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Influence of Combined Supplemental Lighting and Nutrient Solution Concentration on Fruit Production and Quality of Cherry Tomato

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Abstract: We conducted an analysis on the combined effects of two light conditions (L1: greenhouse natural lighting; L2: greenhouse natural lighting plus supplemental lighting (SL)) and three nutrient solution concentrations (EC, NS1: 3.2 dS/m; NS2: 3.7 dS/m; NS3: 4.2 dS/m) on the growth, fruit production, and quality of two cherry tomato cultivars with different fruit coloring ('Baiyu' and 'Qianxi'). The plants subjected to NS2 exhibited enhanced growth, photosynthetic parameters, and fruit production. The utilization of SL further enhanced stem diameter, leaf number, and single fruit weight, resulting in higher fruit weight per plant in 'Baiyu', which was not observed in 'Qianxi'. The growth, fruit size, and fruit weight of both cultivars cultivated under NS3 conditions were suppressed, while these fruits exhibited elevated levels of total soluble solids (TSS), soluble sugars, vitamin C, polyphenols, fructose, glucose, sucrose, citric acid, and carotenoids. These levels were further enhanced by SL treatment. The improvement of fruit quality through the application of SL was found to be cultivar and EC dependent. In 'Baiyu', SL at NS1 significantly enhanced the accumulation of fruit water, minerals (N, P, K, Ca, and Mg), TSS, vitamin C, fructose, sucrose, and carotenoids. However, this effect was not observed in 'Qianxi'. The combination of SL and EC 4.2 dS/m (NS3) generally contributes to the enhancement of fruit quality, while SL and EC 3.7 dS/m can ensure consistent fruit production. The yellowish-white fruit cultivar exhibited higher levels of soluble sugars, vitamin C, and polyphenols under L2NS3 conditions compared to the red fruit cultivar, whereas the carotenoid content showed an opposite trend. The findings are anticipated to establish a theoretical foundation for the consistent annual cultivation of cherry tomatoes in protected horticultural settings.

Keywords: supplemental lighting; nutrient solution; fruit quality; cherry tomatoes

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1. Introduction

Cherry tomatoes (*Solanum lycopersicum* L.) are a popular vegetable and fruit, as they are small size, tasty, colorful, and also rich in nutrients that are beneficial to humans, such as vitamins, amino acids, carotenoids, phenolics, etc. [1–3]. As its demand increases, the year-round industrial-scale cultivation of cherry tomatoes in greenhouses has continuously expanded. However, their output and quality has always changed with climate fluctuation [4–8]. Stable tomato yield and quality depends on the comprehensive regulation of environmental factors in the greenhouse, such as light, temperature, nutrients, water, CO_2, etc. [9].

Proper nutrient regulation is one of the most important pathways to ensure basic growth and development in tomatoes [10–12]. Electrical conductivity (EC) indicates the concentration of total mineral elements in a nutrient solution, which is related to the yield and quality formation of tomatoes grown under soilless conditions [13]. In one study, stable fruit yield and increased sugar concentration in fruits were produced when the EC was increased by 0.1 dS/m/day [14]. As EC increased from 0.6 dS/m to 1.2 dS/m, the fresh fruit weight and total soluble solids (TSS) content of tomatoes also increased [15]. However, fruit weight reduced while fruit quality increased when EC increased from 1.5 dS/m to 2.4 dS/m [16]. The yield reduction was mitigated by a combination of high drainage (20%) and high EC compared with low drainage combined low EC [17]. High-brix tomatoes were produced by controlling EC at 7 dS/m in supply solution and >10 dS/m in drainage solution without reducing the fresh biomass [18]. Generally, an appropriate EC for tomatoes depends on several factors, such as cultivars, solution management, and environmental factors, such as temperature and light conditions.

Insufficient solar radiation always results in delayed, uneven fruit coloring [19–21], and intensive solar radiation results in sun-burned fruits [15,22]. Our previous research showed that tomato fruit coloring disorders were alleviated by increasing phosphorus (P) or/and potassium (K) concentration in the solution under intensive solar radiation and during high-temperature growing seasons [22], implying that physiological disorder caused by an adverse environment could be mitigated through nutrient regulation. On the contrary, the coloring progress of tomato fruits was accelerated by using supplemental lighting (SL) in winter-to-early-spring growing seasons [20,23]. The SL enhanced lycopene synthesis in tomatoes by inducing light receptors that regulate the activation of light transcription factors to mediate key gene expression in lycopene synthesis [19]. Appropriate SL of blue light frequencies promoted fruit ripening 3–4 days ahead by regulating the ethylene production of tomatoes [21]. In addition to fruit coloring or related pigment accumulation, SL also promoted root K uptake and accumulation in fruits, and some K^+ transporter genes (*SlHAK3, SLHAK6, SlHAK19*) have been involved in light-signal-regulated K^+ transport in tomato fruits [20]. In recent decades, the critical role of light in promoting the absorption and utilization of P [24], K [25], and other nutrients in plants were clarified [26]. Studies on the interaction and optimization of SL and nutrient concentration are still insufficient in the literature.

In this study, two fruit-coloring cherry tomato cultivars grown in soilless culture conditions were treated using two light conditions (L1, greenhouse natural lighting; and L2, greenhouse natural lighting plus supplemental lighting (SL, RB PPFD 100 ± 5 μmol/m^2/s)) and three high EC solutions (NS1, 3.2 dS/m; NS2, 3.7 dS/m; NS3, 4.3 dS/m) by adding KH_2PO_4 and KCl based on Enshi formula nutrient solution during the winter–spring cropping season in a multi-span greenhouse. We analyzed the plant growth, photosynthesis, fruit size and weight, fruit coloring, and accumulation of mineral elements, sugars, organic acids, carotenoid, etc. This study explores an integrative understanding of the combination effects of SL and nutrient solution EC on the fruit production and quality of cherry tomatoes, as well as proposing an optimal combination of SL and EC for annual stable output and quality production of cherry tomatoes.

2. Materials and Methods

2.1. Plant Material and Growth Conditions

The experiment was conducted in a multi-span greenhouse. Two cultivars of cherry tomatoes, '*Solanum lycopersicum* Mill. Cv. Baiyu' with a yellowish-white fruit color and '*Solanum lycopersicum* Mill. Cv. Qianxi' with red color fruits, were supplied by 'Huaye seed' Co., Ltd. (Guangzhou, China). Seedlings with five fully expanded leaves (29 October 2021) were transplanted in non-woven bags (5 L/plant) filled with coco-peat with a 25 cm planting distance. The spacing of rows was 1.2 m, and the planting density was about 3 plants/m^2. Plants were pruned vertically with double stems and pinched at the 7th truss. Plant operations such as binding and old leaf, lateral bud, and basal leaf pruning were carried out regularly, while flower and fruit thinning were not carried out. The nutrient solution supply was controlled by a timer, which applied it between 4 (cloudy) and 12 (sunny) times per day, and the fertigation amount was based on the drainage rate of 20–30%, while the pump's flow rate was set at 60 mL/min, with a small amount of high-frequency supply. The management of the nutrient solution and environmental conditions remained consistent with our previous research [27].

2.2. Treatments

Treatments of light conditions (L1 and L2) combined with three nutrient solution concentrations (NS1, NS2, and NS3) were performed from fruit setting (22 November 2021) to the end of the experiment (Table 1). Cherry tomato plants grown in L1 conditions were under greenhouse natural lighting, without any supplemental lighting; plants in L2 light conditions were illuminated by daily supplemental light from 6:00 to 18:00 with a Photosynthetic Photon Flux Density (PPFD) of 100 ± 5 μmol/m^2/s (30 cm from the LEDs) based on a mixed light-emitting diode (LED, red:blue = 2:1), as shown in Figure 1A. The LED lights were produced by iGrowLite Co. (Guangzhou, China; red light: 630–660 nm, blue light: 450–460 nm). The LED lamps were placed on both sides of the plant at a distance of 10 cm from the inner canopy leaves under the first fruit truss, and 30 cm from stems.

Table 1. Electrical conductivity (EC) and macronutrient concentration of the three nutrient solutions used in the experiment with two cherry tomato cultivars (Baiyu and Qianxi) grown in substrate under greenhouse conditions in the winter–spring season.

Nutrient Solution Concentration (NS)	EC (dS/m)		Mineral Elements (mM/L)					
	Vegetative Stage (17 DPA)	Fruiting Stage (24 DPA)	NO_3-N	PO_4-P	K	Mg^+	Ca	NH_4-N
NS1	1.6	3.2 (2.1 + P + K)	14.0	3.6	13.5	1.8	3.5	1.2
NS2	1.6	3.7 (2.4 + P + K)	16.0	4.1	15.4	2.0	4.0	1.4
NS3	1.6	4.2 (2.7 + P + K)	18.0	4.6	17.4	2.3	4.5	1.6

DAP: days after planting.

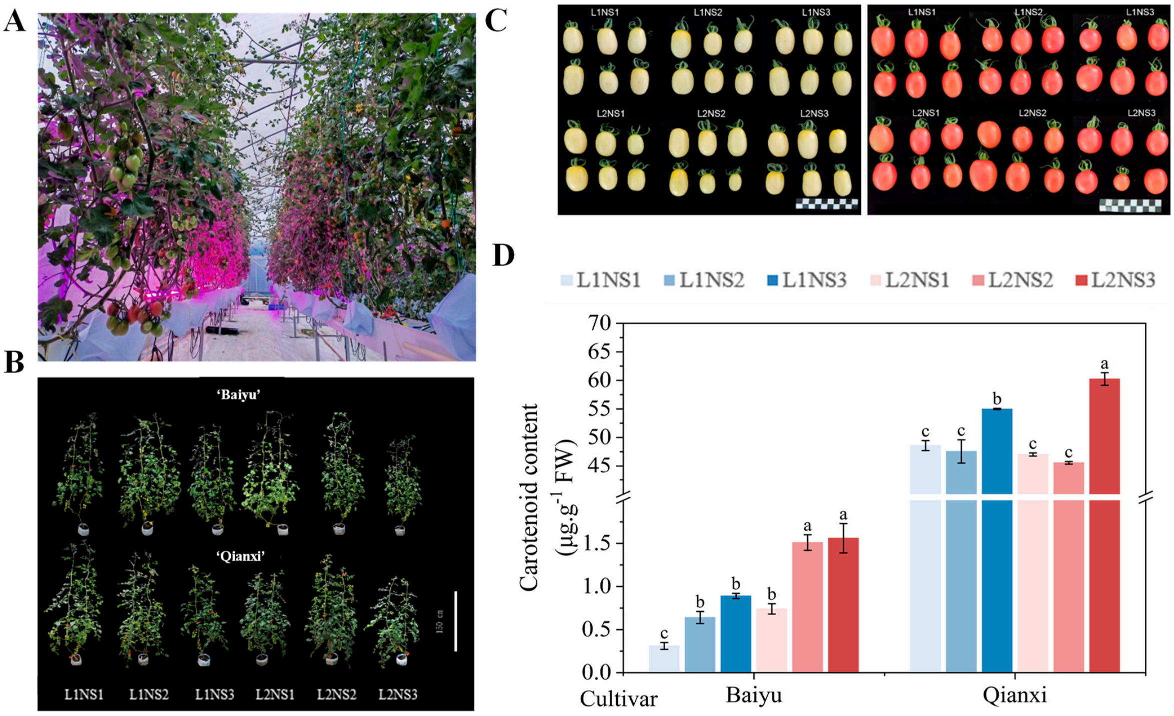

Figure 1. The effects of light conditions and nutrient solution concentration (NS) on plant (**A**,**B**) and fruit (**C**) appearance, and fruit carotenoid content (**D**) of two cherry tomato cultivars grown in substrate under greenhouse conditions in the winter–spring season. The abbreviations L1NS1, L1NS2, L1NS3, L2NS1, L2NS2, and L2NS3 indicate the combinations of two light conditions and three nutrient solution concentrations: natural light without (L1) or with (L2) supplemental lighting; nutrient solution electrical conductivity (EC) of 3.2 (NS1), 3.7 (NS2) or 4.2 dS/m (NS3). Means ± standard error of six replicates. Different letters indicate significant differences among treatments according to Duncan's multiple range test ($p \leq 0.05$).

The NS1, NS2, and NS3 treatments involved Enshi formula nutrient solution at EC 3.2 dS/m, EC 3.7 dS/m, and EC 4.2 dS/m, which was obtained by adding KH_2PO_4 and KCl based on EC 2.1 dS/m, EC 2.4 dS/m, and EC 2.7 dS/m, respectively. The basic composition of the Enshi formula nutrient solution at EC1.6 dS/m, used by transplanting to anthesis, was described in our previous research [17].

A total of six treatments (L1NS1, L1NS2, L1NS3, L2NS1, L2NS2, and L2NS3) were set up in this experiment. Each treatment was repeated three times, with five plants in each repetition. Ten fully matured fruits in each replication were randomly selected for the fresh and dry samples. Fruit seeds, jelly, and placenta were removed. Half of the flesh and pericarp was frozen in liquid nitrogen and stored at −80 °C for quality analysis, and while the other half was oven-deoxidized at 105 °C for 1 h, then oven-dried at 80 °C to constant weight for mineral elements analysis.

2.3. Plant Morphology and Fruit Production

Plant height was measured by a measuring tape for 12 plants at 40 days after treatment. Meanwhile, the stem diameter and the length and diameter of the fully matured fruit were measured by digital calipers. The length and width of the largest functional leaf under the second cluster were measured by a soft ruler to calculate leaf area according to previous research [17], and its SPAD value was also measured by SPAD-502Plus meter (Konica Minolta Business Associates Co. Ltd., Tokyo, Japan). The number of fully expanded true leaves was counted. Fruit production samples were primarily collected from all 7 trusses of each plant, while quality samples were obtained from the 2nd–3rd truss. Fruit weight, size, and quality were recorded in the fruit ripening stage (10 days post-breaker stage), breaker fruits were tagged on a daily basis, and samples were collected from fruits at 10 days after the breaker stage. Fresh fruit samples were dried for 48 h in a ventilated oven (DGG-9140A, Shanghai Ganyi Co. Ltd., Shanghai, China) at 80 °C to estimate the dry weight (DW) and fruit water content, which was calculated as a proportion of fresh weight (FW) water mass.

2.4. Photosynthetic Characteristics

The net photosynthetic rate (*Pn*), stomatal conductance (*Gs*), intercellular CO_2 concentration (*Ci*), and transpiration rate (*Tr*) were measured using a Li-6400 photosynthetic system (Li-6400, L-COR, Lincoln, NE, USA). The red- and blue-light leaf chamber was set at a light intensity of 800 $\mu mol/m^{-2}/s$, while CO_2 flux rate was 420 ppm and humidity was 60%. Leaf gas exchange parameters were measured in the largest functional leaf under the third cluster of the plant for each treatment on a sunny day 40 days after treatment.

2.5. Mineral Element Accumulation

Dry samples of tomato fruit were used for the determination of mineral content. Total nitrogen (N) and phosphorus (P) content were detected by sulphate–hydrogen-peroxide deboiling and distillation titration, a method outlined by [28], and using the vanadate-molybdate method [17], respectively. Total K was detected by a flame photometer after sample digestion. Total calcium (Ca) and magnesium (Mg) were determined by dry ashing, dilute hydrochloric acid dissolving, and flame atomic absorption spectrophotometry, as described in a previous report [29].

2.6. Fruit Quality

The TSS content of fruit in each treatment was detected by a portable refractometer.

The soluble sugar content was detected using anthrone–sulfuric acid colorimetry, as described by previous research [30]. Fresh fruit samples of 0.5 g were heated in a water bath with 50 mL distilled water for 30 min. A measure of 0.2 mL lotion was mixed with 1.8 mL distilled water, 0.5 mL anthrone ethyl acetate, and 5 mL vitriol. The absorbance was measured at 630 nm.

The vitamin C content was detected according to a previous method [31]. Fresh fruit samples of 0.5 g were ground into a pulp with 25 mL of oxalic acid EDTA solution (w/v).

A measure of 10 mL extract solution was mixed with 1 mL phosphate-acetic acid, 2 mL vitriol (5%), and 4 mL ammonium molybdate. The content of vitamin C was detected by UV-spectrophotometer at 705 nm.

The carotenoids content was detected according to [32]. Fresh fruit samples of 0.5 g were extracted with 30 mL mixed solution (hexane:acetone:absolute ethanol = 2:1:1 ($v/v/v$)). The resulting hexane layer was then analyzed for carotenoid concentration using spectrophotometry at 450 nm.

The total content of polyphenol was measured according to a previous method [33]. Fresh fruit samples of 0.5 g were mixed with 8 mL ethanol then centrifuged at 3000 rpm for 15 min. A measure of 1 mL supernatant was mixed with 0.5 mL folin-phenol solution, 1.5 mL 26.7% sodium carbonate solution, and 7 mL distilled water. The absorbance was measured at 760 nm.

2.7. Contents of Soluble Sugar and Organic Acid

The sugar content was analyzed using the methods outlined in previous research [34] with slight adjustments. Fresh fruit samples of 1.0 g were homogenized in 5 mL 90% ethanol. The mortar was bathed in water at 80 °C for 20 min after washing twice with 2 mL of 90% ethanol. After centrifugation at 4000 rpm for 10 min, the supernatant was transferred to a 15 mL glass test tube, and the residue was repeatedly washed with 4 mL 90% ethanol in a water bath at 80 °C for 20 min. Then, it was centrifuged at 4000 rpm for 10 min and then combined with the above supernatant. The supernatant obtained from the sample was evaporated to dryness in a rotary evaporation system (Agilent Technologies, Waldbronn, Germany). Samples of 1.0 mL of the resulting solution were filtered through a 0.45 μm MilliporeTM filter then examined by angilent 1200 HPLC system (Agilent Technologies, Waldbronn, Germany). The content of organic acid was analyzed using a method outlined in previous research [34] with slight adjustments. Fresh fruit samples of 1.0 g were ground in an ice bath with 0.2% (w/v) metaphosphoric acid, the mortar was rinsed several times, and the volume was finally set to 10 mL. The mixture was centrifuged at 4000× g for 10 min. The supernatant was passed through a 0.45 μm filter membrane then analyzed by Agilent 1200 HPLC (test condition: C18 column; the mobile phase was 0.2% (w/v) metaphosphoric acid, the flow rate was set at 1 mL/min, the column temperature was maintained at 35 °C, and the injection volume was 10 μL). The reagents used were chromatographic grade standard, with samples such as sucrose, glucose, fructose, tartaric acid, malic acid, and citric acid.

2.8. Statistical Analysis

The effects of cultivar, light conditions, nutrient solution, and their interaction were compared using analysis of variance (ANOVA) in IBM SPSS Statistics 22.0 software. Microsoft Excel 2020 software and Origin 2018 software were used for data visualization and principal component analysis (PCA).

3. Results

3.1. Plant Morphology

The two cherry tomato cultivars exhibited extremely significant differences in plant height, leaf area, and SPAD (Table 2). The plants treated with NS3 exhibited limited growth (Figure 1B). The plant growth parameters of the two cherry tomatoes were significantly influenced by the EC levels, as shown in Table 2. As compared to NS1, plant height, stem diameter, leaf number and area, and SPAD value were reduced to different degrees under NS3 but increased under NS2 (Table 2). Two-way ANOVA analysis indicated that the plant growth of cherry tomatoes was significantly affected by the EC but not by the interaction of SL and EC (Table 2).

Table 2. The effects of light conditions and nutrient solution (NS) concentration on the growth parameters and leaf SPAD value of two cherry tomato cultivars grown in substrate under greenhouse conditions during the winter–spring season. The abbreviations L1NS1, L1NS2, L1NS3, L2NS1, L2NS2, and L2NS3 indicate the combinations of two light conditions and three nutrient solution concentrations: natural light without (L1) or with (L2) supplemental lighting; nutrient solution electrical conductivity (EC) of 3.2 (NS1), 3.7 (NS2) or 4.2 dS/m (NS3).

Treatments			**Plant Height (cm)**	**Stem Diameter (mm)**	**Leaf Number Per Plant**	**Leaf Area (dm^2 Plant^{-1})**	**SPAD**
Cultivar (C)	**Light Conditions (L)**	**Nutrient Solution Concentration (NS)**					
‘Baiyu’	L1	NS1	133.25 ± 4.56 ab	14.93 ± 1.29 c	33.00 ± 0.63 ab	8.41 ± 1.07 a	48.18 ± 1.26 ab
		NS2	135.13 ± 2.78 a	16.99 ± 0.34 abc	31.67 ± 0.33 b	8.67 ± 0.21 a	48.05 ± 1.11 ab
		NS3	136.78 ± 0.94 a	15.90 ± 0.44 bc	32.83 ± 0.6 ab	8.29 ± 0.41 a	47.13 ± 0.95 ab
	L2	NS1	137.17 ± 1.14 a	17.76 ± 0.86 ab	31.67 ± 0.42 b	8.52 ± 0.45 a	50.42 ± 1.34 a
		NS2	136.26 ± 2.41 a	18.78 ± 0.83 a	33.83 ± 0.6 a	8.33 ± 0.65 a	46.94 ± 1.19 ab
		NS3	126.35± 3.18 b	15.15 ± 0.79 c	32.67 ± 0.49 ab	7.38 ± 0.51 a	45.55 ± 1.23 b
‘Qianxi’	L1	NS1	104.14 ± 1.03 ab	17.05 ± 0.39 ab	32.17 ± 0.48 abc	5.71 ± 0.27 a	56.98 ± 1.65 a
		NS2	108.42 ± 4.50 a	17.78 ± 0.32 a	34.00 ± 0.68 a	5.12 ± 0.2 ab	54.55 ± 2.19 a
		NS3	96.66 ± 0.70 bc	15.59 ± 0.59 b	32.00 ± 0.77 bc	4.54 ± 0.32 b	52.00 ± 2.03 a
	L2	NS1	97.60± 0.70 bc	17.93 ± 0.62 a	31.33 ± 0.67 bc	5.54 ± 0.13 a	56.25 ± 1.97 a
		NS2	99.24 ± 1.81 bc	17.79 ± 0.45 a	33.00 ± 0.68 ab	5.98 ± 0.61 a	56.60 ± 3.32 a
		NS3	92.68 ± 1.86 c	16.14 ± 0.53 b	31.00 ± 0.26 c	4.56 ± 0.14 b	52.93 ± 2.18 a
ANOVA significance		C	**	*NS*	*NS*	**	**
		L	**	*	*NS*	*NS*	*NS*
		NS	**	**	*	*	*
		C × L	*NS*	*NS*	*NS*	*NS*	*NS*
		C × NS	*NS*	*NS*	*	*NS*	*NS*
		L × NS	*NS*	*NS*	*NS*	*NS*	*NS*
		C × L × NS	*	*NS*	*NS*	*NS*	*NS*

Note: Means ± standard error of six replicates. Different letters indicate significant differences among treatments according to Duncan’s multiple range test ($p \leq 0.05$); *NS* means not significantly different; * and ** mean significantly different at 5% and 1% levels, respectively.

The fruit appearance of ‘Baiyu’ is yellowish white, while ‘Qianxi’ is red (Figure 1C), and the latter has about five times the carotenoid content than the former (Figure 1D). High EC (NS3) increased carotenoid content in the fruits of both cultivars. SL further increased the carotenoid content at NS1, NS2, and NS3 in ‘Baiyu’, and at NS3 in ‘Qianxi’. With the increase in EC, carotenoid content increased by 13–16% and 28–32% under L1 and L2, respectively, in ‘Qianxi’ (Figure 1D). The combination of SL and NS3 contributed to the accumulation of carotenoid in both cultivars.

3.2. Photosynthesis Capacity

The photosynthetic parameters of ‘Qianxi’ were higher than those of ‘Baiyu’ (Table 3). NS2 had the highest level of leaf *Pn*, followed by NS1, and lastly by NS3. The *Pn* under L2NS3 was significantly higher than it was under L1NS3. SL alleviated the effect of the reduction in NS3 on *Pn* in ‘Baiyu’. *Ci* and *Gs* were affected by the interaction of SL and EC. *Ci* was affected by the interaction of C × L × NS (Table 3).

3.3. Fruit Production

The combinations of SL and EC had extremely significant effects on fruit production characteristics, such as single fruit weight, fruit diameter, and fruit water content (Figure 2, Table 4). With the increase in EC, fruit diameter and length decreased, while the lowest fruit size was found under L2NS3 treatment. The SL reduced fruit diameter and length at NS3 in both cultivars (Figure 2A,B). The SL significantly increased the single fruit weight at NS2 in ‘Baiyu’ but not in ‘Qianxi’ (Figure 2C). The highest fruit weight per plant was found under NS2, followed by NS1, and the lowest was NS3, which was further increased by SL at NS2 in both cultivars, but there was no significance (Figure 2D). Fruit water content was increased significantly by SL at NS1 in both cultivars (Figure 2E). In conclusion, the combination of SL and NS2 significantly enhanced fruit production under the experimental conditions.

Table 3. The effects of light conditions and nutrient solution concentration (NS) on leaf gas exchange parameters of two cherry tomato cultivars grown in substrate under greenhouse conditions in the winter–spring season. The abbreviations L1NS1, L1NS2, L1NS3, L2NS1, L2NS2, and L2NS3 indicate the combinations of two light conditions and three nutrient solution concentrations: natural light without (L1) or with (L2) supplemental lighting; nutrient solution electrical conductivity (EC) of 3.2 (NS1), 3.7 (NS2), or 4.2 dS/m (NS3). Means ± standard error of six replicates. Different letters indicate significant differences among treatments according to Duncan's multiple range test ($p \leq 0.05$); *NS* means not significantly different; * and ** mean significantly different at 5% and 1% levels, respectively.

Treatments			***Pn* (μmol m^{-2} s^{-1})**	***Ci* (μmol mol^{-1})**	***Gs* (mol m^{-2} s^{-1})**	***Tr* (mmol m^{-2} s^{-1})**
Cultivar (C)	**Light (L)**	**Nutrient Solution (NS)**				
'Baiyu'	L1	NS1	13.53 ± 0.18 bc	264.00 ± 4.04 a	0.19 ± 0.01 b	1.15 ± 0.15 ab
		NS2	15.17 ± 0.62 a	264.00 ± 1.68 a	0.24 ± 0.00 a	1.31 ± 0.05 a
		NS3	10.67 ± 0.47 d	272.00 ± 2.08 a	0.16 ± 0.01 bc	1.14 ± 0.04 ab
	L2	NS1	12.83 ± 0.35 c	236.33 ± 5.36 c	0.15 ± 0.02 c	0.99 ± 0.08 b
		NS2	14.47 ± 0.58 ab	233.00 ± 2.08 c	0.14 ± 0.01 cd	1.15 ± 0.04 ab
		NS3	12.27 ± 0.45 c	251.67 ± 6.17 b	0.13 ± 0.01 d	1.02 ± 0.01 ab
'Qianxi'	L1	NS1	20.80 ± 1.42 ab	282.33 ± 1.45 a	0.19 ± 0.00 b	1.36 ± 0.06 b
		NS2	21.63 ± 0.47 a	275.33 ± 2.33 a	0.27 ± 0.01 a	1.15 ± 0.00 c
		NS3	14.73 ± 1.03 cd	253.33 ± 12.25 a	0.18 ± 0.02 b	1.28 ± 0.07 bc
	L2	NS1	17.63 ± 0.87 bc	272.33 ± 7.97 a	0.19 ± 0.00 ab	1.57 ± 0.03 a
		NS2	21.87 ± 1.45 a	215.00 ± 15.59 b	0.15 ± 0.01 b	1.11 ± 0.05 c
		NS3	13.73 ± 1.45 d	278.00 ± 3.06 a	0.17 ± 0.04 b	1.18 ± 0.08 c
Significance		C	**	**	*	**
		L	*NS*	**	**	*NS*
		NS	**	**	**	*NS*
		C × L	*NS*	**	*NS*	*
		C × NS	**	**	*NS*	**
		L × NS	*NS*	**	**	*NS*
		C × L × NS	*NS*	**	*NS*	*NS*

Note: Net photosynthetic rates (*Pn*). Stomatal conductance (*Gs*). Intercellular CO_2 concentration (*Ci*). Transpiration (*Tr*).

Table 4. The results of the three-way analysis of variance of the fruit parameters measured in two cherry tomato cultivars grown in substrate under greenhouse conditions in the winter–spring season.

Significance	**C**	**L**	**NS**	**C × L**	**C × NS**	**L × NS**	**C × L × NS**
Single fruit weight	*NS*	*NS*	**	*NS*	*NS*	**	*NS*
Fruit weight per plant	*NS*	*NS*	**	*NS*	*NS*	*NS*	*NS*
Fruit diameter	**	*NS*	**	*NS*	*	**	*NS*
Fruit length	**	**	**	*NS*	*NS*	*NS*	*NS*
Fruit water content	*NS*	*NS*	*NS*	*NS*	*NS*	**	*NS*
N content	**	**	**	**	**	**	**
P content	**	**	**	*NS*	**	**	**
K content	**	*NS*	**	**	**	**	**
Ca content	**	*	**	**	**	**	**
Mg content	*NS*	**	**	*	**	**	**
Total soluble solid	**	**	**	*NS*	**	**	*
Soluble sugar	*NS*	*NS*	**	*NS*	**	**	*NS*
Vitamin C	**	**	**	*NS*	*	**	*
Polyphenols	**	**	*NS*	*NS*	*NS*	**	*NS*
Carotenoid	**	*	**	**	**	**	**
Sucrose	**	**	**	**	**	**	**
Glucose	*NS*	*	**	*NS*	**	**	*NS*
Fructose	**	*	**	*NS*	**	**	*NS*
Malic acid	*NS*	*NS*	**	*NS*	**	*NS*	*NS*
Citric acid	*NS*	*	**	*NS*	*NS*	*	*NS*
Tartaric acid	*NS*	*	**	*NS*	*NS*	**	*NS*

Note: *NS* means not significantly different; * and ** mean significantly different at 5% and 1% levels, respectively.

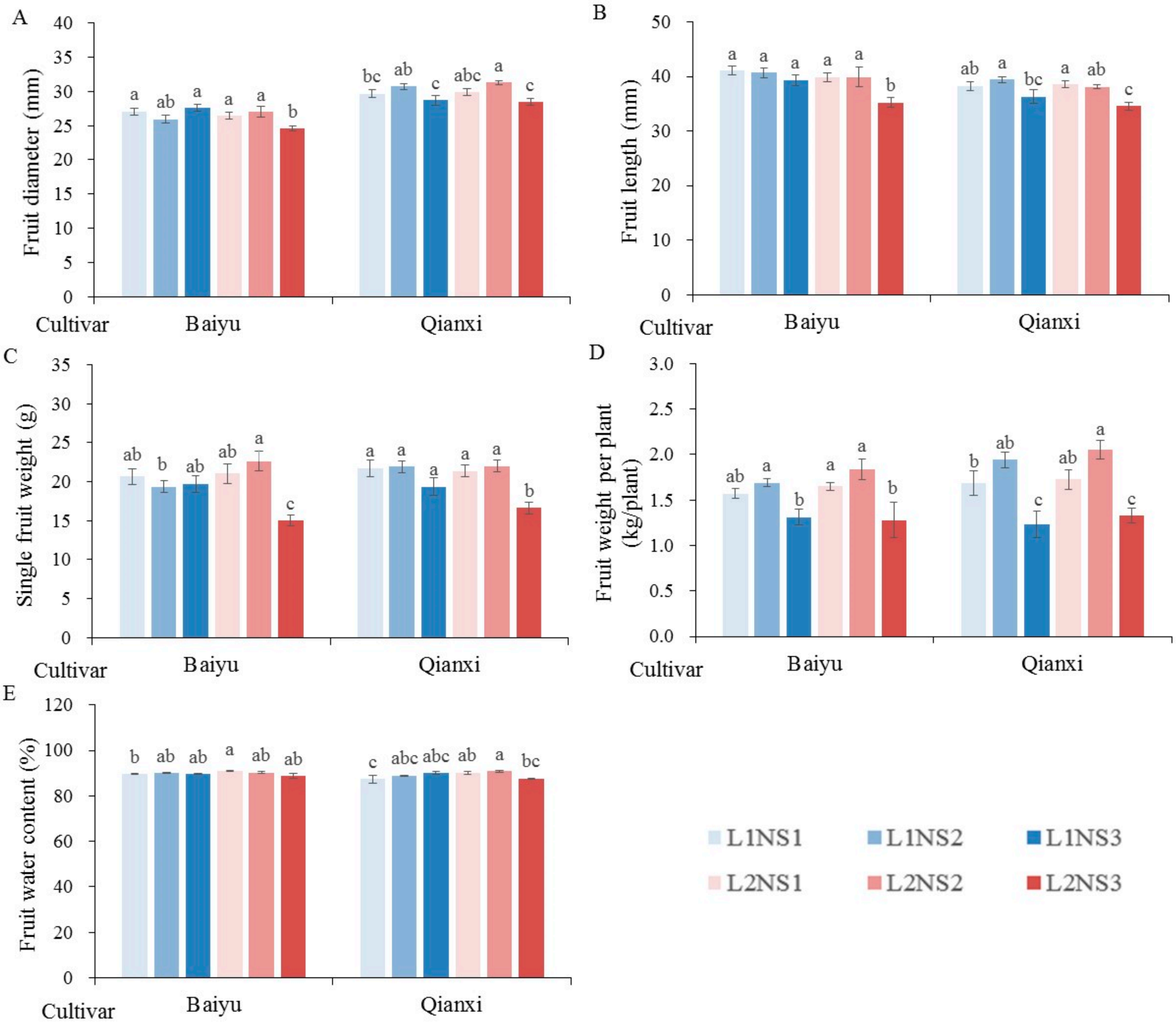

Figure 2. The effects of light conditions and nutrient solution concentration (NS) on fruit production characteristics of two cherry tomato cultivars grown in substrate under greenhouse conditions in the winter–spring season: fruit diameter (**A**), fruit length (**B**), single fruit weight (**C**), fruit weight per plant (**D**), and fruit water content (**E**). The abbreviations L1NS1, L1NS2, L1NS3, L2NS1, L2NS2, and L2NS3 indicate the combinations of two light conditions and three nutrient solution concentrations: natural light without (L1) or with (L2) supplemental lighting; nutrient solution electrical conductivity (EC) of 3.2 (NS1), 3.7 (NS2), or 4.2 dS/m (NS3). Means ± standard error of six replicates. Different letters indicate significant differences among treatments according to Duncan's multiple range test ($p \leq 0.05$).

3.4. Mineral Element Content

The SL, EC, and their combinations had significant effects on mineral element accumulation in the fruits of the two cultivars (Figure 3). NS2 had the highest N content in 'Qianxi', while SL significantly increased the N content at NS1 in 'Baiyu' (Figure 3A). The highest P content was observed for L2NS2 in both cultivars. The SL significantly increased P content at NS1 in 'Baiyu', and at NS2 and NS3 in 'Qianxi' (Figure 3B). K content significantly decreased with an increase in EC in both cultivars, and SL significantly increased the K content at NS1 in 'Baiyu' (Figure 3C). With increases in EC, Ca content significantly increased under L1 but decreased under L2 in 'Baiyu'. The highest Ca content was found at NS2 in 'Qianxi' (Figure 3D). The highest Mg content was observed at NS2, and SL significantly increased Mg at NS1 in both cultivars (Figure 3E). Generally, the increase in EC promoted N, Ca, and Mg accumulation, while it inhibited the accumulation of P and K. Additionally, the application of SL promoted the accumulation of N, P, K, Ca, and Mg in 'Baiyu' fruits under NS1 treatment.

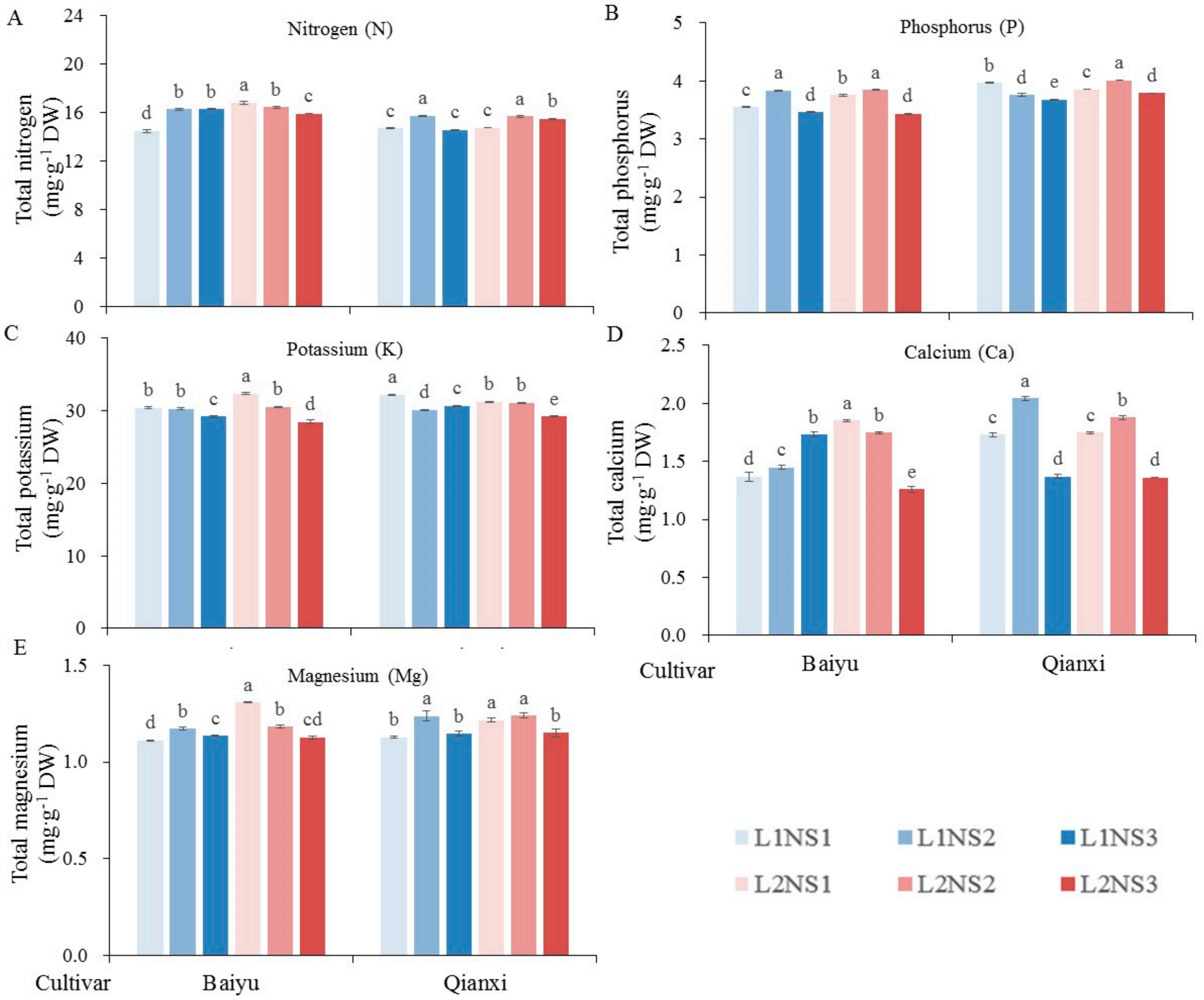

Figure 3. The effects of light conditions and nutrient solution concentration (NS) on the fruit mineral content of two cherry tomato cultivars grown in substrate under greenhouse conditions in the winter–spring season: total nitrogen (**A**), phosphorus (**B**), potassium (**C**), calcium (**D**), and magnesium (**E**). The abbreviations L1NS1, L1NS2, L1NS3, L2NS1, L2NS2, and L2NS3 indicate the combinations of two light conditions and three nutrient solution concentrations: natural light without (L1) or with (L2) supplemental lighting; nutrient solution electrical conductivity (EC) of 3.2 (NS1), 3.7 (NS2), or 4.2 dS/m (NS3). Means ± standard error of six replicates. Different letters indicate significant differences among treatments according to Duncan's multiple range test ($p \leq 0.05$).

3.5. Fruits Quality

Fruits quality was significantly affected by SL, EC, and their combinations (Figure 4). 'Baiyu' was more sensitive to increases in EC than 'Qianxi'. The content of TSS, soluble sugar, and vitamin C increased with an increase in EC, and SL further significantly enhanced the fruit quality parameters at NS3 in 'Baiyu' (Figure 4). However, SL significantly decreased the content of soluble sugar and vitamin C at NS2 in 'Baiyu' (Figure 4B,C). For 'Qianxi', the highest contents of fruit TSS, vitamin C, soluble sugar, and polyphenol were found under the L2NS3 treatment (Figure 4).

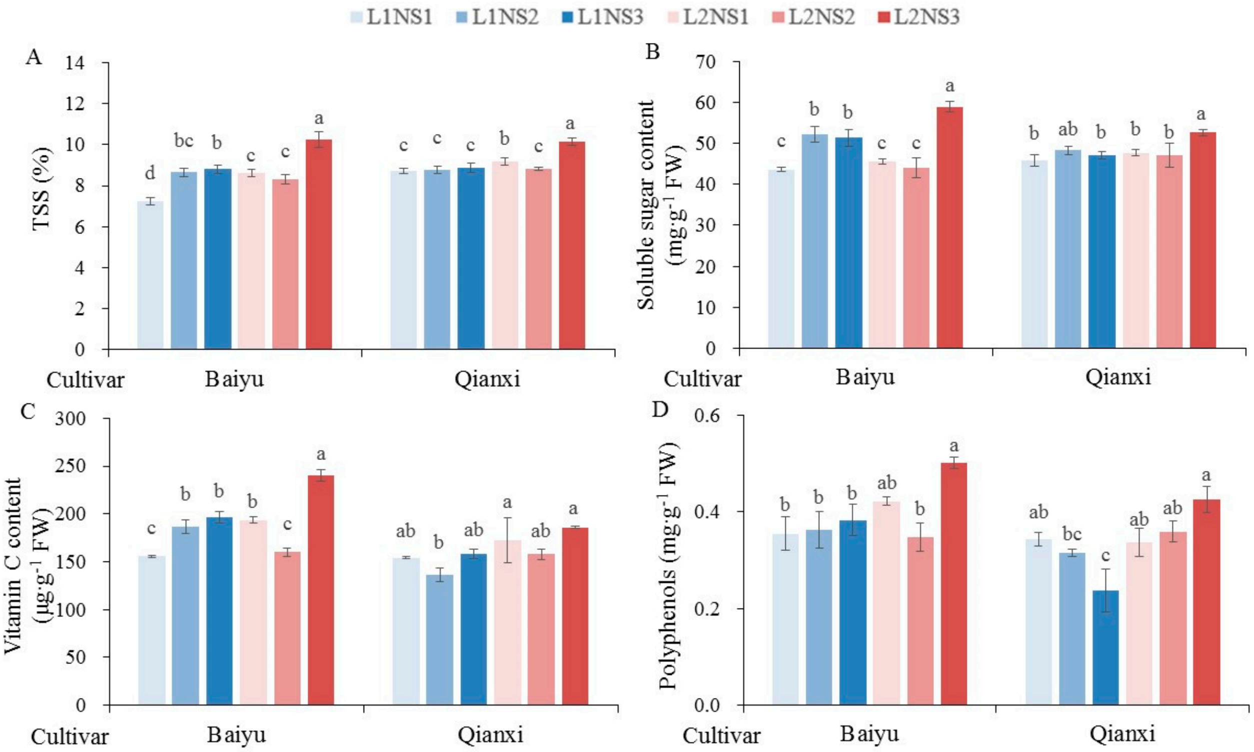

Figure 4. The effects of light conditions and nutrient solution concentration (NS) on fruit nutritional quality of two cherry tomato cultivars grown in substrate under greenhouse conditions in the winter–spring season: total soluble solids (TSS) (**A**), total soluble sugars (**B**), vitamin C (**C**), and polyphenols (**D**). The abbreviations L1NS1, L1NS2, L1NS3, L2NS1, L2NS2, and L2NS3 indicate the combinations of two light conditions and three nutrient solution concentrations: natural light without (L1) or with (L2) supplemental lighting; nutrient solution electrical conductivity (EC) of 3.2 (NS1), 3.7 (NS2), or 4.2 dS/m (NS3). Means ± standard error of six replicates. Different letters indicate significant differences among treatments according to Duncan's multiple range test ($p \leq 0.05$).

3.6. Contents of Soluble Sugars and Organic Acids

As with TSS, the contents of soluble sugars and organic acids were significantly affected by SL, EC, and their combinations (Figure 5). 'Baiyu' was more sensitive to increases in EC than 'Qianxi'. With an increase in EC, soluble sugars content increased but organic acid content decreased (Figure 5). Both of them were significantly higher in L1NS2 and L1NS3 than in L1NS1 in the 'Baiyu' cultivar (Figure 5A,B). Both were higher after L2NS3 treatment than L1NS3, and higher for L1NS2 than L2NS2. These indicated that SL significantly reduced the fructose and glucose at NS2 but increased both of them at NS3. Both cultivars had the lowest citric acid content under L1NS3 treatment (Figure 5D). SL and EC had no significant effect on malic acid accumulation (Figure 5E). The tartaric acid content was reduced by higher EC (NS2 and NS3) and SL at NS1 (Figure 5F).

The above results indicated that the combination of SL and NS3 promoted the accumulation of TSS, vitamin C, polyphenol, fructose, glucose, sucrose, citric acid, and carotenoids in cherry tomato fruits. 'Baiyu' contained more metabolites than 'Qianxi', but the opposite was the case for carotenoid content.

3.7. Interactions, PCA, and Heat Map Analysis

The contents of minerals (N, P, K, Ca, Mg), TSS, vitamin C, carotenoids, and sucrose were significantly influenced by C × L × NS. Significant interactions were observed between L and NS for the fruit quality parameters (Table 4).

Principal component analysis (PCA) and heatmaps were used to analyze and visualize the combination effects of SL and EC of nutrient solution on the growth, fruit production, and fruit quality of both cultivars (Figure 6). Overall, PC1 explained 41.9% and 39.7%

and PC2 explained 16.4% and 14% in 'Baiyu' and 'Qianxi', respectively (Figure 6A,B). For 'Baiyu', with the exception of L1NS1 in lower quadrants, the other treatments distributed in the upper quadrants were characterized by higher fruit nutritional and flavor quality after L1NS3 and L2NS3 treatments, while higher plant growth and fruit production was found after L2NS1 and L2NS2 treatments (Figure 6A). For 'Baiyu', treatments distributed to the upper quadrant were characterized by higher fruit quality (L2NS3) and growth (L1NS2) (Figure 6B).

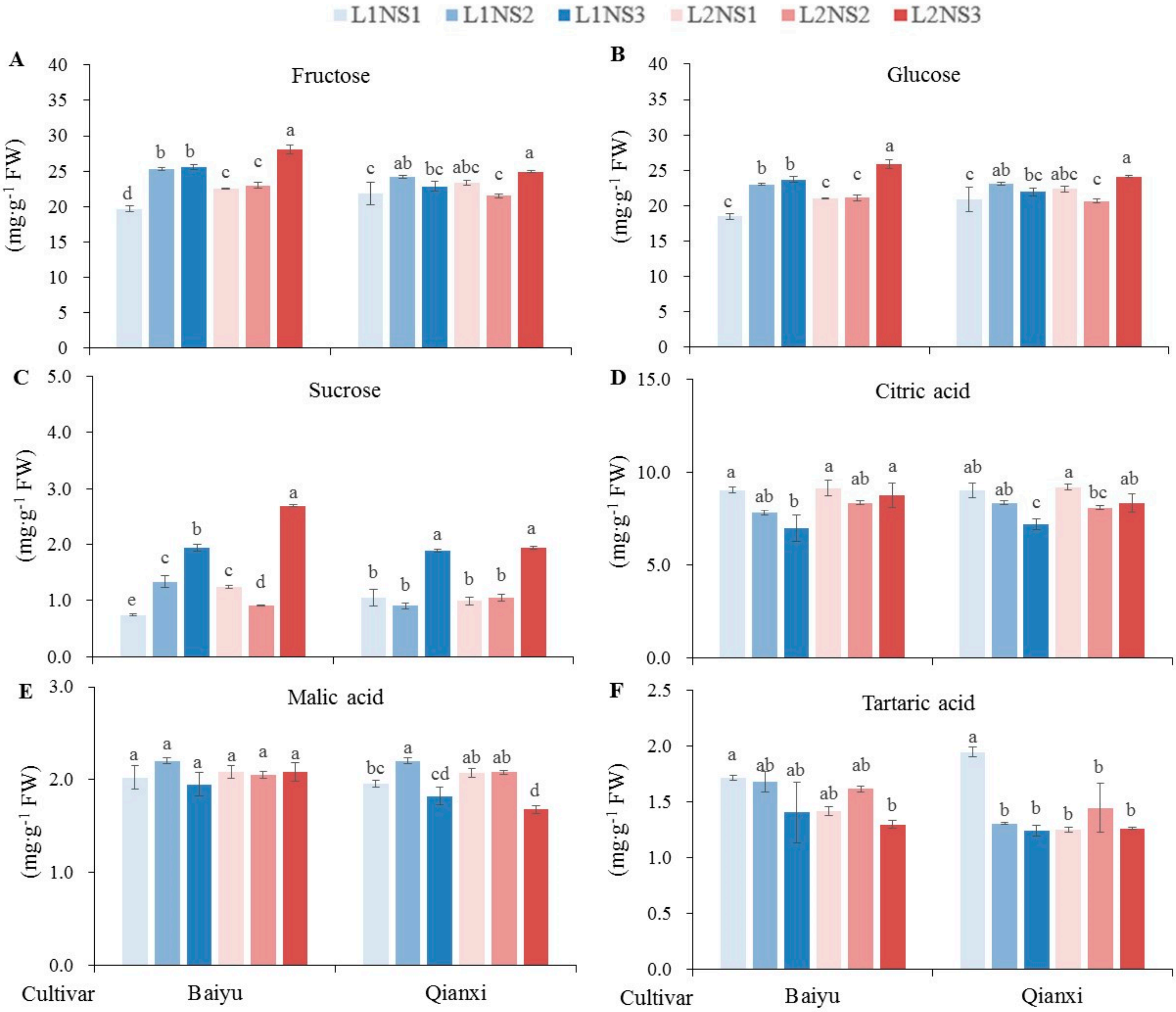

Figure 5. The effects of light conditions and nutrient solution concentration (NS) on the fruit content of soluble sugars and organic acids of two cherry tomato cultivars grown in substrate under greenhouse conditions in the winter–spring season: fructose (**A**), glucose (**B**), sucrose (**C**), citric acid (**D**), malic acid (**E**), and tartaric acid (**F**). The abbreviations L1NS1, L1NS2, L1NS3, L2NS1, L2NS2, and L2NS3 indicate the combinations of two light conditions and three nutrient solution concentrations: natural light without (L1) or with (L2) supplemental lighting; nutrient solution electrical conductivity (EC) of 3.2 (NS1), 3.7 (NS2), or 4.2 dS/m (NS3). Means ± standard error of six replicates. Different letters indicate significant differences among treatments according to Duncan's multiple range test ($p \leq 0.05$).

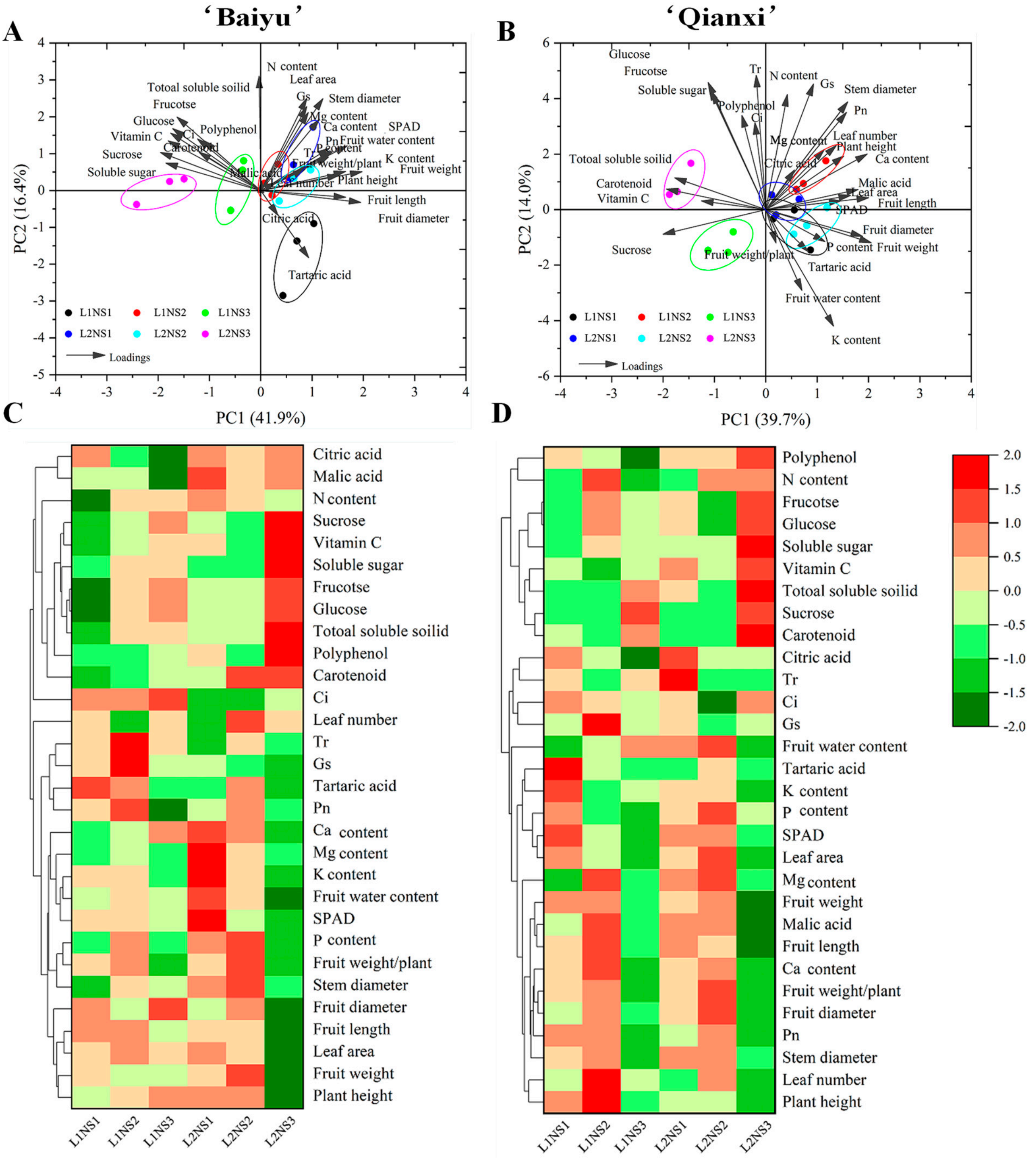

Figure 6. Principle component and cluster heat map analysis of the plant and fruit parameters measured in two cherry tomato cultivars grown in substrate under greenhouse conditions in the winter–spring season. Principle component analysis of 'Baiyu' and 'Qianxi' (**A**,**B**). Cluster heat map analysis of 'Baiyu' and 'Qianxi' (**C**,**D**). Results are visualized using a false color scale with red and green exhibiting the increase and decrease response, respectively. L1NS1, L1NS2, L1NS3, L2NS1, L2NS2, and L2NS3 indicate the combinations of two light conditions and three nutrient solution concentrations.

According to SL and EC treatments, the parameters were grouped into different clusters across the heatmaps (Figure 6C,D). Lower growth and fruit production but higher fruit quality were exhibited in L2NS3 cluster for both cultivars. 'Baiyu' grown under L2NS1 was separated from the other treatments because of its higher K, Ca, and Mg content, SPAD, fruit water content, and fruit malic acid content (Figure 6C). 'Qianxi' grown under L1NS2 was separated from the other treatments due to its plant height, leaf number, fruit size, *Gs*, fruit malic acid content, and N, Ca, and Mg mineral content (Figure 6D).

4. Discussion

4.1. Combination Effects of Supplemental Lighting and Nutrient Solution Concentration on Growth and Photosynthesis of Cherry Tomato Plants

The EC of the nutrient solution determines the yield and quality formation of tomatoes grown via soilless cultivation [13]. In the current study, we increased the EC and meanwhile added KH_2PO_4 and KCl in nutrient solution to form three high-EC solutions (3.2, 3.7, 4.2 dS/m). In general, NS2-treated cherry tomato plants showed more vigorous plant growth and higher net photosynthesis rate (*Pn*, Table 3), while NS3 treatment exhibited the opposite effects (Figure 1A and Table 2). Similar results indicated that high-EC (5.5 dS/m)-treated tomato seedlings result in decreased chlorophyll content and leaf area index, which was not found at EC 3–4 dS/m [35]. Tomato plant fresh weight was reduced by salinized nutrient solution at EC 7 dS/m [18]. The vegetative growth parameters of tomatoes were negatively correlated with increased levels of EC (i.e., 2.5, 6.0, 9.0 dS/m) [36]. Tomatoes are moderately salt-tolerant crops [14], but the reported appropriate EC levels for tomatoes vary with the salt tolerance of cultivars, cultivation pattern, nutrient solution management, and environmental factors, such as temperature and light condition. EC ranging from 0.6 to 1.2 dS/m combined with small-amount and high-frequency drip irrigation was appropriate for tomatoes [15,37]. EC 4.8 dS/m combined with 20% drainage rate markedly promoted tomato plant growth [17]. The production of better-quality cherry tomatoes without negative yield effects in NFT systems can be realized at EC 10 dS/m [10]. In this study, EC 3.7 dS/m was the appropriate nutrient solution concentration for cherry tomatoes grown in the present greenhouse conditions.

Crops' response to SL is complex and sensitive, including from the perspective of orientation, lighting intensities, periods, wavelength, etc. [38]. The applied SL significantly increased plant biomass by increasing stem diameter and root length of wild dwarf 'Micro-Tom' tomatoes [8,20]. The application of SL from underneath the canopy promoted plant growth and leaf photosynthetic activities [8,39,40]. In current study, SL lamps were adjusted to near the clusters of two infinite-growth cherry tomatoes, which were in the fruit enlargement and ripening stage, thus, the SL source was concentrated at the bottom of the canopy (Figure 1A). The effects of SL on growth improvement of 'Baiyu' was reflected in the stem diameter at NS1 and leaf number at NS2 (Table 2). In 'Baiyu', the leaf *Pn* after L2NS3 treatment was significantly higher than after L1NS3 treatment, indicating that SL could alleviate the reduction in *Pn* caused by high EC. *Ci* and *Gs* were affected by the interaction of SL and EC. *Ci* was affected by the interaction of C × L × NS (Table 3). In general, SL's ability to improve growth and *Pn* was cultivar- and EC-dependent in the current culture conditions.

4.2. Combination Effects of Supplemental Lighting and Nutrient Solution Concentration on Fruit Production

In keeping with the improvement of plant growth and leaf *Pn* by NS2 and repression by NS3 (Tables 2 and 3), the highest fruit weight per plant of both cultivars were observed under NS2, and the lowest was under NS3 (Figure 2D). As we know, fruit weight per plant is closely related to fruit size, single fruit weight, fruit water content, fruit number per plant, etc. Decreased fruit size and weight is a typical symptom of tomato plants subjected to salt stress [27,41]. In the current study, fruit size and single fruit weight were both significantly decreased after L1NS3 treatment (Figure 2A–C), suggesting that L1NS3 (EC 4.2 dS/m) has caused salinity stress to cherry tomato plants. However, the response of yield to salinity stress was also different for different cultivars or under different culture conditions. The use of nutrient solution combined with salinity stress at EC 6.0 dS/m resulted in a higher tomato yield as compared with that at EC 2.5 dS/m [36]. EC 7 dS/m reduced tomato fruit fresh weight, but fruits' dry matter content was significantly increased [18]. In the current study, there were no significant differences in fruit water content among EC treatments

(Figure 2E). This suggests that EC affects the fruit production of both cherry tomatoes mainly by regulating fruit size and single fruit weight but not fruit water content.

The use of SL increased the biomass and yield of tomato plants by enhancing plant growth and increasing the fruit weight [20,39,42]. In the current study, in keeping with the promoted plant growth, the fruit weight per plant of both cultivars were increased after L2NS2 treatment as compared with NS2 alone, but there was no significance (Figure 2D). SL significantly increased the single fruit weight at NS2 in 'Baiyu' but not in 'Qianxi' (Figure 2C); this was related to the enhanced plant height, stem diameter, and leaf number after L2NS2 treatment than after L1NS2 treatment in 'Baiyu' (Table 2). In general, two cultivars grown under L1NS2 conditions showed stronger growth and photosynthesis parameters, which is conducive to the fruit's development. The use of SL could further enhance stem diameter, leaf number, and single fruit weight, resulting in a higher fruit weight per plant in 'Baiyu', which was not observed in 'Qianxi'.

4.3. Combination Effects of Supplemental Lighting and Nutrient Solution Concentration on Fruit Mineral Content

Mineral accumulation in plants has been directly related to EC [43,44]. In the current study, mineral accumulation in fruits was affected by the interaction of cultivar, light, and EC and also related to plant growth and fruit production. Increases in EC promoted N, Ca, and Mg accumulation but repressed P and K accumulation in cherry tomato fruits (Figure 3), suggesting that the added KH_2PO_4 and KCl in the nutrient solution was not effectively absorbed by the plants. However, supplementation of P and K fertilizer has increased root uptake rate of K^+ and PO_4^{3-} [22]. The increased EC value and K^+ and PO_4^{3-} content were too high for the present cultivar and reduced the root uptake of K^+ and PO_4^{3-}.

Light plays a vital role in growth and development in terms of energy source and signal transduction [26,39,45]. The critical role of light signals in promoting the uptake of nutrients in plants has been clarified in recent decades [25,46]. The optimal ratio of light quality, intensity, and photoperiod can effectively affect nutrient uptake [26]. Supplemental intra-canopy red LEDs significantly increased the content of K, Mg, and Ca in tomato fruit as compared with HPS lamps [47]. The use of SL promoted K accumulation in tomato fruits [20]. In this study, SL significantly promoted N, P, K, Ca, and Mg accumulation in 'Baiyu' fruits at NS1, which was not observed in 'Qianxi' (Figure 3). In keeping with SL's impact on minerals, the accumulation of fruit water, TSS, vitamin C, fructose, sucrose, and carotenoids in 'Baiyu' fruits was also significantly promoted by SL at NS1. These metabolites all belong to TSS in fruits. We speculated that the 'Baiyu' plants grown under L2NS1 conditions and exhibited higher metabolites are necessarily related to sufficient fruit water and minerals. Further research should be carried out to discuss how their relationships are regulated by SL.

4.4. Combination Effects of Supplemental Lighting and Nutrient Solution Concentration on Fruit Quality

TSS content is generally used to evaluate tomato quality, which determines the taste intensity [11]. TSS is mainly composed of sugars (fructose, glucose, and sucrose, ~60%), organic acids and amino acids (citric and malic, ~15%), and other metabolites (phenols, minerals, ~25%) [48]. Soluble sugar and organic acid content were enhanced markedly by high EC (4.5 dS/m) as compared with low EC (2.2 dS/m) [11]. High-TSS tomatoes have been produced by controlling the EC in the supply solution at 7 dS/m and in drainage solution >10 dS/m [18]. In this study, the effects of EC on quality regulation was cultivar dependent. Fruit quality parameters exhibited increased tendency with increases in EC in 'Baiyu', which were only significantly increased at NS3 in 'Qianxi' (Figures 4 and 5). The highest contents of TSS, soluble sugar, fructose, glucose, and sucrose were observed after L2NS3 treatment (Figures 4 and 5). Both cultivars had the lowest citric acid content after L1NS3 treatment, but this was increased under L2NS3 conditions as compared with L1NS3 (Figure 5D).

Increases in EC caused moderate salt stress, resulted in an improvement in the fruit quality of tomatoes [11,49,50]. The enhancement of metabolites in tomato fruits exposed to salinity stress has been reported as a 'concentration effect' that occurs with a decrease in fruit water and size [51]. On the other hand, salinity conditions have been shown to regulate the activity of enzymes involved in the translocation of carbohydrates to fruit [27,41], induce gene expression involved in assimilate metabolism [51,52], or promote fruit dry matter production [18]. In this study, we speculated that plants grown under NS3 suffered a degree of salinity stress and showed repressed growth and reduced fruit size and weight but exhibited higher fruit quality. The use of SL could further improve fruit quality. In practical production, cherry tomatoes with a TSS content higher than 10% have been identified as high-sugar brand tomatoes. In this study, the highest content of TSS reached up to 10.25% in 'Baiyu' and 10.13% in 'Qianxi' after L2NS3 treatment (Figure 4A), implying that high-quality cherry tomato production can be realized through combing SL and high EC (4.2 dS/m) in greenhouse conditions.

Carotenoids, polyphenols, and vitamin C are well-known antioxidants and health-promoting components for the human diet [53,54]. Carotenoids determine the coloration of ripe tomato fruits, a crucial indicator of nutritional and commercial quality [55]. High EC has been shown to increase the lycopene content of pepper fruits [56]. The tomato fruit coloring has been significantly correlated with root K+ uptake rate [20,22]. Total carotenoids have been shown to increase when increasing K levels in the nutrient solution [57]. Our results were consistent with these observations: the carotenoid content of both cherry tomatoes was significantly increased by high EC (4.2 dS/m), which was further improved by SL (Figure 1D). Light intensity significantly improved the accumulation of vitamin C, carotenoids, and phenolic compounds in tomatoes [5]. SL plays a crucial role in promoting fruit coloring and total carotenoid accumulation by regulating lycopene metabolism gene expression [19], ethylene production [21,58], and mineral uptake [20,25]. Nighttime LED inter-lighting has been shown to significantly increase the content of vitamin C in tomato fruits [59]. An increase in blue light proportion in SL promotes the synthesis of phenolic compounds [7]. This study produced similar results: the combination of SL and NS3 increased the contents of carotenoids, vitamin C, and polyphenols in both cultivars, and 'Baiyu' demonstrated a higher increase than 'Qianxi' (Figure 4C). This means that the accumulation of carotenoids, polyphenols, and ascorbic acid in fruits under high EC play a crucial role in antioxidant protection.

Diverse soil nutrient conditions has been shown to lead to variations in the metabolic composition of tomato fruits, while the impact of supplemental red light exhibits variability depending on nutrient conditions [60]. Similarly, in this study, fruit production and quality were primarily influenced by the NS status, while the promotion effect of SL was observed under high-EC conditions. We hypothesized that the diminished fruit size and weight observed in plants cultivated under L2NS3 conditions constituted a primary factor contributing to the heightened metabolite levels in fruits, while SL also functioned as a signaling molecule regulating metabolite accumulation in this study. Additionally, cherry tomato plants respond to high EC by accumulating sugars (glucose, fructose, and sucrose), which are a precursor of metabolites and osmotic substances. In conclusion, SL combined with high EC could be considered for improving fruit coloring and nutritional and health-promoting quality in the winter–spring season.

5. Conclusions

In this study, the effects of the combination of supplemental lighting and nutrient solution treatment on fruit production and quality in two fruit-colorings of cherry tomatoes have been studied. The results indicated that supplemental lighting combined with a moderate nutrient solution concentration (EC 3.7 dS/m) contributed to an improvement in fruit weight. However, the combination of supplemental lighting and high nutrient solution (EC 4.2 dS/m) enhanced the fruit content of total soluble solids, carotenoids, glucose, fructose, sucrose, and citric acid in both cherry cultivars. Moreover, the effect of supplemental lighting on fruit quality depended on cultivar and nutrient solution concentration. Supplemental lighting enhanced the fruit quality of 'Baiyu' in plants irrigated with the highest nutrient solution concentration (EC 3.2 dS/m) by increasing the content of minerals, total soluble solids, vitamin C, fructose, sucrose, and carotenoids.

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Data Availability Statement: Data available in a publicly accessible repository.

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