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RESEARCH ARTICLE

Effect of additional potassium and nickel on Hoagland solution combined with environmental condition for high antioxidants tomato production

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Abstract

Plant nutrient management and environmental conditions significantly affect plant growth, development and antioxidant contents. This research aims to identify the most effective plant nutrient management and environmental conditions for enhancing high-antioxidant tomato production. The Sweet Girl and Ranger tomato cultivars were evaluated for yield, fruit quality and antioxidant contents under 2 conditions: E1 (temperature ranging from 29 to 38 °C and relative humidity between 71–73 %) and E2 (temperature ranging from 32 to 36 °C and relative humidity between 75–80 %). These conditions were subjected to 6 different nutrient formulas, including Hoagland solution as control (H), H with 400 ppm potassium (H+K400), H with 300 ppm potassium (H+K300), H with 20 ppm nickel (H+Ni20), H with 10 ppm nickel (H+Ni10), H with 300 ppm potassium and 10 ppm nickel (H+K300+Ni10). The nutrient formulas did not yield significantly different results in terms of per-plant yields for the 2 cultivars. However, the H+K400 treatment showed notably higher lycopene contents, with increases of 1.2-fold for Ranger and 1.24-fold for Sweet Girl cultivars. Additionally, this treatment led to significant enhancements in total soluble solids (TSS) and β-carotene content in the Sweet Girl cultivar, by 1.09-fold and 1.10-fold compared to the control respectively. Environment E2 provided more favorable conditions for achieving increased antioxidant tomato production, including improvements in fruit color index (red/yellow) by 1.11 to 1.18-fold, fruit firmness by 1.13 to 1.14-fold, TSS by 1.10 to 1.24-fold, lycopene by 1.98 to 2.45-fold and β-carotene by 3.29 to 5.68-fold. Therefore, the H+K400 nutrient treatment and/or the E2 greenhouse conditions are recommended for producing high-antioxidant tomatoes, which have significant potential for fresh consumption or as materials for the nutraceutical or food industry.

Keywords

Lycopene; nickel; potassium; tomato; β-carotene

Introduction

Global tomato (*Solanum lycopersicum* L.) production reached 186.1 million tons, covering 4.9 million ha, with the tomato market valued at 181.7 billion USD in 2022. Thailand is a key contributor to tomato cultivation, with an approximate area of 6,065 ha and yield of around 137325 tons in 2022 (1, 2).

This economically significant crop is known for its rich content of various nutrients, including carotenoids such as β-carotene (ranging from 3677.4–10206.9 µg/100 g), lycopene (from 5020.0–11110.0 µg/100 g); monounsaturated fatty acids (11.0–17.7 g/100 g); essential minerals like potassium (16.6–1097.0 mg/100 g), sodium (56.9–80.7 mg/100 g) and calcium (48.5–162.1 mg/100 g); phytosterols (ranging from 918.0–1570.0 mg/kg); proteins (10.5–25.0 g/100 g) and vitamins including vitamin A (from 267.3–833.0 IU/100 g), vitamin C (from 10.9–85.0 mg/100 g) and vitamin K (98.3 µg/100 g) (3). Lycopene, a prominent carotenoid present in ripe tomato fruits, serves as a crucial antioxidant. Its role extends to providing protection against harmful UV rays and mitigating oxidative damage to cellular structures. Additionally, lycopene has shown promising effects in managing various conditions such as heart disease, atherosclerosis, cancer, high cholesterol levels and blood pressure regulation (4). As a result, lycopene emerges as a key component contributing to the nutritional value of tomatoes. Furthermore, environmental factors such as nutrients, temperature, light intensity and relative humidity (RH) influence the physiological processes of tomatoes, thereby impacting their quality and antioxidant content (5, 6).

Macronutrients, including nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca) and micronutrients such as iron (Fe), sulfur (S), copper (Cu), boron (B), molybdenum (Mo), manganese (Mn), cobalt (Co), zinc (Zn), nickel (Ni) and chloride (Cl), play pivotal roles in plant metabolism and growth (7). Among the macronutrients, N, P and K concentrations exhibits a robust correlation with the presence of various compounds in tomato fruits, including phenolics, flavonoids, β-carotene and lycopene (8). Additionally, higher levels of N have been positively associated with increased sweetness and firmness of tomato fruit (9). Conversely, studies have shown a negative correlation between N levels (ranging from 0–420 kg/ha) and the presence of titratable acidity (0.404–0.374 %). Plants predominately utilize phosphorus in the form of calcium-based phosphates, with limited uptake potential from certain aluminum-based phosphates. Phosphorus present in ferric-based phosphates and other forms is generally considered inaccessible for direct utilization in human activities (9). Optimal levels of P play a pivotal role in regulating root development, stimulating early flowering and promoting fruit set in tomatoes (10). Additionally, P contributes to improving the skin and pulp color, taste, texture and vitamin C content of the fruit. K, on the other hand, activates enzymes involved in adenosine triphosphate production, which is crucial for regulating plant growth, early flowering and fruit setting in tomatoes. Furthermore, it facilitates the transport of glucose from the source to the sink, which affects the quality of tomato fruits, including taste, acidity level and sweetness (11). The application of NPK fertilizers can significantly increase yield by 1.58-fold and lycopene content by 2.09-fold compared to untreated conditions (12). In soilless culture, maintaining a high level of K (350–450 ppm) can promote lycopene accumulation in tomato fruits (5). Additionally, during the fruit development phase, it is crucial to maintain the ideal K:N ratio, which significantly influences both the quantity and quality of tomatoes (13). Research findings indicate that a nutrient solution with a K:N ratio of 2:1 resulted in increased plant yield, enhanced fruit firmness and higher total soluble solids (TSS) content. Among micronutrients, Ni plays a pivotal role in influencing various enzyme activities that directly impact plant growth and development. However, excessive Ni concentration can have negative effects on plant growth and yield inhibition (14, 15). Application of 50 µM Ni induced stress but also activated antioxidant enzymes, including guaiacol peroxidase and ascorbate peroxidase (16). Moreover, Ni levels ranging from 15 to 50 ppm have been found to increase the accumulation of N, P and K as well as vitamin C, and TSS in tomato fruits (16, 17). Additionally, applying liquid fertilizer through a drip irrigation system has been demonstrated to enhance fertilizer use efficiency and improve the quality of tomatoes in cultivation (18, 19).

Elevated temperatures during the fruit ripening phase can accelerate ethylene production, leading to an increased accumulation of carotenoids in tomato fruits (20). However, excessively high temperatures can induce stress in tomatoes and reduce the quality of yield (21). Natural light exposure generally results in higher yields and increased TSS in tomato fruits compared to shaded conditions. Conversely, shading conditions can enhance lycopene content (22). Maintaining an appropriate RH level is also crucial for promoting antioxidants and fruit quality in tomatoes. Different RH levels have varying effects on tomato fruit quality in greenhouse conditions. For example, maintaining an RH of 72 % at a temperature of 32.4 °C could lead to higher TSS and lycopene content compared to an RH of 62 % at the same temperature (23). Optimal nutrient supply and environmental conditions are essential for maximizing yield and quality in tomato cultivars. Therefore, this research aimed to identify the most suitable nutrient management practices for enhancing antioxidant content in 2 tomato cultivars.

Materials and Methods

Experimental design and plant materials

The greenhouse experiment was conducted in Nakhon Ratchasima, Thailand (latitude 14° 52' N, longitude 102° 0' E), using a randomized complete block design (RCBD) with 3 replications, each consisting 20 plants. The experiment spanned 2 distinct conditions: environment 1 (E1) and environment 2 (E2), from January to April 2020 and June to September 2020 respectively. Daily temperature and relative humidity (RH) measurements were recorded using a thermo-hygrometer (TFA Accuracy). E1 represented the dry season, characterized by an average monthly temperature ranging from 29 to 38 °C and RH levels between 71 % and 73 %. In contrast, E2 corresponded to the wet season, with an average monthly temperature of 32 to 36 °C and RH levels between 75 % and 80 %. Two tomato cultivars, namely Ranger and Sweet Girl, were utilized in this study. The growth process began with germination of seeds in

trays containing peat moss. Once the seedlings reached 30 days of age, they were carefully transplanted into 2-L pots filled with coco coir. The arrangement of these pots maintained inter-row and within-row spacing set precisely at 50 × 50 cm.

Drip irrigation was utilized to administer the nutrient solution once daily, ensuring an electrical conductivity (EC) of 1.5 dS/m and a pH level of 6.5, in accordance with the Hoagland and Arnon nutrient solution (24). Fifty days before flowering, the tomato plants were subjected to various nutrient formulations, including the Hoagland solution (H) as the control, H with 400 ppm potassium (H+K400), H with 300 ppm potassium (H+K300), H with 20 ppm nickel (H+Ni20), H with 10 ppm nickel (H+Ni10) and H with 300 ppm potassium and 10 ppm nickel (H+K300+Ni10) (Table 1). These nutrient treatments were maintained from the flowering stage until harvest, with adjustments made to the solution's EC, which was raised to 2.5 dS/m, while pH was maintained at 6.5.

Table 1. Plant nutrient formulas were used in this research.

Nutrients	Concentration (ppm)					
	H	H+K400	H+K300	H+Ni20	H+Ni10	H+K300+Ni10
N	242.65	242.65	242.65	242.65	242.65	242.65
P	30.86	30.86	30.86	30.86	30.86	30.86
K	231.22	400.00	300.00	231.22	231.22	300.00
Ca	202.37	202.37	202.37	202.37	202.37	202.37
Mg	48.22	48.22	48.22	48.22	48.22	48.22
S	63.69	63.69	63.69	63.69	63.69	63.69
Fe	4.99	4.99	4.99	4.99	4.99	4.99
Zn	0.05	0.05	0.05	0.05	0.05	0.05
Cu	0.02	0.02	0.02	0.02	0.02	0.02
Mn	0.50	0.50	0.50	0.50	0.50	0.50
B	0.51	0.51	0.51	0.51	0.51	0.51
Mo	0.01	0.01	0.01	0.01	0.01	0.01
Ni	–	–	–	20.00	10.00	10.00

Data collection

Yield and fruit quality

The experiment followed a RCBD with three replications, each consisting of 20 plants per replication. Forty-five days after anthesis, 5 ripe tomato fruits from the Ranger cultivar and 20 fruits from the Sweet Girl cultivar were randomly selected and harvested from each plant to estimate the yield per plant. Subsequently, the harvested tomato fruits underwent quality assessments. Specifically, 2 fruits per plant were randomly selected from a second cluster near the trunk of each plant. These fruits were subjected to 3 measurements: fruit color index using a CR-400 Chroma Meter (Konica Minolta, Osaka, Japan) and expressed numerically as a^*/b^*, representing redness/yellowness; fruit firmness (N), measured with a TA–XT2i texture analyzer (Stable Micro Systems, Surrey, UK) and TSS content (^{0}Brix), measured using a refractometer (Optika, Italy) (16).

Antioxidant contents

The experiment was arranged in a RCBD with three replications, each consisting of 20 plants per replication. From each tomato plant, 2 fruits were selected and collected for the analysis of antioxidant contents, including lycopene and β-carotene (25). For lycopene analysis, the tomato fruit was homogenized, and 1 g of fresh tomato was mixed with 20 mL of hexane: acetone: ethanol (2:1:1, v:v:v) in darkness and shaken at 180 rpm for 15 min. Subsequently, 10 mL of pre-cooled deionized water was added to the mixture, followed by continued shaking for 5 min. The upper layer (non-polar) was transferred to a glass cuvette and absorbance was measured at 503 nm using a UV-Visible Spectrophotometer-UH5300 (Hitachi High-Tech Corporation, Tokyo, Japan) (26). The lycopene content, correlated with the absorbance at 503 nm, was estimated in mg per 100 g of fresh weight (FW) using equations:

$$\text{Lycopene (mg/100 g FW)} = (X/Z) \times A_{503} \times 3.12 \ldots\ldots\ldots \text{(Eqn. 1)}$$

where X and Z were hexane volume (mL) and tomato sample FW (g)

For β-carotene content analysis, a similar extraction procedure as for lycopene was followed. The upper layer (non-polar) was transferred to a glass cuvette and absorbance was measured at 663, 645, 505 and 453 nm using UV-Visible Spectrophotometer-UH5300 (Hitachi High-Tech Corporation, Tokyo, Japan). These measurements were compared to a blank containing hexane solvent (27). The β-carotene content, which correlates with all absorbance above, was estimated in mg per 100 g of FW using the following equations (28):

$$\beta\text{-carotene (mg/100 g FW)} = 0.216A_{663} - 1.22A_{545} - 0.304A_{505} + 0.452A_{453} \ldots\ldots\ldots\ldots\ldots \text{(Eqn. 2)}$$

where, A_{663}, A_{545}, A_{505} and A_{453} are absorbance at 663 nm, 545 nm, 505 nm and 453 nm respectively.

Data analysis

Trait variances were analyzed using SPSS version 16. Upon identifying significant differences, mean comparisons were conducted through Duncan's New Multiple Range Test (DMRT). Correlation coefficients were then employed to assess the relationships between yield, fruit quality and antioxidant contents. The E1 condition and Hoagland solution treatments served as standards for comparison with the E2 condition and other nutrient treatments respectively. Quantifying the correlation involved determining whether the folds increased (positively) or decreased (negatively) compared to the standard.

Results

Yield and fruit quality of Ranger cultivar

Table 2. Effects of plant nutrient management on yield, fruit quality and antioxidants of tomato cultivar Ranger.

	Yield (g/plant)	Fruit color index (*a*/b**)[1]	Fruit firmness (N)	TSS (°Brix)[2]	Lycopene (mg/100 g FW)	β-carotene (mg/100 g FW)
Environment (E)						
E1	1,445	0.94^{b}	14.06^{b}	4.62^{b}	5.22^{b}	0.93^{b}
E2	1,377	1.04^{a}	15.97^{a}	5.75^{a}	10.32^{a}	5.28^{a}
p-value	ns	**	**	**	**	**
Nutrient formula (T)						
H	1,530	1.03^{ab}	16.41^{a}	5.73^{ab}	9.35^{ab}	3.31
H+K400	1,431	1.05^{a}	15.27^{abc}	5.84^{a}	11.14^{a}	3.34
H+K300	1,401	1.04^{a}	15.22^{abc}	5.33^{abc}	8.23^{ab}	2.79
H+Ni20	1,386	0.93^{c}	15.00^{abc}	4.93^{bcd}	5.86^{c}	3.22
H+Ni10	1,419	0.97^{b}	13.65^{c}	4.72^{d}	6.11^{c}	2.83
H+K300+Ni10	1,370	0.96^{b}	15.51^{ab}	5.34^{abc}	5.92^{c}	3.16
p-value	ns	**	*	**	*	ns
E × T	ns	ns	ns	*	**	ns

[1]***a*/b**** = fruit color index as a ratio between redness and yellowness, [2]**TSS** = total soluble solid, Mean followed by the same letter do not differ significantly according to DMRT at p ≤ 0.01 (**) or 0.01 < p ≤ 0.05 (*); **ns**: non-significantly different.

The yield, quality and antioxidant content of tomato cv. Ranger are summarized in Table 2 and their qualifying correlation is showed in Supplementary Table 1. Yield per plant did not exhibit significant differences between the 2 environmental conditions (1377–1445 g/plant) and plant nutrient formulas (1370–1530 g/plant). However, tomato fruit quality and antioxidant content showed significant differences between the 2 environmental conditions. The E1 condition, characterized by increasing monthly temperatures during the reproduction period and lower RH, appeared to have a significant negative impact on fruit quality compared to the E2 condition. Noticeable reductions were observed in parameters such as *a*/b** (from 1.04 to 0.94), fruit firmness (from 15.94 to 14.06 N), TSS (from 5.75 to 4.62 °Brix), as well as antioxidant contents, including lycopene (from 10.32 to 5.22 mg/100 g FW) and β-carotene (from 5.28 to 0.93 mg/100 g FW) in the tomato cultivar Ranger. Consequently, the fruit quality (*a*/b**, fruit firmness, TSS) and antioxidant contents (lycopene, β-carotene) of E2 were notably higher than those of the E1 condition, with increases ranging from 1.11 to 1.24-fold for fruit quality parameters and 1.98 to 5.68-fold for antioxidant contents. The investigated nutrient formulations had a notable influence on parameters such as *a*/b**, fruit firmness, TSS and lycopene content, but did not affect the levels of β-carotene. Combinations of Hoagland solution and Ni, such as H+K400 and H+K300, did not result in significant improvements in *a*/b** (1.05–1.05), fruit firmness (between 15.22 and 15.27 N), TSS (ranging from 5.33 to 5.84 °Brix) and lycopene content (ranging from 8.23 to 11.14 mg/100 g FW) compared to Hoagland solution. Meanwhile, combinations of Hoagland solution and Ni including H+Ni20 and H+Ni10 seemed to have a negative effect on *a*/b** (0.93–0.97), fruit firmness (13.65 N), TSS (4.72 °Brix) and lycopene content (5.86–6.11 mg/100 g FW) compared with Hoagland solution, with a *a*/b** (1.03), fruit firmness (16.41 N), TSS (5.73 °Brix) and lycopene content (9.35 mg/100 g FW). Consequently, the *a*/b** of H+Ni20 and fruit firmness of H+Ni10 were significantly decreased by 1.11 and 1.20-folds respectively, when compared to Hoagland solution. The lycopene content of these 2 treatments was also significantly decreased by 1.53 to 1.60-folds. The negative effects observed with H+Ni20 and H+Ni10 treatments were mitigated when Hoagland solution was supplemented with 300 ppm K combined with 10 ppm Ni, resulting in *a*/b** of 0.96, fruit firmness of 15.51 N and TSS of 5.34 °Brix. Moreover, the interaction between environmental conditions and nutrient formulations produced discernible effects on TTS and lycopene content (Fig. 1). Under the E2 condition, the tomato cv. Ranger could maximize the produced lycopene content (17.01 mg/100 g FW) and fruit firmness (17.81 – 18.50 N) by being treated with H+K400 and H, or H+K300+Ni10 formula respectively.

Table 3 presents the correlation coefficients between yield, fruit quality and antioxidants of the tomato cultivar Ranger. The results reveal a negative correlation

between tomato yield and parameters such as *a*/b**, TSS and β-carotene. Conversely, positive correlations are observed between *a*/b** and TSS, lycopene, β-carotene; fruit firmness and TSS, β-carotene; TSS and lycopene and β-carotene; as well as lycopene and β-carotene. Notably, The yield, quality and antioxidant content of tomato cv. Sweet Girl exhibited significant differences between the 2 environmental conditions. In the E1 condition, the yield reached 892.8 g/plant, surpassing E2 conditions (745.7 g/plant) by 1.20 times. Conversely, E2 conditions significantly enhanced fruit quality parameters, including *a*/b** (from

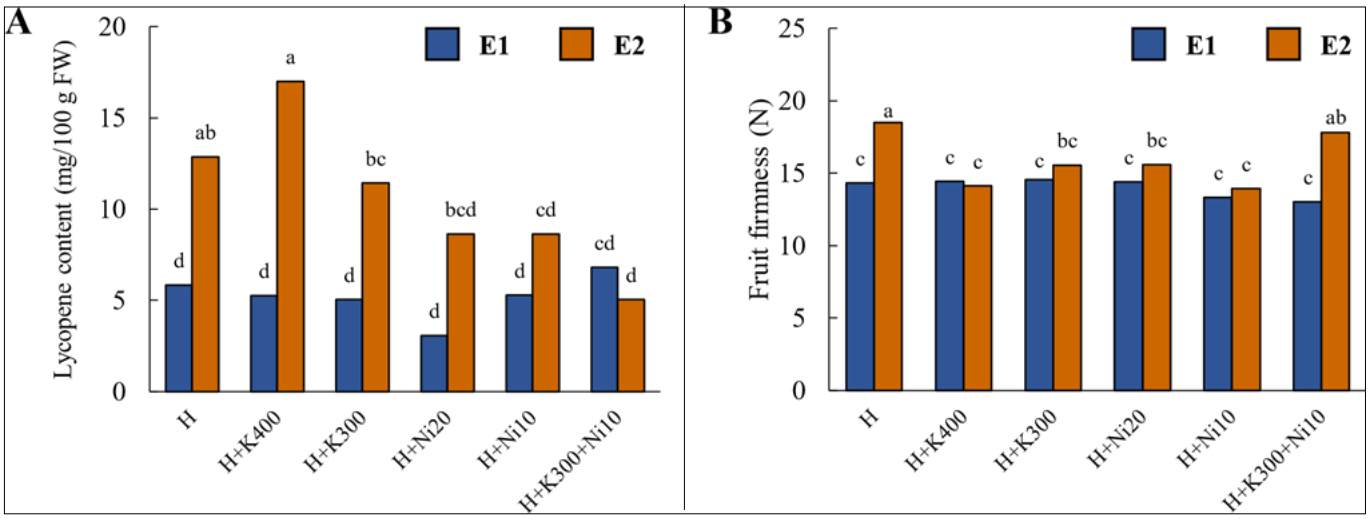

Fig. 1. Combined effects of environmental conditions and plant nutrient formulas on lycopene content (**A**) and fruit firmness (**B**) of tomato cultivar Ranger. Data represent mean value of three replication. The letter shows significant at p<0.05 in DMRT.

Table 3. Correlation coefficients between yield, yield quality and antioxidants of tomato cultivar Ranger.

Traits	*a*/b** [1]	Fruit firmness	TSS[2]	Lycopene content	β-carotene content
Yield/plant	–0.36*	–0.29	–0.41*	–0.11	–0.35*
a/b**		0.22	0.65**	0.57**	0.55**
Fruit firmness			0.57**	–0.06	0.48**
TSS				0.51**	0.72**
Lycopene					0.46**

[1]***a*/b**** = fruit color index as a ratio between redness and yellowness, [2]**TSS** = total soluble solid, Mean followed by the same letter do not differ significantly according to DMRT at p ≤ 0.01 (**) or 0.01 < p ≤ 0.05 (*); ns: non-significantly different.

TSS and β-carotene exhibited a strong correlation coefficient of 0.72.

Yield and fruit quality of Sweet Girl cultivar

0.95 to 1.12), fruit firmness (from 14.41 to 16.31 N), TSS (from 7.09 to 7.77 °Brix) as well as antioxidant traits such as lycopene (from 4.24 to 10.37 mg/100 g FW) and β-carotene (from 0.86 to 2.83 mg/100 g FW), compared to

Table 4. Effects of plant nutrient management on yield, fruit quality and antioxidants of tomato cultivar Sweet Girl.

	Yield (g/plant)	Fruit color index (*a*/b**)[1]	Fruit firmness (N)	TSS (°Brix)[2]	Lycopene (mg/100 g FW)	β-carotene (mg/100 g FW)
Environment (E)						
E1	892.8^{a}	0.95^{b}	14.41^{b}	7.09^{b}	4.24^{b}	0.86^{b}
E2	745.7^{b}	1.12^{a}	16.31^{a}	7.77^{a}	10.37^{a}	2.83^{a}
p–value	**	**	*	**	**	**
Nutrient formula (T)						
H	854.7	1.06^{ab}	16.15^{a}	7.31^{b}	7.66^{bc}	1.98^{ab}
H+K400	758.5	1.11^{a}	15.37^{ab}	7.99^{a}	9.53^{a}	2.18^{a}
H+K300	813.9	1.09^{a}	15.20^{ab}	7.57^{ab}	8.08^{ab}	1.85^{abc}
H+Ni20	891.2	0.98^{c}	14.40^{b}	7.59^{ab}	8.10^{ab}	1.48^{c}
H+Ni10	793.8	1.00^{bc}	15.87^{a}	7.11^{b}	4.46^{d}	1.94^{ab}
H+K300+Ni10	803.3	0.97^{c}	15.17^{ab}	7.31^{b}	5.99^{cd}	1.64^{bc}
p-value	ns	**	*	*	**	**
E x T	ns	ns	*	ns	**	ns

[1]***a*/b**** = fruit color index as a ratio between redness and yellowness, [2]**TSS** = total soluble solid, Mean followed by the same letter do not differ

E1 conditions (Table 4, Supplementary Table 2). Consequently, the fruit quality (*a*/b**, fruit firmness, TSS) and antioxidant contents (lycopene, β-carotene) were 1.10 to 1.18 times higher in E2 conditions and exhibited 2.45 to 3.29 times higher levels, respectively, than those observed in E1 conditions. Regarding nutrient formulations, they did not produce notable variations in the yield per plant. However, these formulations did influence the quality of the fruits and their antioxidant content in the Sweet Girl tomato variety. The addition of K to the nutrient formulas did not markedly improve the quality and antioxidant levels in Sweet Girl tomato fruits compared to the Hoagland solution, except for the H+K400 treatment, which demonstrated enhancements in both TSS (7.99 °Brix) and lycopene content (9.53 mg/100 g FW). As a result, the TSS and lycopene content in the H+K400 treatment were 1.09 and 1.24 times higher than those in the Hoagland solution, respectively.

Meanwhile, the formulas with added Ni showed no significant improvements in tomato fruit quality or antioxidant contents, including *a*/b** (0.98–1.00), fruit firmness (14.40–15.87 N), lycopene (4.46–8.10 mg/100 g FW) and β-carotene (1.48–1.94 mg/100 g FW) with no significant improvements observed. Consequently, *a*/b**, fruit firmness of H+Ni20 and lycopene of H+Ni10 were decreased by 1.08, 1.12 and 1.72-fold compared with the Hoagland solution respectively. Interestingly, while the H+Ni10 treatment resulted in a 1.72-fold decrease in lycopene content, the H+Ni10 treatment yielded a 1.06-fold increase. The inclusion of Ni in the nutrient formulas seemed to exacerbate the outcomes when contrasted with the H treatment. Moreover, the introduction of 300 ppm K did not ameliorate the adverse effects of Ni, which was similar tomato cv. Ranger.

The synergistic impacts of environmental conditions and nutrient formulas were investigated, notably evident in terms of fruit firmness and lycopene content. Among the tomato cv. Sweet Girl plants, those grown under the E2 condition with the H and H+Ni10 treatments exhibited the highest fruit firmness and their values were statistically similar to those of the H+K400 and H+K300 treatments. As for lycopene content, the tomatoes cultivated under the E2 condition with the H+K400 treatment showed the highest level at 13.62 mg/100 g FW and these values were not significantly different from those obtained with the H, H+K300 and H+Ni20 treatments (Fig. 2).

The correlation coefficients between yield, fruit quality and antioxidants of the tomato cultivar Sweet Girl are shown in Table 5. The results demonstrate a negative correlation between tomato yield and parameters including *a*/b**, fruit firmness and β-carotene, while positive correlations were evident between *a*/b** and all other traits; fruit firmness and lycopene, β-carotene; TSS and lycopene, β-carotene; lycopene and β-carotene. Among these, fruit firmness and β-carotene showed a strong correlation coefficient (0.75).

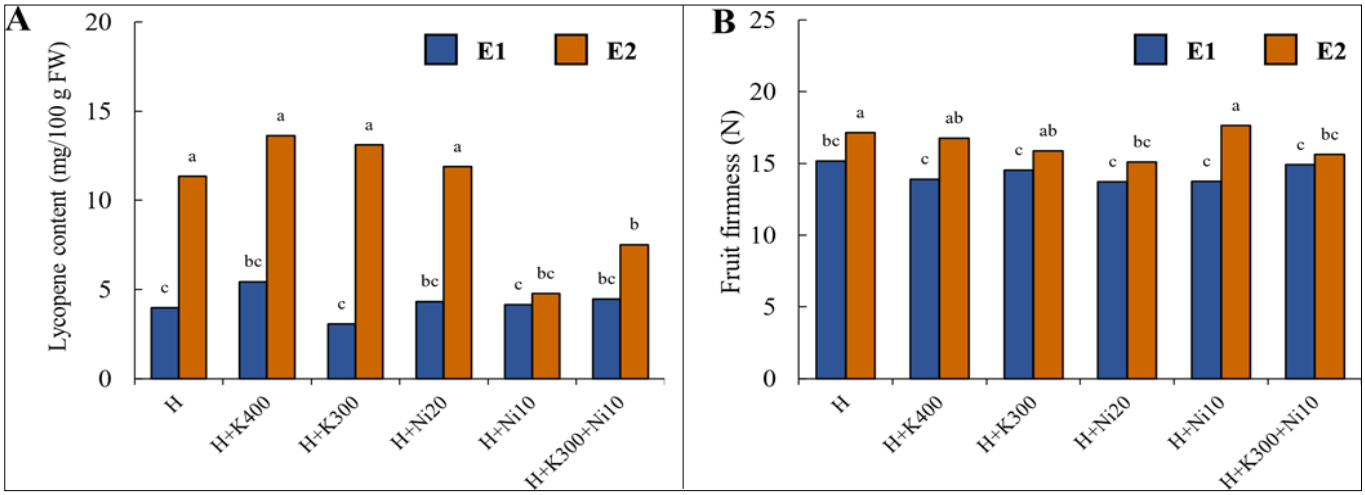

Fig. 2. Combined effects of environmental conditions and plant nutrient formulas on lycopene content (**A**) and fruit firmness (**B**) of tomato cultivar Sweet Girl. Data represent mean value of three replication. The letter shows significant at p<0.05 in DMRT.

Table 5. Correlation coefficients between yield, yield quality and antioxidants of tomato cultivar Sweet Girl.

Traits	*a*/b**[1]	Fruit firmness	TSS[2]	Lycopene content	β-carotene content
Yield/plant	−0.41*	−0.37*	−0.25	−0.07	−0.43**
a/b**		0.53**	0.42*	0.52**	0.67**
Fruit firmness			0.23	0.38*	0.75**
TSS				0.46**	0.49**
Lycopene					0.68**

[1] ***a*/b**** = fruit color index as a ratio between redness and yellowness, [2] **TSS** = total soluble solid, Mean followed by the same letter do not differ significantly according to DMRT at p ≤ 0.01 (**) or 0.01 < p ≤ 0.05 (*).

Discussion

The results suggest that neither Ranger nor Sweet Girl tomato yields were significantly affected by nutrient formu-

las. However, these formulas did impact the fruit quality and antioxidant content of both tomato cultivars. The H+K400 treatment slightly increased TSS and lycopene by 1.02 and 1.19-fold respectively, compared with the H treatment in Ranger cultivar. Conversely, H+Ni10 significantly reduced TSS and lycopene by 1.21 and 1.53-folds, respectively. In the Sweet Girl cultivar, the H+K400 treatment significantly increased TSS lycopene and β-carotene by 1.09, 1.24 and 1.10-folds respectively, compared with the H treatment, while H+Ni20 significantly reduced β-carotene by 1.34-folds. Notably, the Hoagland solution, rich in N and K crucial for enzyme cofactor biosynthesis, demonstrated potential for high-yield production. Additionally, the supplementation of N and K increased soluble sugar levels, leading to starch accumulation, as reported in previous studies (29). A study reported an increase in fruit firmness and sweetness and a decrease in titratable acids with a high K concentration (10). In this research, the high K concentration formula (H+K400) could maximize increased TSS (5.84 to 7.99 °Brix) and lycopene content (9.53 and 11.14 mg/100 g FW) in tomato fruits, particularly in the Sweet Girl cultivar. The H+K400 also has the highest β-carotene content in the Sweet Girl cultivar, reaching 2.18 mg/100 g FW. This finding may be attributed to K's role in activating phytoene synthase, leading to increased lycopene and β-carotene production in tomatoes (6).

Furthermore, the potassium-to-nitrogen (K:N) ratio has been identified as a key factor influencing both tomato production and fruit quality (13). In this study, the Hoagland solution with a K:N ratio of 1:1 (242.65 and 231.22 ppm) led to a slight increase in yield compared to other nutrient formulas. However, the yield of Ranger and Sweet Girl cultivars was reduced by up to 1.07 and 1.13-folds respectively, when the concentration of K was increased to 400 ppm, although this was not statistically significantly. This aligns with previous findings indicating that fruit production peaks when the K:N ratio is set at 1:1, particularly at concentrations of 188.7 and 177.2 ppm respectively (30). Application of a K:N ratio (2:1) increased tomato fruit yield by 1.27-folds compared to a ratio of 1:1, but applying K without a balanced N ratio resulted in reduced tomato fruit yield (31). Moreover, a K:N ratio of 2:1 led to increased TSS and fruit firmness in tomatoes, while a ratio of 4:1 maximally increased ascorbic acid content (13). However, an elevated concentration of K may disrupt the equilibrium of cations (K^+, Ca^{2+}, Mg^{2+} and Na^+) within the plant, potentially reducing the uptake of calcium ions (Ca^{2+}) and magnesium ions (Mg^{2+}). Elevated levels of magnesium ions, known for their growth-enhancing properties, have been linked to increased plant growth and yield (32). Additionally, a relatively high K:Ca ratio of 1:1 can promote both plant growth and tomato yield. Furthermore, the Hoagland solution, featuring a lower K concentration (242.65 ppm), may induce greater Ca uptake compared to nutrient formulas with higher K concentrations (H+K400 and H+K300) (33).

Ni, although required in low concentration in plant tissue, is an essential micronutrient for plant growth and development as it is involved in N metabolism (15). Toxicity symptoms typically occur due to high Ni concentrations, resulting in chlorosis, necrosis, oxidative damage and inhibition of photosynthesis and transpiration processes (34). These high Ni concentrations (10–20 ppm) may have a toxic effect on tomatoes and could inhibit lycopene synthesis (35). In this study, the lycopene content and a^*/b^* in tomato cv. Ranger decreased by up to 1.11 and 1.60-folds with H+Ni10 and H+Ni20 respectively. Similarly, a^*/b^* in both treatments of the Sweet Girl cultivar decreased by up to 1.08-fold. While H+Ni20 increased lycopene content by 1.06-fold, H+Ni10 decreased it by 1.72-fold in the Sweet Girl cultivar. The applied Ni (5–30 ppm) in tomato could increase N accumulation, which subsequently led to reduced lycopene content (17). Similarly, the application of 30 ppm Ni maximized plant growth parameters, auxin and gibberellin content in both shoot and root plants, while applying Ni at 45–60 ppm led to a reduction in vegetative growth and auxin and gibberellin content (36).

The ideal temperature range for the cultivation and reproduction of tomatoes is generally regarded as falling within 18–32 °C (37, 38). In this study, the E1 condition (with temperatures of 29–38 °C and relative humidity of 71 –73 %) appeared to favor the growth of both tomato cultivars, significantly increasing yields by 1.05 and 1.20-folds compared to the E2 condition in the Ranger and Sweet Girl cultivar respectively. The temperature in the first 2 months in the E1 condition fell within the optimal range for tomato growth and development, providing a plausible explanation for the observed increase in yield. On the other hand, the E2 condition, characterized by higher temperatures during the first 2 months (32–36 °C), exceeded the optimal range for tomatoes, inducing stress and resulting in reduced yields. The E2 condition significantly surpassed the E1 condition in terms of color index (a^*/b^*), firmness and TSS by 1.11, 1.14 and 1.24-folds in the Ranger cultivar and 1.18, 1.13 and 1.10-folds in the Sweet Girl cultivar respectively. Furthermore, the lycopene and β-carotene of the E2 condition were significantly increased by 1.98 and 5.68-fold in the Ranger cultivar and 2.45 and 3.29-fold in the Sweet Girl cultivar. These results align with previous research on the effects of elevated temperatures on flower and fruit drop as well as irregular fruit development (39). Although the E1 condition led to higher yields, it compromised the fruit quality and antioxidant content of both tomato varieties. This can be attributed to the higher temperatures (35.4–37.6 °C) during the fruit development and ripening stages in the E1 condition, whereas in the E2 condition, the temperature remained within the optimal range. Moreover, tomato fruit quality and antioxidant content can be improved under conditions with an air temperature of 33.4 °C but may decline at 35.4 °C due to limitations in lycopene biosynthesis rates and degradation (20). Additionally, temperatures exceeding 30 °C can lead to reduced lycopene and β-carotene accumulation in tomatoes (40). RH also played a pivotal role in determining the quality of fruits and their antioxidant levels. Maintaining an optimal RH range of 55–90 % has been recommended for achieving optimal photosynthesis in greenhouse-grown tomatoes (41). In this study, both the E1 and E2 con-

ditions successfully maintained RH within this recommended range. An RH of 72 % resulted in tomatoes with higher lycopene content compared to those grown at 62 % RH under similar air temperature conditions (23). Considering both environmental factors, the E2 condition appears to be more favorable for producing tomatoes with elevated antioxidant levels.

On the other hand, managing greenhouse residues is also crucial for sustainable crop production. Initially, hot maceration is employed to break down the tomato plant matter, followed by the removal of easily degradable organic matter through washing. This is followed by either an upflow anaerobic sludge bed reactor or steam-explosion technology coupled with stirred batch anaerobic fermentation to produce methane (42). The nutrients from coco coir and tomato matter could be recovered through a circular economy approach (43). Both tomato matter and coco coir have high potential to produce biochar, which can be used as sorbents to capture phosphorus and also for soil-improving practices (44, 45). Additionally, tomato matter and coco coir, with high lignin content, could be extracted to produce silica nanoparticles using the acidic sol-gel method, which can improve seed germination (46).

Conclusion

The treatment involving the addition of 400 ppm K to the Hoagland solution (H+K400) resulted in a significant increase in lycopene content in both cultivars, along with improvements in β-carotene content and TSS in the Sweet Girl cultivar compared to the Hoagland solution alone. Moreover, the E2 condition (with temperatures of 32–36 °C and RH of 75–80 %) could be utilized to enhance tomato production with higher antioxidant contents (lycopene and β-carotene) and fruit quality parameters including color index (a*/b*), TSS, and firmness. Developing a nanoformulation based on the Hoagland solution with 400 ppm potassium could be a promising strategy for further enhancing antioxidant content in tomato production. Planting tomatoes in the field during the June-September season or in a greenhouse with controlled temperature (32 –36 °C) and RH (75–80 %) is recommended for producing fruits with high antioxidant content. Additionally, besides being consumed as fresh fruit, these high antioxidant tomatoes could serve as valuable raw material for the nutraceutical and food industry.

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Authors' contributions

TM, NK, SW carried out the greenhouse studies, participated in antioxidant analysis and drafted the manuscript. NHH, TLT, KB edited the manuscript. TM, NK, SW participated in the design of the study and performed the statistical analysis. NHH, TLT, KB conceived of the study and participated in its design and coordination. All authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None.

Supplementary data

Supplementary Table 1**.** Quantifying the correlation of yield, fruit quality, and antioxidants between E1 with E2 condition and Hoagland solution with other nutrient treatments of tomato cultivar Ranger

Supplementary Table 2**.** Quantifying the correlation of yield, fruit quality and antioxidants between E1 with E2 condition and Hoagland solution with other nutrient treatments of tomato cultivar Sweet Girl

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