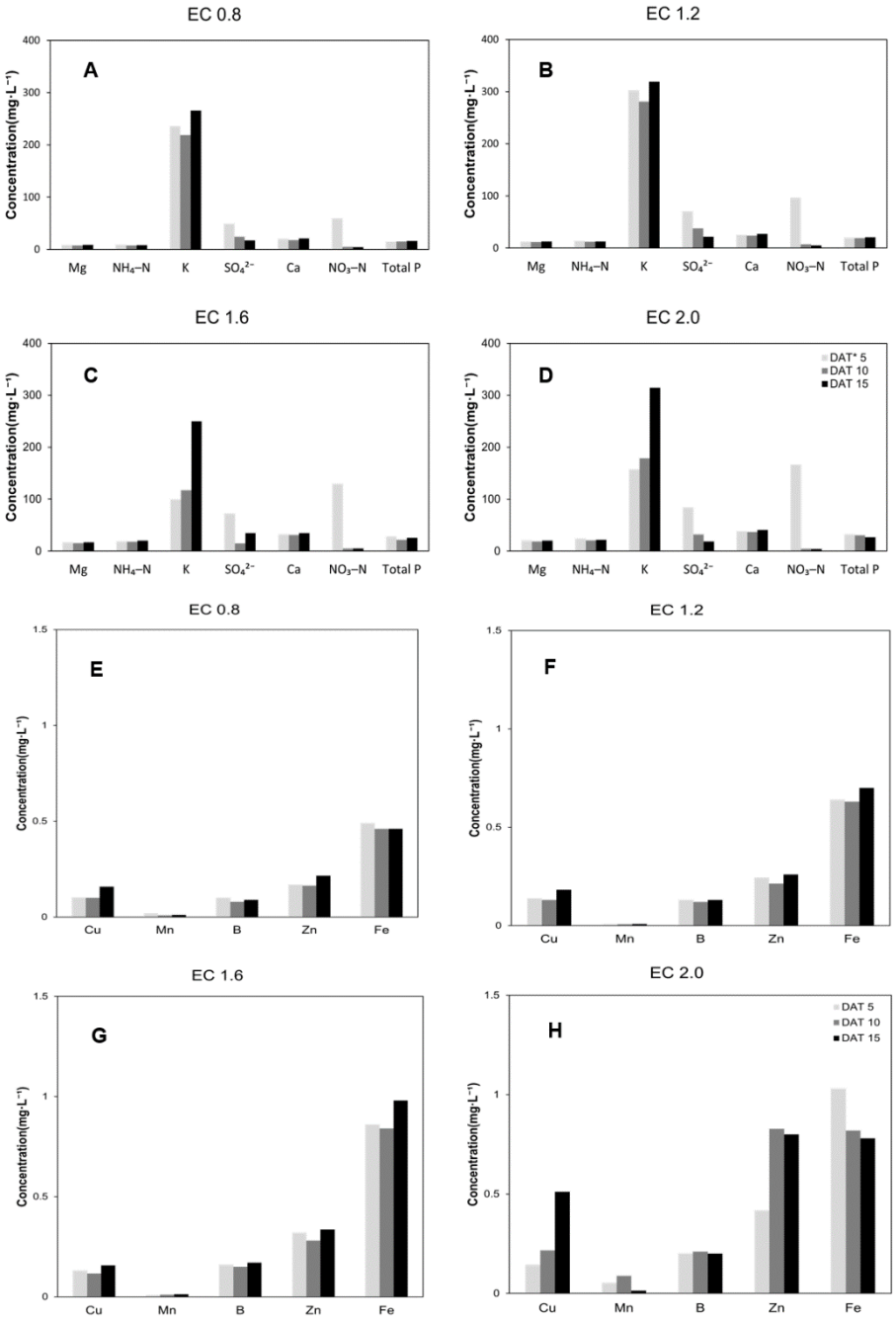


Figure-5. Changes in macronutrient (A, B, C and D) and micronutrient (E, F, G and H) concentrations of the nutrient solution. The nutrient solution was replaced every 5 days after growth measurements. There is only one replication (n = 1) for this experiment.

*DAT mean Days after treatment.

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Relationships between growth and biochemical parameters

Correlation analysis was used to explore associations among growth and biochemical variables (Figure 6). Growth parameters, including plant height, root length, number of roots and leaves, and shoot and root fresh and dry weights, showed generally positive relationships with one another.

Associations between growth traits and biochemical variables were comparatively weaker and more variable. Correlations among TPC, TFC, DPPH, and ABTS responses were not uniformly positive, indicating that the different biochemical assays captured partially distinct aspects of antioxidant composition. Because correlation does not establish causation, these relationships should be interpreted as associations rather than evidence that one trait directly determines another.

The positive association observed between DPPH and ABTS responses may reflect their shared sensitivity to antioxidant compounds capable of donating electrons or hydrogen atoms. Conversely, weak or negative associations among TPC, TFC, and radical-scavenging responses may result from differences in antioxidant composition and the different chemical reactivities of the analytical assays.

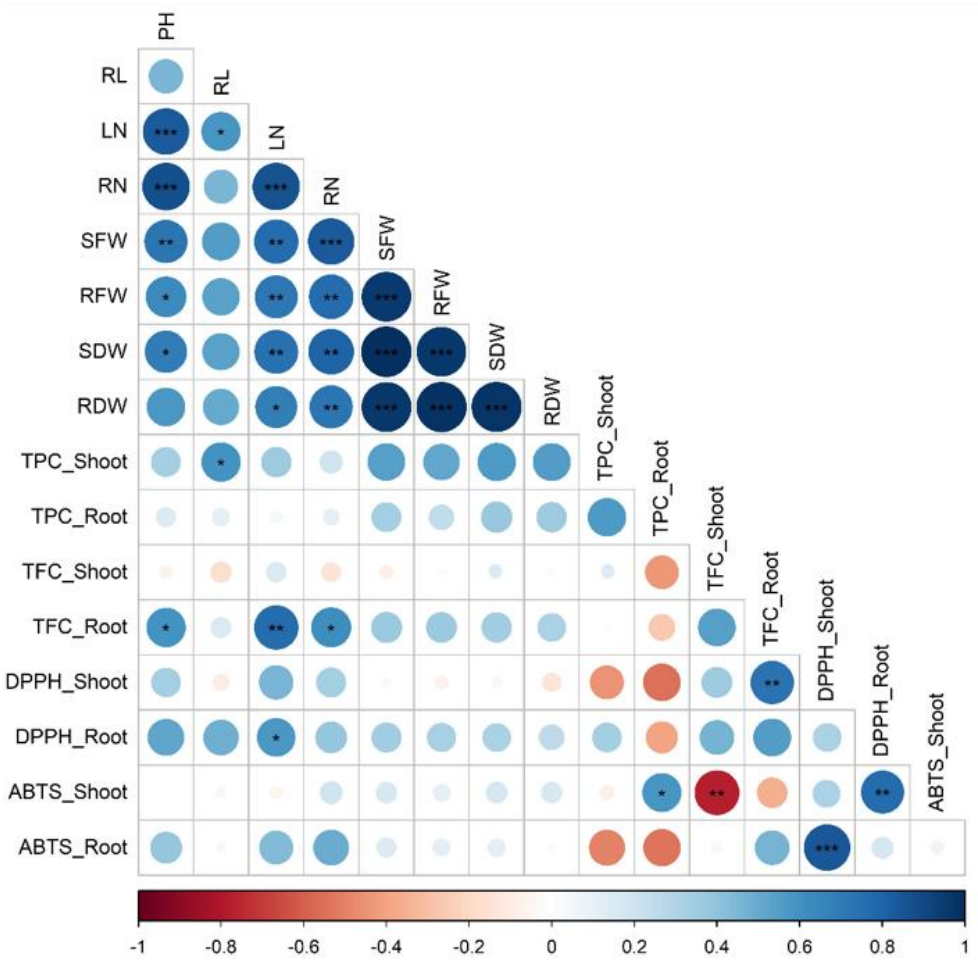


Figure-6. Pearson correlation matrix for different growth and biochemical attributes of Chinese chives under varied ECs level. PH, plant height; RL, root length, LN, number of leaves; RN, number of roots; SFW, shoot fresh weight; RFW, root fresh weight; SDW, shoot dry weight; RDW, root dry weight; TPC_Shoot, total polyphenol content in shoot; TPC_Root, total polyphenol content in root; TFC_Shoot, total flavonoid content in shoot; TFC_root, total flavonoid content in root; DPPH_Shoot, DPPH radical scavenging activity in shoot; DPPH_root, DPPH radical scavenging activity in root; ABTS_Shoot, ABTS radical scavenging activity in shoot; ABTS_Root, ABTS radical scavenging activity in root. *, ** and *** denoting significant correlation at $P < 0.05$, $P < 0.01$ and $P < 0.001$ levels, respectively. Heatmap shows the positive and negative correlation.

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Discussion

The present study demonstrates that nutrient-solution EC influenced the growth and biochemical characteristics of Chinese chives grown in an aeroponic system, although the responses were not uniform across all measured traits. The principal finding was that moderate EC levels, particularly 1.2 and 1.6 dS m^{-1}, generally supported favorable vegetative growth under the experimental conditions. In contrast, biochemical responses varied according to tissue type and analytical method. This distinction is important because EC optimization should consider both productivity and quality rather than assuming that increasing nutrient concentration necessarily improves all plant characteristics. Previous studies have likewise demonstrated that plant responses to EC are species- and system-dependent and that excessive nutrient concentrations may cause nutritional imbalance and reduce dry-matter production (Bugbee, 1995; Schwarz, 1995).

The favorable growth observed at moderate EC is consistent with previous studies showing that crop-specific EC management is important in hydroponic systems. Tzortzakis et al. (2020) identified EC management as a key factor in successful hydroponic production, while Pinter et al. (2003) emphasized the importance of appropriate nutrient concentrations and elemental balance for plant growth and development. Chinese chives have previously demonstrated physiological and metabolic responses to mild salinity, with moderate stress capable of modifying growth, nutrient status, and flavor-related metabolism (Huang et al., 2017; Liu et al., 2022; Xie et al., 2023). Similarly, studies of other hydroponically cultivated vegetables have shown that the optimum EC depends on crop species, cultivar, environmental conditions, and nutrient formulation rather than following a universal threshold (Hosseini et al., 2021; Dewir and Alsadon et al., 2022).

The reduced performance observed at the highest EC for some growth variables may be associated with increasing osmotic pressure of the nutrient solution. At excessive EC, plants may face greater difficulty maintaining water uptake even when nutrients are abundant. Moreover, elevated concentrations of individual ions can alter nutrient balance and competition for uptake sites. Bugbee (1995) and Schwarz (1995) reported that excessive ion uptake might disturb nutritional balance and consequently reduce plant dry-matter production. Similarly, Samarakoon et al. (2006) observed reductions in marketable yield, fresh weight, leaf number, leaf area, and plant height of lettuce as EC increased from 1.5 to 3.5 dS m^{-1}. Thus, the response at 2.0 dS m^{-1} suggests that additional nutrient concentration did not necessarily provide a proportional growth advantage.

Recent research supports the need to distinguish EC from the concentration of individual nutrients. The response of nutrient uptake to EC is complex because increasing solution concentration can increase the uptake of some ions while simultaneously interfering with the absorption or utilization of others (Bugbee, 1995; Schwarz, 1995). Moreover, nutrient absorption can vary according to the cultivation method and nutrient-management strategy (Son et al., 2020). In a recirculating hydroponic system, nutrient concentrations changed over time even when EC was maintained, and nutrient uptake efficiencies differed markedly among elements. Therefore, the nutrient-solution results of the present study provide useful preliminary evidence of temporal nutrient dynamics, but replicated nutrient analyses and plant-tissue mineral measurements are needed before nutrient-specific recommendations can be made.

The observed response is also broadly consistent with previous reports on chive and other hydroponically cultivated crops. Dewir and Alsadon (2022) reported that an EC of 2.1 dS m^{-1} adversely affected several vegetative characteristics compared with a lower EC of 0.7 dS m^{-1}, whereas Salas et al. (2020) reported different responses at 3.0 dS m^{-1}. These differences further indicate that optimum EC cannot be transferred directly among cultivation systems. Hosseini et al. (2021) reported favorable growth of lettuce and basil within an EC range of approximately 0.9–1.2 dS m^{-1}, while Dewir et al. (2005) identified 1.2 dS m^{-1} as an appropriate EC for *Spathiphyllum cannifolium*. Collectively, these findings support the concept that EC should be optimized according to crop, cultivar, cultivation method, and nutrient formulation rather than using a single universal value.

The biochemical responses further indicate that moderate EC should not be regarded as a universal inducer of antioxidant accumulation. TPC, TFC, DPPH, and ABTS did not exhibit identical response patterns. This may be expected because phenolic and flavonoid assays provide broad estimates of compound classes, whereas DPPH and ABTS measure overall radical-scavenging capacity and can respond to compounds that are not quantified by TPC or TFC assays. Consequently, the absence of a consistent

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relationship among these measurements does not necessarily indicate inconsistency in plant physiology. Previous research has shown that mild salinity or nutritional stress can stimulate secondary metabolism through stress-responsive pathways, whereas excessive stress can impair growth and antioxidant homeostasis. Abiotic stress has been associated with enhanced phenolic biosynthesis, suggesting that moderately stressed plants might accumulate greater concentrations of phenolic compounds (Naczk and Shahidi, 2004). Krauss et al. (2006) similarly reported increased phenolic and antioxidant concentrations in tomato under elevated EC, which was associated with stress-related responses. However, Ali et al. (2014) found no significant differences in total phenolics under moderate EC conditions, demonstrating that biochemical responses are not uniform across crops or stress intensities. Taârit et al. (2012) further reported that total phenolic content in *Salvia sclarea* increased under low-to-moderate salinity but declined under more severe stress. Similar responses have been reported in several vegetable crops (Hajiboland et al., 2009; Yin et al., 2010; Reich et al., 2017). The present findings are compatible with this general concept, but the experiment did not directly measure ROS, antioxidant enzymes, osmotic potential, ion concentrations in plant tissue, or gene expression. Therefore, mechanisms involving ROS signaling or activation of antioxidant pathways should be regarded as possible explanations rather than demonstrated mechanisms.

The decline in growth and biochemical responses at the higher EC might also reflect osmotic and ion-specific effects. High EC can reduce the osmotic potential of the nutrient solution and consequently restrict water movement into plant tissues (Dorais et al., 2001). Salinity may additionally cause nutritional disorders through competition among ions during uptake, transport, and partitioning (Grattan and Grieve, 1999). Moya et al. (2017) likewise reported that high EC can impose water-deficit effects that negatively affect crop performance. Although relatively high EC during early growth might sometimes contribute to stronger cell-wall development, excessive EC can ultimately constrain plant growth and productivity (Dorais et al., 2001).

The nutrient responses observed in the present study should also be interpreted in the context of ion interactions. Salinity can alter the availability, uptake, transport, and accumulation of both macro- and micronutrients, with the direction and magnitude of these effects depending on the crop, nutrient composition, and salinity level (Grattan and Grieve, 1999). Interactions between nitrate and chloride, for example, can influence nitrate uptake under saline conditions (Dorais et al., 2001). Similarly, salinity-related changes in micronutrient accumulation might be variable; Chrysargyris et al. (2021) reported nutrient responses in Chinese chives under salinity, while Grattan and Grieve (1999) highlighted that salinity may increase, decrease, or have little effect on micronutrient accumulation depending on the experimental conditions. Thus, the nutrient patterns observed here provide useful indications but should not be interpreted as evidence of a universal nutrient-uptake response to increasing EC.

The study also has several limitations. First, only three experimental units were used per EC treatment, which limits statistical power. Second, repeated growth observations require a repeated-measures analytical framework rather than treating each time point as an independent observation. Third, nutrient-solution analyses were based on a single analytical sample per treatment-time combination; consequently, these data cannot provide statistically supported estimates of treatment effects or nutrient uptake. Fourth, the experiment covered only a 15-day treatment period and therefore does not establish long-term yield or repeated-harvest performance. Finally, the study evaluated one cultivar and one nutrient formulation under controlled experimental conditions. These limitations should be considered when extrapolating the recommended EC range to commercial aeroponic production.

The novelty of the present study therefore lies not in demonstrating a universal optimum EC, but in providing cultivar- and system-specific information on the simultaneous responses of growth, biomass, biochemical characteristics, and nutrient-solution dynamics of Chinese chives under aeroponic cultivation. This integrated assessment offers a useful foundation for subsequent experiments involving longer cultivation periods, repeated harvests, replicated nutrient analyses, and tissue mineral measurements. The findings of Son et al. (2020); Tzortzakis et al. (2020), Hosseini et al. (2021) and Dewir and Alsadon (2022) further support the need for system-specific EC optimization, while the reported variability in biochemical responses to salinity (Krauss et al., 2006; Taârit et al., 2012; Ali et al., 2014) indicates that productivity and nutritional/functional quality should be evaluated together.

Conclusion

Under the conditions of the present experiment, moderate nutrient-solution EC levels of 1.2–1.6 dS m^{-1} generally supported favorable vegetative growth of Chinese chives in the tested aeroponic system. However, responses of TPC, TFC, DPPH, and ABTS were tissue- and assay-dependent, and therefore the results do not support a generalized conclusion that moderate EC uniformly enhances antioxidant capacity. Nutrient-solution measurements indicated temporal changes in individual nutrients, but these observations were descriptive because the nutrient analyses were not replicated.

Accordingly, an EC range of 1.2–1.6 dS m^{-1} may be considered a preliminary operational range for the tested cultivar and experimental conditions rather than a definitive optimum for Chinese chive production. Further studies should include more independent experimental units, repeated nutrient-solution analyses, plant-tissue mineral measurements, longer cultivation periods, repeated harvests, and evaluation of additional cultivars. Such experiments would allow more robust determination of EC thresholds and nutrient-use efficiency for commercial aeroponic production of Chinese chives.

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Contribution of Authors

Yaseen I & Lee BS: Conceptualized the research work.

Yaseen I & Park BT: Conducted the experiment, collected samples and performed laboratory analyses under supervision of Lee BS.

Yaseen I & Mukhtar T: Analyzed data and drafted the manuscript.

Lee BS, Mukhtar T & Yaseen I: Critically edited the manuscript.

All authors read and approved the final draft of the manuscript.

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