



Article

When Tomatoes Hit the Winter: A Counterattack to Overwinter Production in Soft-Shell Solar Greenhouses in North China

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Abstract: In North China, the overwintering production of the tomato (*Solanum lycopersicum* L.) encounters difficulties posed by extreme weather conditions and the high costs of traditional greenhouses. Soft-shell solar greenhouses present a viable alternative because of their low cost and excellent heat-retaining properties. This study establishes a technical framework for high-yield and high-quality winter tomato production in soft-shell greenhouses through analyzing dynamic light, temperature, and humidity parameters, cultivar responses, and optimized production–marketing models. Field experiments monitored microclimate data in soft-shell solar greenhouses during different growth stages of six cherry tomato and three large tomato varieties, combined with yield, quality, and economic return analysis. The results showed that (1) soft-shell greenhouses increased average daily temperatures by 10–15 °C, reduced low-temperature stress duration by 25%, achieved 82% light saturation compliance, and decreased humidity fluctuations by 23%; (2) the yield per cluster of cherry tomatoes increased first and then decreased for early maturing varieties, and decreased for middle and late maturing varieties, while the yield of large tomatoes decreased first and then increased; (3) light intensity was positively correlated with Brix accumulation, and humidity was negatively correlated with yield; (4) cherry tomato yields were more temperature-sensitive, whereas large-fruited tomatoes were more influenced by light intensity; (5) a “variety optimization + scenario-based sales” model integrating multi-cultivar layouts and gift-box marketing strategies improved economic returns. This research provides an integrated environmental regulation and market adaptation solution for North China’s protected agriculture, offering a reference value for greenhouse agriculture development in global cold regions.

Keywords: winter tomato cultivation; varietal adaptability; yield and quality; microclimate regulation; economic benefit



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1. Introduction

The tomato (*Solanum lycopersicum* L.), as one of the world’s most consumed vegetable crops, plays a strategic role in ensuring global food security through its year-round supply. FAO data show that global tomato production reached 180 million tons, accounting

for 12.3% of total vegetable output, with China ranking among the top three producers worldwide with an annual yield of nearly 70 million tons [1–3]. Notably, China's tomato production exhibits significant regional disparities, with northern regions contributing only 28% of winter output, creating a structural imbalance characterized by oversupply in summer–autumn and undersupply in winter–spring [4–7]. Research indicates China's tomato consumption is transitioning from “quantity demand” to “quality demand,” with premium fruits (soluble solids $\geq 6.5\%$) commanding a 7.3% annual market growth, driving higher technical requirements for facility agriculture [7–9].

Against the backdrop of global warming, extreme weather events pose severe threats to controlled environment agriculture [10]. The IPCC Sixth Assessment Report warns that a 1 °C rise in global average temperature could reduce tomato yields by 6–10% [11]. Mediterranean agroclimatic studies show that winter nighttime temperatures < 10 °C reduce the fruit set by 35% and increase malformed fruit rates by 22% [12]. USDA data reveal that North American winter tomato imports surged 40% in 2022 to compensate for inadequate local protected production [13]. Northern China faces acute challenges, with winter extreme cold events increasing 67% compared to the 1990s, causing 23–35% yield losses in traditional solar greenhouses while emitting 87.85% more carbon per unit area than open-field production [14–16]. A Tsukuba University study highlights that elevated CO₂ concentrations enhance photosynthesis and yields but degrade fruit quality, creating complex yield–quality trade-offs complicating environmental controls [17]. Facility agriculture is critical for China's year-round vegetable supply, with North China as the national hub cultivating over 1 million hectares annually, including 20% tomato acreage [18]. Beijing, a regional technological and policy hub [19], drives innovations in water-efficient irrigation and precision environmental control, enhancing productivity across the Jing-Jin-Ji and Bohai Rim regions and setting national sustainable benchmarks [20,21]. To meet Beijing's “vegetable basket” standards ($\geq 7.5\%$ Brix, ≤ 0.01 mg kg^{−1} pesticide residue), a production optimization–market traceability system addresses cropping obstacles, modeling high-quality metropolitan agriculture under regional coordination [22]. The Beijing 14th Five-Year Rural Revitalization Plan emphasizes enhancing facility agriculture's intelligent coverage, underscoring the capital's role in modernizing China's sector [23].

The solar greenhouse is an important facility for winter vegetable production in North China, which can achieve a high indoor and outdoor temperature difference without heating or a small amount of heating to meet the growth needs of indoor crops [24,25]. As the structural forms of solar greenhouses have continuously evolved, there have been substantial changes in the structural forms and materials of their back walls [26]. Based on the historical development of solar greenhouse structures and the structural types of solar greenhouses in different regions, the walls of solar greenhouses can be classified into earthen walls, brick walls, reinforced concrete walls, and prefabricated steel walls that have emerged in recent years [27,28]. With the increase in labor and material costs, earthen, brick, and reinforced concrete walls are expensive in terms of materials and involve complex and time-consuming construction processes. As a result, they account for a large proportion of the total greenhouse construction cost [29]. The newly developed soft-shell solar greenhouse uses a prefabricated steel structure as the main framework. The back wall and the two gable walls are covered with insulation quilts, forming the soft-shell walls. This type of greenhouse not only has low construction costs but also does not damage the soil tillage layer. It is an ideal structural form for solar greenhouse walls, offering better thermal insulation and being more effective in blocking the heat exchange between the indoor and outdoor environments. This enables winter vegetable production without additional heating in northern regions and ensures the safe overwintering of crops [30,31]. However, despite these structural advantages, the unique microclimate dynamics created

by soft-shell wall systems (particularly during critical winter overwintering periods) remain poorly understood in terms of their impacts on vegetable growth and development. This knowledge gap limits the optimization of environmental management strategies and sustainable production practices in these advanced greenhouse systems.

Despite significant global advancements in facility agriculture environmental regulation, existing research remains primarily focused on single-factor studies [32–34]. Environmental control parameters were often empirically determined, failing to enable precision dynamic management. Additionally, economic benefit evaluation systems remain disconnected from real-world production scenarios, limiting their utility in guiding varietal distribution and market strategies. This research addresses the gaps in soft-shell solar greenhouse microclimate management and cultivar–market alignment by systematically characterizing dynamic light, temperature, and humidity conditions across key growth stages during winter overwintering in Beijing-region greenhouses, evaluating cultivar-specific yield and quality responses through multi-variety trials with six cherry and three large tomato varieties to identify microclimatic impacts on early-, mid-, and late-maturing types, and developing an integrated “variety optimization + scenario-based sales” model that combines adaptive varietal layouts with targeted marketing strategies like gift-box sales and festival-oriented distribution to align production with Beijing’s high-value market demands, collectively establishing a technical framework for sustainable winter tomato production in North China and offering a scalable solution for cold-region greenhouse systems globally by integrating environmental regulation, cultivar adaptability, and economic viability.

2. Materials and Methods

2.1. Study Area

The experiment was conducted at Jinhuinong Rural Cooperative (40°19′ N, 116°39′ E, elevation 41 m) in Beijing Changping District, located in North China (Figure 1). The total facility agriculture production area across Beijing exceeds 11,500 hectares [35]. The initial soil properties of the experimental site were as follows: pH 7.1; bulk density, 1.31 g cm^{−3}; organic matter content, 23.1 g kg^{−1}; total nitrogen content, 2.25 g kg^{−1}; available phosphorus content, 139 mg kg^{−1}; and available potassium content, 490 mg kg^{−1}. The experiment period was from 30 August 2024 to 5 March 2025, which is a growth cycle for tomatoes.

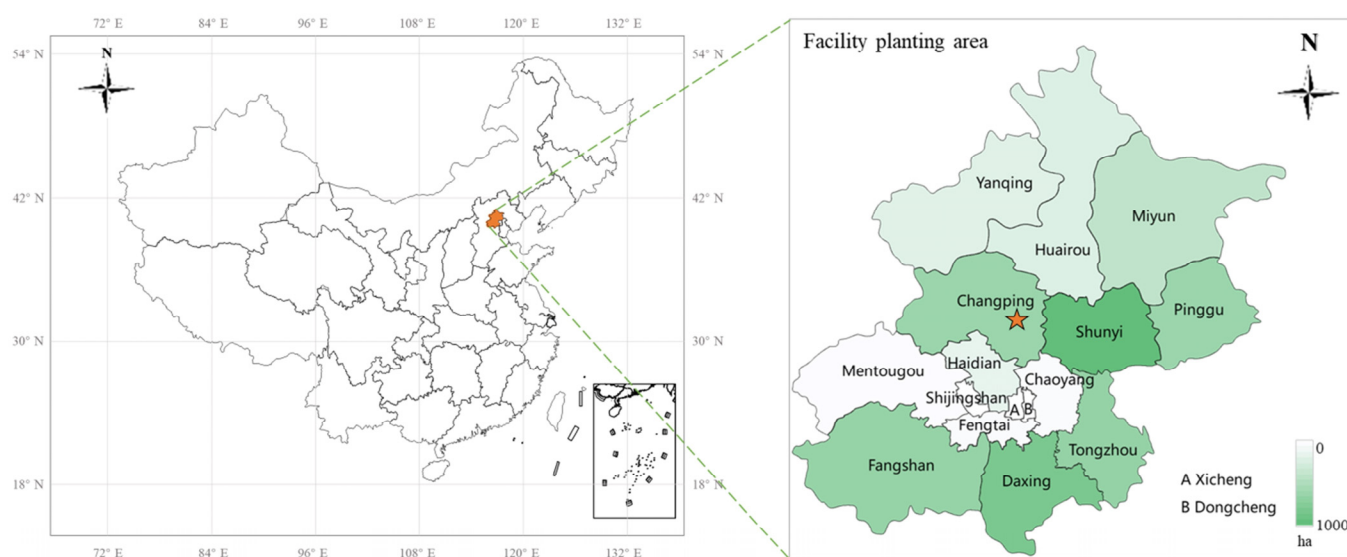


Figure 1. Study area.

2.2. Study Design and Materials

The experiment selected six cherry tomato varieties, namely the early-maturing varieties Qingxia 66 (QX66) and Jumi 1 (JM1), mid-maturing varieties Guanshu Hongzhu (GSHZ) and Guanshu Mingzhu (GSMZ), and late-maturing varieties Heixiaoge (HXG) and Baifei (BF). Additionally, three large tomato varieties were included: early-maturing variety Jingcai 8 (JC8), mid-maturing variety Jingcai 901 (JC901), and late-maturing variety Provence (PRVC) (Table 1). All varieties were F1 hybrid seeds with stable traits, and all seeds required for the experiment were provided by Beijing Beinong Seed Industry Co., Ltd. (Beijing, China). The planted varieties were all tomato varieties widely promoted within the region. The soft-shell solar greenhouse structure, the planting arrangement of the tomato varieties, and the performance of these varieties are shown in Figure 2. The planting density of the tomatoes was 22,500 plants per hectare (ridge width: 90 cm, furrow width: 60 cm, plant spacing: 25 cm, double-row and single-stem planting). The tomato planting method was seedling transplanting soil, and the tomato seedlings were cultivated by the cooperative’s own nursery shed. In each greenhouse, approximately 400 plants of each cherry tomato variety were planted in 20 rows, and around 800 plants of each large tomato variety were planted in 40 rows. When sampling, the middle positions with consistent growth and not shaded by the greenhouse framework were selected to avoid sampling errors.

Table 1. Classification of different tomato varieties, planting period and maturing period of individual fruit per cluster.

Type	Maturing	Variety	Transplanting Date	Tomato Ripening Period (DAT)						Growth Period (DAT)
				1	2	3	4	5	6	
Cherry tomato	Early-	QX66	31 August 2024	67	81	96	113	131	152	152
		JM1		69	82	98	116	135	155	155
	Mid-	GSHZ		71	85	100	118	138	161	161
		GSMZ		72	86	102	121	141	164	164
	Late-	HXG		74	88	104	124	145	169	169
		BF		74	89	106	127	149	174	174
Large tomato	Early-	JC8		83	101	124	150	162		162
	Mid-	JC901		88	108	133	161	174		174
	Late-	PRVC		91	114	140	171	184		184

Note: DAT: days after transplanting.

All agricultural operations, including irrigation, fertilization, plant pruning, pesticide spraying, and greenhouse environment control, were carried out in accordance with high-quality cultivation standards and were kept consistent across all greenhouses and varieties [36]. Throughout the growth cycle, a drip irrigation system was used to precisely control moisture, stabilizing root-zone humidity at 75–85% during seedlings for robust root development and employing intermittent micro-sprinkling to maintain 62.8–78.1% humidity (23% less fluctuation than conventional methods) during fruit expansion, with irrigation triggered by three consecutive days of midday leaf wilting (1–5 m³ per plot, 27 times total). Plant protection included yellow sticky traps for whiteflies/thrips, curative sprays of 22.4% spirotetramat (1500×) or 10% bromoxynil (700×) every 7–10 days, soil disinfection via solarization (50 °C, 15–20 days) and sulfur fumigation (1 kg/667 m²), foliar treatments of 30% cyprodinil-tebuconazole (800×) or 10% fluopyram (2000×) for gray mold/early blight every 10–14 days, and bumblebee pollination reducing malformed fruit by 35%. Nutrient management combined 6–8 t/ha decomposed organic fertilizer

+ 100 kg/ha fermented soybean meal as base, 70% potassium humate (1 kg/ha, 5 times) for root development, high-potassium fertilizers (N-P-K = 12-3-45, 3–5 kg/ha, 20 times) from fruit coloring, and foliar chelated calcium (500–1000×) during fruit enlargement to prevent blossom end rot.

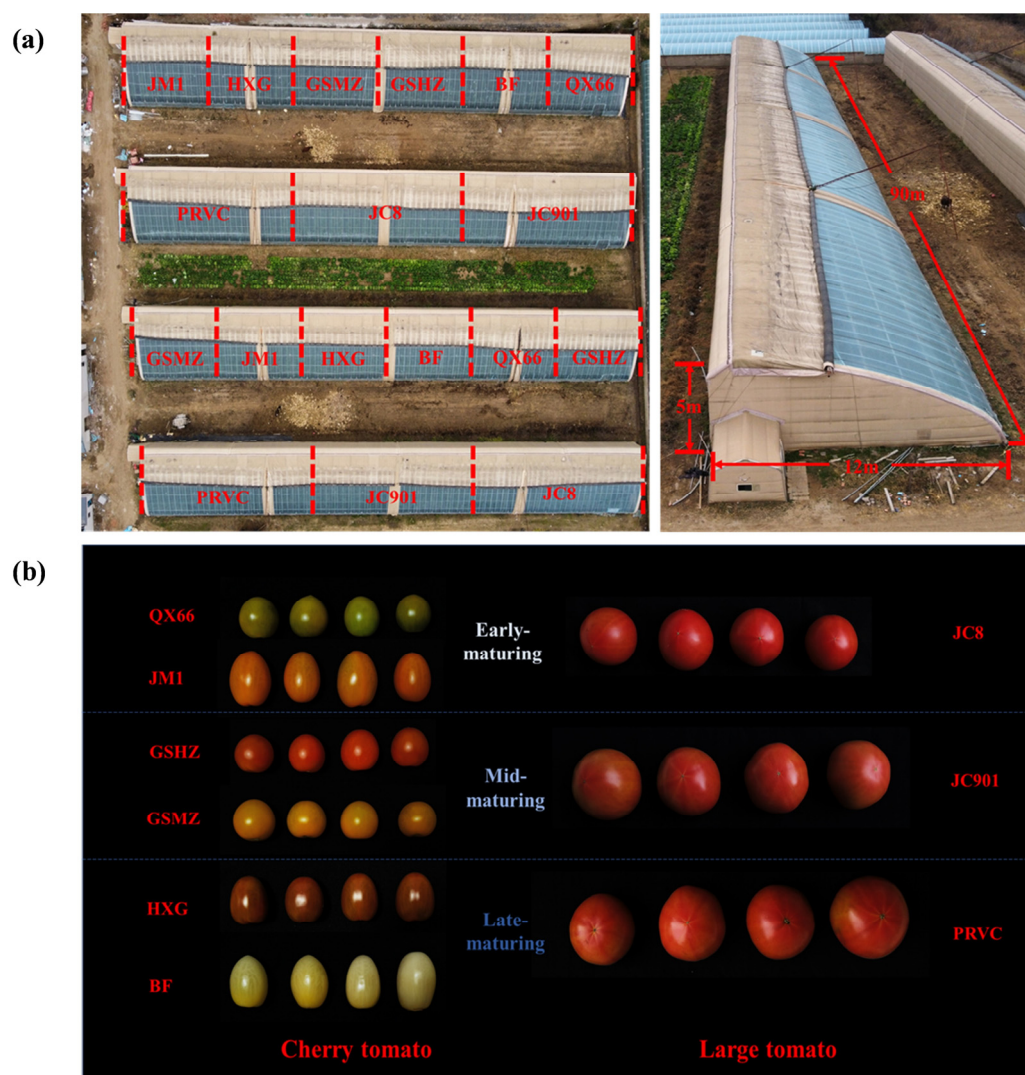


Figure 2. The greenhouse structure, planting arrangement of tomato varieties (a) and maturity classification of varieties (b).

2.3. Tomato Fruit Yield Parameters

The numbers of inflorescence and fruiting branches of the tomato plants were investigated during the whole cultivation period. We harvested tomato fruit from individual labeled plants ($n = 30$) at the ripening stage to determine the agronomic traits. The fresh weights of 30 fruits per cluster of different plants were determined. The marketable yield was determined by summing the weight of all the tomato fruits [37].

2.4. Tomato Fruit Quality

The total soluble solid (TSS or Brix) content and total acidity of each tomato cluster were measured by a portable Brix-acidity meter (PAL-BX | ACID3 Master Kit, ATAGO Co., Ltd., Tokyo, Japan). The sugar/acid ratio (% Brix $\div$ % acid) was calculated by dividing the Brix degree with the citric acid percentage [38]. All determinations were carried out in 9 replicates per cluster of different plants.

2.5. Data Sources

The monitoring of light, temperature and humidity in outdoor climate and in the microclimate of greenhouses were carried out, respectively, by the small meteorological monitoring stations and the greenhouse intelligent sensors provided by Beijing Tianchuang Jinong Technology Co., Ltd. (Beijing, China) (<http://www.bjtcjn.com/facility.html#facility> (accessed on 15 March 2025)). The monitoring data were provided by the company's internal platform. Among them, the light saturation compliance was determined by the proportion of time when the light intensity inside the greenhouse reached or exceeded the light saturation point ($\text{light} \geq 200 \text{ W/m}^2$) during the tomato growth cycle; the integrated regulation compliance refers to the proportion of time when the light intensity, temperature and humidity ($\text{light} \geq 200 \text{ W/m}^2$, temperature $15\text{--}25 \text{ }^\circ\text{C}$, humidity $60\text{--}80\%$) in the greenhouse meet the optimal growth threshold at the key growth stage of the tomatoes.

2.6. Data Analysis

In this experiment, the measured data were analyzed and plotted using Microsoft Excel 2023, IBM SPSS Statistics 25 and Origin 2024. The analysis of variance (ANOVA) at $p < 0.05$ was used to identify differences. Before the analysis, the normality of the data was inspected through descriptive statistics (mean, standard deviation, skewness, kurtosis) and the Shapiro–Wilk test. Non-conforming data were either transformed or analyzed using non-parametric tests. The homogeneity of variance was evaluated with the Levene test. In the case of an unequal variance, the Welch correction was used in the analysis of variance, and the weighted least squares method was adopted in the regression analysis. These procedures ensured the rationality of the data assumptions and provided strong statistical support for the conclusions.

The data used for correlation analysis were the average light intensity, temperature, humidity, yield, and quality traits during the color-turning process of individual trusses in the tomatoes. The partial least squares path model (PLS-PM) was used to investigate the influence and contribution of microclimate in greenhouses on yield and quality of tomatoes under tomato type and maturity (cherry tomato and large tomato were defined as 1 and 2, respectively, early-, mid- and late-maturing were defined as 1, 2 and 3, respectively). An economic analysis of tomato production is performed by assessing a range of components, including production costs, total tomato value, net income and benefit–cost ratios. These components were calculated based on the actual prices of inputs and outputs recorded during the growing season. The total value of tomatoes is calculated by multiplying the yield by the selling price, the net income is calculated by subtracting the cost of production from the total value, and the daily net income is the net income divided by the number of days during the total growth period of the variety.

3. Results

3.1. Soft-Shell Solar Greenhouse Environmental Factors

Based on interior and exterior environmental monitoring data, this study systematically analyzed the stage-specific regulation characteristics of light, temperature, and humidity in soft-shell solar greenhouses during overwintering tomato production (Figure 3). According to tomato growth patterns, the production cycle was divided into five stages with the following regulatory performances: the Seedling Recovery stage maintained light intensity at $128.1\text{--}228.3 \text{ W/m}^2$ ($58.7\text{--}76.3\%$ of outdoor levels) (Figure 3a), average daily temperature at $23.1\text{--}28.2 \text{ }^\circ\text{C}$ ($5.0\text{--}7.6 \text{ }^\circ\text{C}$ higher than outdoor) (Figure 3b) and humidity at $78.9\text{--}88.1\%$, with root-zone humidity stabilized at $75\text{--}85\%$ via drip irrigation (Figure 3c). The Vegetative Growth stage achieved an average daily temperature of $19.5\text{--}25.5 \text{ }^\circ\text{C}$ (diurnal variation $12.5\text{--}18.3 \text{ }^\circ\text{C}$), light intensity significantly increased to $185.8\text{--}366.0 \text{ W/m}^2$

(68.7–82.3% of outdoor levels), and humidity at 65.7–79.1%. The Flowering and Fruiting stage maintained an average daily temperature of 15.2–19.9 °C (7.1–8.8 °C higher than exterior), light intensity at 128.1–228.3 W/m² (62.4–71.2% of exterior levels), and humidity at 75.1–89.8%. The Fruit Expansion stage achieved an average daily temperature of 12.5–17.3 °C (night temperature 8.0–12.0 °C via thermal screens), light intensity at 123.4–245.5 W/m² (51.4–65.2% of outdoor levels), and humidity at 62.8–88.7%. The Color Turning and Maturity stage maintained an average daily temperature of 10.1–19.3 °C (diurnal variation 15.2–22.6 °C), light intensity recovered to 237.6–343.5 W/m² (74.2–85.5% of outdoor levels), and humidity was controlled at 62.8–78.1% via intermittent micro-sprinkling.

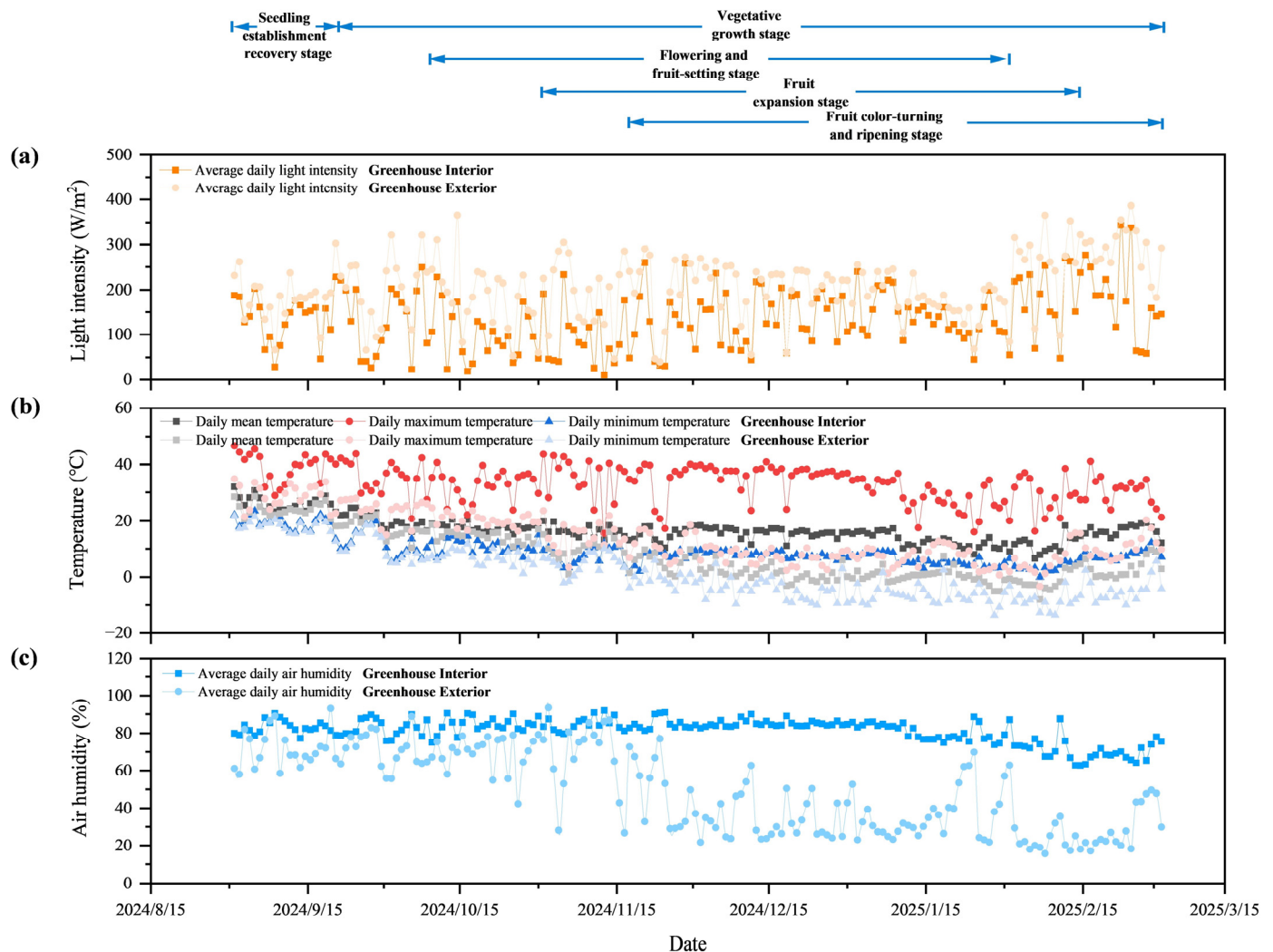


Figure 3. The climatic conditions in the interior and exterior of the greenhouse. (a) Light intensity; (b) air temperature; (c) air humidity.

Soft-shell solar greenhouse monitoring data results showed that the average daily temperature increased by 10–15 °C compared to outdoors, low-temperature stress periods (≤ 15 °C) decreased from 70% to 45% (Figure 3b), light saturation compliance reached 82% (Figure 3a), and humidity variation was reduced by 23% (Figure 3c). Key growth stages (vegetative and maturity) achieved 80% integrated regulation compliance, a 35% improvement over natural conditions. Monitoring data indicated that during sensitive periods (18% of total) with <12 °C and <200 W/m², thermal insulation and humidity control maintained environmental factors above tomato growth thresholds, effectively ensuring growth requirements at all stages. This study provides a replicable environmental

regulation model for overwintering tomato production within the region, achieving stable and high yields under extreme climatic conditions through precise regulation of light, temperature, and humidity.

3.2. Cherry and Large Tomato Yield Parameters

The results indicated that maturity stages and truss positions significantly influenced yield components in both cherry tomatoes and large-fruited tomatoes (Figures 4 and 5). For cherry tomatoes (Figure 4), the individual fruit fresh weight (IFW) showed a parabolic trend with delayed maturity. Early-maturing varieties QX66 and JM1 reached maximum IFW at trusses 3–4 (24.38–28.47 g), while late-maturing variety BF peaked at truss 3 (27.94 g). Mid-maturing varieties GSHZ and GSMZ achieved highest IFW at truss 3 (22.48 g) and truss 2 (23.77 g), respectively (Figure 4a). Fruit number per truss (FN) displayed a significant downward trend with ascending trusses: early-maturing varieties had 14.56 fruits (QX66) and 11.17 fruits (JM1) at truss 1, compared to late-maturing BF's 10.3 fruits at truss 1, which sharply dropped to 4.5 fruits at truss 6 (Figure 4b). Yield performance showed early-maturing varieties had higher yields at middle trusses (2–4), such as QX66 (0.52 t ha⁻¹ at truss 2) and JM1 (0.55 t ha⁻¹ at truss 2). Although late-maturing BF reached maximum yield at truss 3 (0.50 t ha⁻¹), its yield at truss 6 was only 0.16 t ha⁻¹ (Figure 4c). ANOVA revealed extremely significant effects of maturity ($p < 0.001$) and truss position ($p < 0.001$) on IFW, FN, and yield, with significant interactions for IFW and yield ($p < 0.05$).

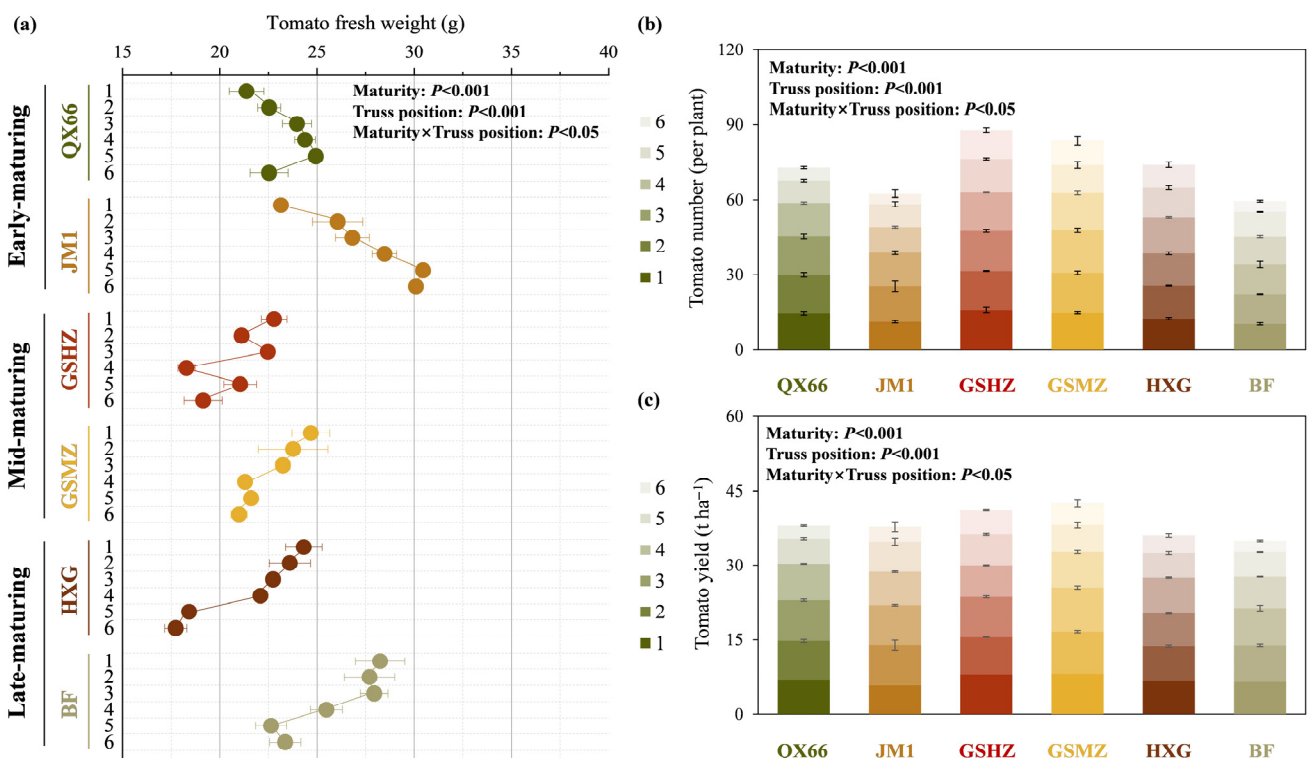


Figure 4. Cherry tomato yield parameters. (a) Fresh tomato weight of individual fruit per cluster; (b) tomato number of per cluster; (c) tomato yield of per cluster.

Large-fruited tomatoes exhibited distinct patterns from cherry tomatoes (Figure 5). Early-maturing cultivar JC8 showed significant IFW decline from truss 1 (92.89 g) to truss 5 (77.58 g) (Figure 5a), with FN decreasing from 4.4 to 1.57 fruits (Figure 5b), leading to a yield reduction from 0.61 to 0.18 t ha⁻¹ (Figure 5c). The mid-maturing variety JC901 performed outstandingly at truss 1, achieving 195.31 g IFW, 4.1 fruits, and 1.20 t ha⁻¹ yield, which were significantly higher than at the other trusses. Late-maturing variety PRVC

reached maximum IFW (288.44 g) and yield (1.70 t ha⁻¹) at truss 1, maintaining relatively high IFW (183.52 g) and yield (0.62 t ha⁻¹) at truss 5. FN was generally lower in large tomatoes: JC8 had only 4.4 fruits at truss 1 versus PRVC's 3.93 fruits. Statistical analysis showed extremely significant effects of maturity ($p < 0.001$) and truss position ($p < 0.001$) on IFW and yield, with extremely significant interactions for both traits ($p < 0.001$).

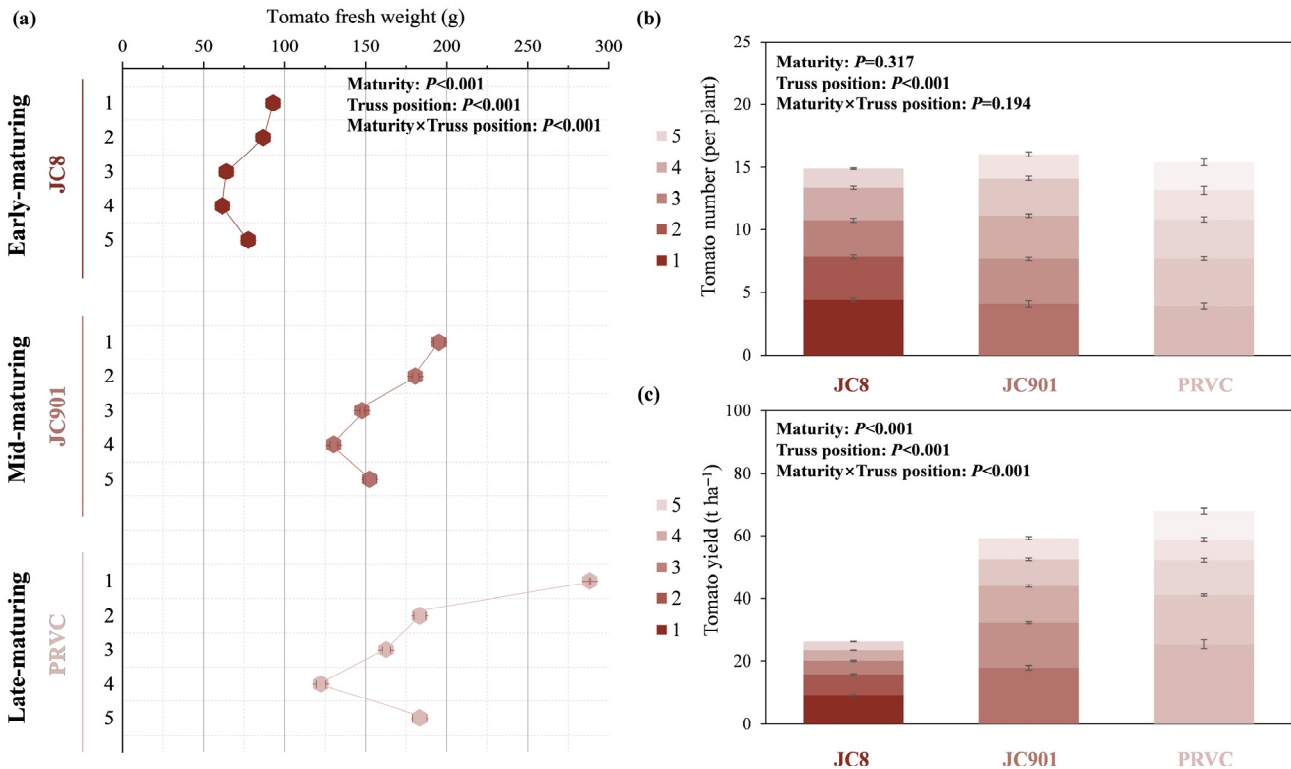


Figure 5. Large tomato yield parameters. (a) Fresh tomato weight of individual fruit per cluster; (b) tomato number per cluster; (c) tomato yield per cluster.

3.3. Cherry and Large Tomato Fruit Quality

The results indicated that maturity stages and truss positions significantly affected fruit quality traits (Brix, acid, and Brix/acid ratio) in both cherry tomatoes and large-fruited tomatoes (Figures 6 and 7). For cherry tomatoes (Figure 6), soluble solid content (Brix) showed a significant increasing trend with delayed maturity ($p < 0.001$). Early-maturing varieties QX66 and JM1 reached maximum Brix at truss 5 (6.42%) and truss 3 (6.30%), respectively, while late-maturing BF achieved 6.38% at truss 1. Truss position effects on Brix varied among varieties: mid-maturing GSHZ peaked at truss 1 (6.40%), and GSMZ reached 7.43% at truss 1 (Figure 6a). Titratable acid content (acid) showed an opposite trend: early-maturing JM1 had the highest acid at truss 1 (0.233%), and late-maturing BF reached 0.303% at truss 1 (Figure 6b). The Brix/acid ratio was highest in early-maturing QX66 at truss 2 (32.78) and late-maturing HXG at truss 1 (28.58) (Figure 6c). ANOVA revealed significant effects of maturity ($p < 0.001$) and truss position ($p < 0.05$) on Brix, with no significant interaction ($p = 0.109$). Acid content was extremely significantly influenced by maturity and truss position ($p < 0.001$), with a significant interaction ($p < 0.001$).

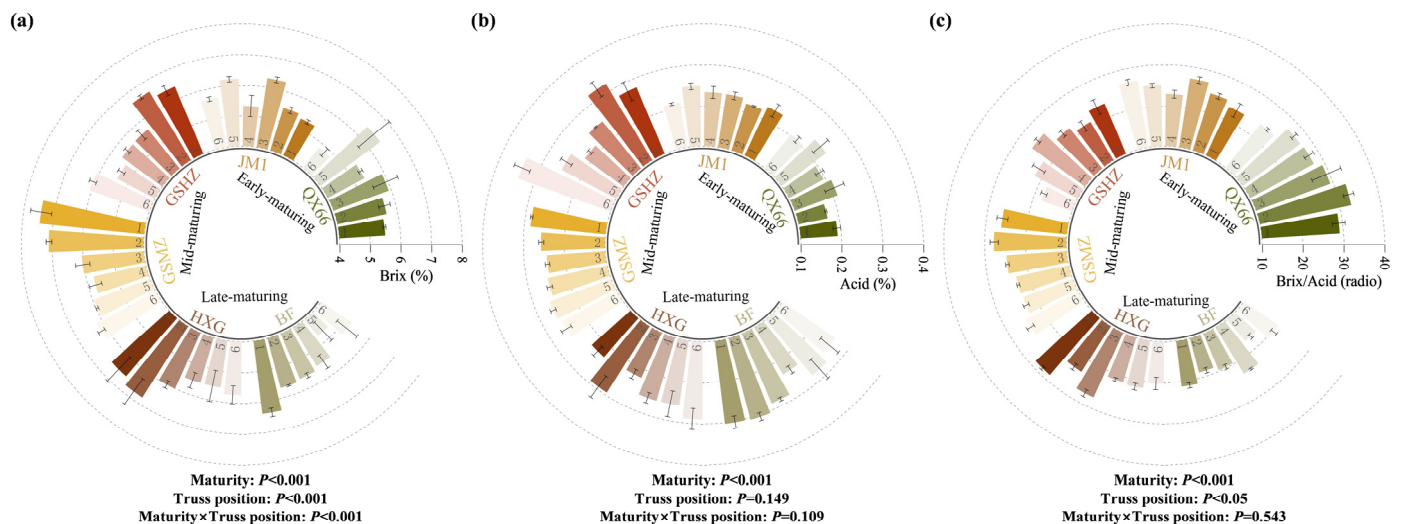


Figure 6. Cherry tomato quality. (a) Brix of individual fruit per cluster; (b) acid of individual fruit per cluster; (c) Brix/acid ratio.

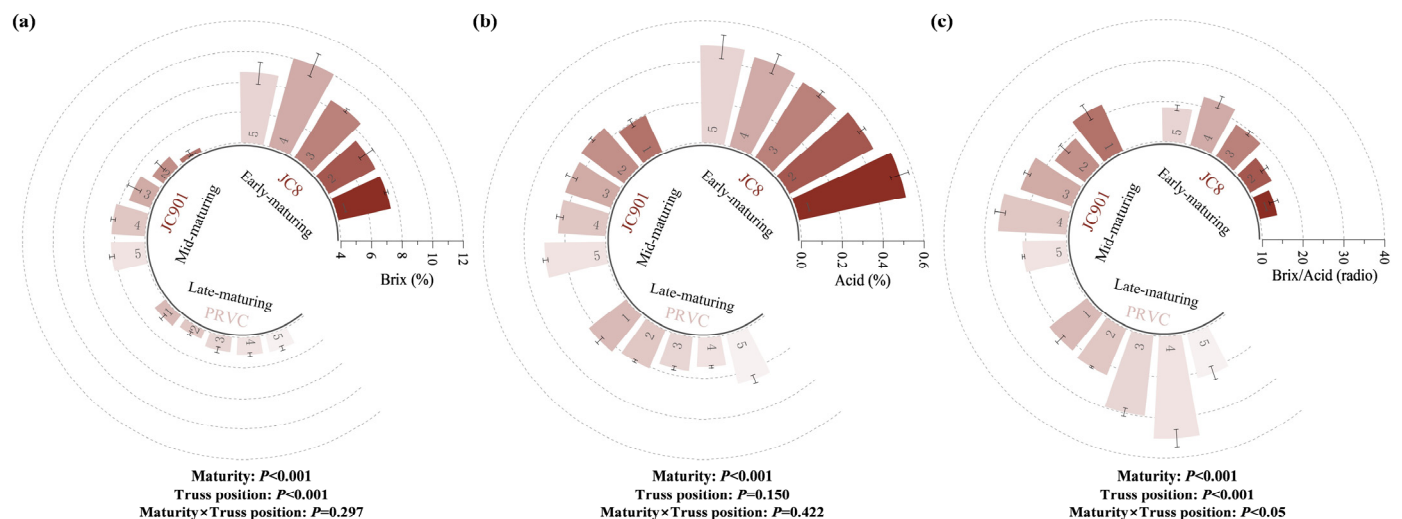


Figure 7. Large tomato quality. (a) Brix of individual fruit per cluster; (b) acid of individual fruit per cluster; (c) Brix/acid ratio.

Large-fruited tomatoes exhibited distinct quality patterns compared to cherry types (Figure 7). Early-maturing JC8 showed a significant Brix increase from truss 1 (7.50%) to truss 4 (10.02%), while mid-maturing JC901 peaked at truss 4 (6.18%) (Figure 7a). Late-maturing PRVC achieved the highest Brix at truss 4 (5.15%) but the highest Brix/acid ratio at truss 3 (29.76). Titratable acid content was highest in early-maturing JC8 at truss 1 (0.535%) and lowest in late-maturing PRVC at truss 3 (0.169%) (Figure 7b). The Brix/acid ratio was maximized in late-maturing PRVC at truss 4 (35.19), significantly higher than other trusses (Figure 7c). Statistical analysis indicated extremely significant effects of maturity ($p < 0.001$) and truss position ($p < 0.001$) on Brix and acid, with significant interactions for Brix ($p < 0.05$) and Brix/acid ratio ($p < 0.001$). The Brix of late-maturing PRVC increased by 5.8% from truss 1 to 4, whereas early-maturing JC8 showed a 33.6% increase over the same period.

3.4. Impact of Soft-Shell Solar Greenhouse Environment on Tomato Production

This study systematically revealed the influence mechanism of light, temperature, humidity and variety characteristics on tomato yield in soft-shell solar greenhouses through

correlation analysis and PLS-PM path analysis (Figure 8). The results of the correlation analysis clearly demonstrate the correlations between environmental factors (temperature, humidity, light intensity) and fruit yield (fresh weight, fruit number, yield), as well as quality indicators (Brix, acid, Brix/acid ratio) in cherry tomatoes and large tomatoes (Figure 8a). For cherry tomatoes, light intensity has a significant positive correlation with the Brix (reflected by the deep red color and significance symbols in the matrix), indicating that sufficient light effectively promotes sugar accumulation. The negative correlation between humidity and yield suggests that increased humidity may inhibit the yield of cherry tomatoes. In the production of large tomatoes, light intensity shows an obvious positive correlation with fruit number, indicating that ample light is conducive to the increase in fruit quantity. The negative correlation between humidity and fresh weight indicates that humidity will have a negative impact on the individual fruit fresh weight of large tomatoes.

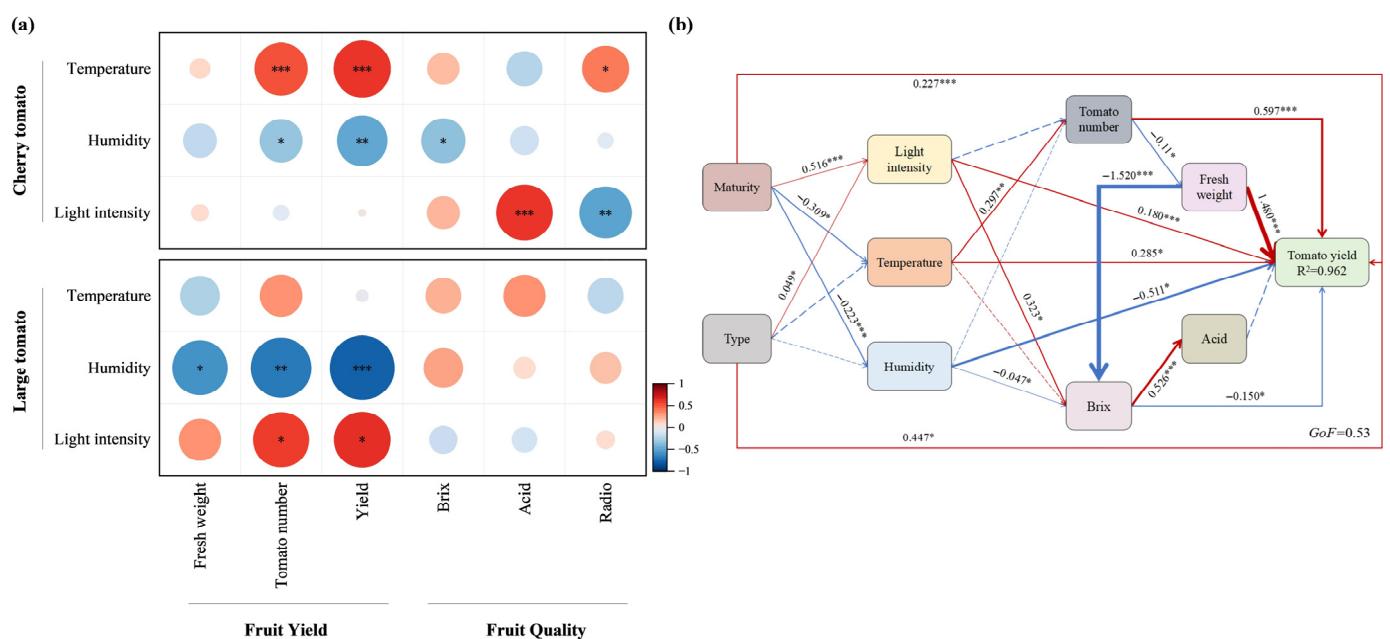


Figure 8. (a) Correlation analysis between environmental factors and fruit yield and quality factors; (b) PLS-PM path analysis of the influence of light, temperature and humidity on yield of tomatoes in soft-shell solar greenhouses under different tomato types and maturities. The thickness of the lines indicates the degree of influence, the red and blue lines indicate the positive and negative influence, respectively, and the solid and dashed lines indicate the significant influence, respectively, ($p < 0.05$) and no significant effect ($p > 0.05$). *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

Based on the correlation analysis results, further PLS-PM path analysis was conducted to explore the deep action mechanisms of various factors on tomato yield (Figure 8b). From the perspective of variety characteristics, maturity has a significant negative impact on humidity (coefficient -0.223), which means that the statistical value of greenhouse humidity is lower during the production stage of late-maturing varieties. The positive effect of variety type on maturity (0.049) reflects the differences in maturity performance between cherry tomatoes and large tomatoes. In the correlation between environmental factors and intermediate variables, the significant positive influence of temperature on tomato numbers (0.297) indicates that an increase in temperature is conducive to the increase in fruit quantity, forming a synergistic effect of environmental factors with the promoting effect of light on fruit number in correlation analysis results. The positive effect of light intensity on the Brix (0.323) further verifies the conclusion that light promotes sugar accumulation in correlation analysis results. In addition, the positive effect of maturity

Table 2. Cont.

		QX66	JM1	Cherry Tomato		HXG	BF	Large Tomato		
				GSHZ	GSMZ			JC8	JC901	PRVC
Before Planting	Pesticide Soaking for Seeds	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
	Sulfur Fumigation for Shed	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011
	Organic Fertilizer	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211
	Soybean Meal	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042
	Microbial Bactericide	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042
After Planting	Mechanical Land Preparation	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032
	Potassium Fertilizer	0.253	0.253	0.253	0.253	0.253	0.253	0.211	0.211	0.211
	Root-promoting Fertilizer	0.063	0.063	0.063	0.063	0.063	0.063	0.053	0.053	0.053
	Foliar Fertilizer	0.025	0.025	0.025	0.025	0.025	0.025	0.021	0.021	0.021
	Insulation Quilt Maintenance	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032
Harvesting Others	Male Bee	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063
	Insecticide	0.101	0.101	0.101	0.101	0.101	0.101	0.084	0.084	0.084
	Fungicide	0.126	0.126	0.126	0.126	0.126	0.126	0.105	0.105	0.105
	Yellow Sticky Board	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032
	Packaging Materials	0.666	0.662	0.722	0.747	0.633	0.614	0.518	1.081	1.242
	Greenhouse Expense	0.822	0.831	0.866	0.883	0.909	0.952	0.770	0.831	0.892
	Land Rent	0.219	0.222	0.231	0.235	0.242	0.254	0.205	0.222	0.238
	Water Fee	0.092	0.093	0.098	0.100	0.103	0.109	0.086	0.093	0.102
	Electricity Fee	0.092	0.093	0.097	0.099	0.103	0.108	0.086	0.093	0.101
	Labor Cost	0.750	0.758	0.790	0.806	0.829	0.869	0.703	0.758	0.814
Total Cost of Production		41.295	41.470	41.645	42.312	43.070	43.939	35.874	42.814	45.596
Gross Tomato Value		207.742	206.668	225.333	233.059	197.375	191.704	169.116	282.807	349.625
Net Income		166.447	165.198	183.688	190.747	154.305	147.765	133.242	239.993	304.028
Daily Net Income		1.074	1.046	1.120	1.142	0.897	0.835	0.808	1.356	1.626

Note: 1 USD = 7.122 yuan.

Table 3. The sales form of tomatoes.

Fruit Type	Sales Form	Selling Price (USD kg ^{−1})	Sales Percentage (%)
Cherry Tomato	Gift Box	8.425	10
	Farm Park Picking	8.425	20
	Vegetable Box	5.617	20
	Group Purchase	4.212	30
	Retail	2.808	20
Large Tomato	Gift Box	8.425	10
	Farm Park Picking	7.021	20
	Vegetable Box	5.617	20
	Group Purchase	2.106	20
	Retail	1.685	30
JC8	Gift Box	8.425	50
	Farm Park Picking	7.021	10
	Vegetable Box	5.617	20
	Group Purchase	2.808	10
	Retail	1.685	10

Note: 1 USD = 7.122 yuan.

4. Discussion

4.1. Analysis of Environmental Regulation Efficiency and Ecological Benefits of Soft-Shell Solar Greenhouses

The environmental regulation system of soft-shell solar greenhouses demonstrates significant advantages in winter tomato production by integrating structural innovation with adaptive microclimate control, achieving remarkable improvements in thermal stability, light utilization, and humidity management [30,39]. The soft-shell wall of the greenhouse, composed of prefabricated steel frameworks and multi-layer insulation quilts, can effectively trap heat, increasing the average daily temperature by 10–15 °C compared to outdoor conditions and reducing the duration of low-temperature stress (≤ 15 °C) by 25%. Nighttime insulation measures, such as deploying automated quilts at sunset, maintain a critical diurnal temperature difference (15.2–22.6 °C during the maturity stage), which promotes photosynthetic accumulation and fruit development, consistent with research findings that optimal nighttime temperatures reduce the rate of malformed fruits [40,41]. The dynamic regulation of light, temperature, and humidity creates stable growth conditions across all stages. The south-facing orientation and high-transmittance films ensure suitable light intensity, enhancing photosynthesis and Brix accumulation, especially for late-maturing varieties. Temperature regulation through thermal screens and soil heat storage maintains the warmth of the root zone. Daytime temperatures during key stages support vigorous canopy development, while nighttime temperatures above 8 °C prevent cold damage [29]. Humidity control through forced ventilation and micro-sprinkling reduces fluctuations by 23%, mitigating fungal diseases and improving fruit quality parameters such as the sugar–acid ratio [36]. During key growth stages (vegetative and maturity stages), these adjustments result in an 80% compliance rate for tomato growth. From an ecological perspective, the greenhouse reduces carbon emissions by minimizing auxiliary heating. This achievement validates the feasibility of structural innovation in agricultural facilities and provides a technical paradigm for the sustainable development of protected agriculture in cold regions. However, long-term operational challenges remain, including the need to verify the thermal stability of wall materials and address the energy consumption costs of intelligent control systems. Future optimization of the energy structure can be achieved through new energy integration technologies [42–45]. Additionally, the air circulation efficiency inside the greenhouse is constrained by the structural design, causing the CO₂ concentration to drop below the compensation point during sunny midday periods, thus affecting photosynthetic efficiency. This issue can be resolved through CO₂ gas fertilization or improved ventilation system designs [46,47].

4.2. Yield and Quality Performance of Tomato Varieties Under Environmental Regulation

The yield and quality performance of cherry and large tomatoes in soft-shell greenhouses reflect distinct responses to microclimate regulation, underscoring the need for cultivar-specific management. Early-maturing cherry tomatoes (QX66, JM1) showed peak yields at middle trusses (2nd–4th), driven by compact growth and efficient photosynthate distribution, while late-maturing large tomatoes (PRVC) achieved higher single-fruit weights at basal trusses, relying on robust sink capacity despite lower fruit numbers. Light intensity positively correlated with Brix, with late-maturing varieties benefiting from increased light during maturity, whereas humidity negatively impacted yield and fruit weight, likely due to reduced stomatal activity and heightened disease risk [48,49]. Early-maturing cherries maintained superior sugar–acid ratios under low light, indicating metabolic adaptations for flavor stability, while late-maturing large tomatoes exhibited stronger heat stress resistance with 60% lower malformation rates. These findings highlight the importance of stage-specific interventions, supporting mid-truss development in early

cherries and enhancing light transmission for late-maturing large tomatoes. Gaps remain in understanding root-zone temperature effects on sugar transport and genotype-specific irrigation impacts, urging future research to integrate physiological modeling for precision management. Overall, tailoring environmental controls to cultivar traits balances productivity and quality, advancing cold-region greenhouse cultivation.

4.3. Innovation and Practical Challenges of Production–Market Synergy Models

The innovation of the production–market synergy model lies in breaking through traditional production-oriented business models. Through differentiated varietal layouts and scenario-based sales strategies, it maximizes product value. Studies show that adopting the “early-maturing variety + gift box” model can achieve product premiums 2–3 times higher than conventional markets, while the “late-maturing variety + picking experience” model extends the industrial chain, with much higher daily income over the production cycle of greenhouse tomatoes than for the traditional model [50]. The core of this model is the deep integration of agricultural production with consumption scenarios, creating a direct field-to-table channel to effectively avoid profit losses from intermediate links. However, this model faces multiple challenges during promotion. Multi-varietal cultivation imposes higher requirements on greenhouse environmental regulation, and differences in nutrient demands among varieties may reduce fertilization precision [51,52]. Gift box sales rely on cold chain logistics support, but rural cold chain coverage in North China is seriously insufficient, resulting in a high transportation loss rate [53]. Differences in consumer perceptions of tomato quality leads to fluctuating market acceptance, necessitating the establishment of unified grading standards and quality traceability systems [54]. Notably, existing sales models do not fully account for dynamic changes in consumer preferences—we have conducted a market survey, and younger groups have significantly different flavor requirements compared to traditional markets, requiring continuous market research and product innovation.

4.4. Limitations and Exploration of Sustainable Development Pathways

Despite significant progress, this study has multiple limitations. At the production level, experiments only covered a single planting cycle, leaving soil degradation risks under long-term continuous cropping unclear. Additionally, maintenance costs of intelligent control systems were relatively high. At the market level, sales models were based on idealized market environment assumptions, and actual production may face risks such as price fluctuations and poor market access—during especially extreme weather or market saturation, fruit loss rates can be beyond imagination. Labor shortages are particularly prominent during harvest seasons, and the labor cost accounts for a high proportion of the total cost, restricting production efficiency improvements [55]. Future research should expand in the following directions: developing IoT-based intelligent decision systems to achieve dynamic optimization of varietal layouts and environmental regulation; exploring digital management models for the entire production–processing–marketing chain to reduce circulation losses; strengthening policy support for protected agriculture to promote cold chain logistics infrastructure development; and conducting varietal research on storability and transportability to develop specialized varieties suitable for long-distance transportation. These improvements will help enhance the comprehensive benefits of soft-shell solar greenhouse systems and promote the transformation of protected agriculture in North China toward high efficiency, low carbon, and sustainability. Furthermore, this study does not involve adaptability verification under organic cultivation models. Future research can explore synergistic applications of organic substrates and microbial agents to further improve tomato quality and soil health.

5. Conclusions

This study systematically reveals the comprehensive benefits and regulatory mechanisms of soft-shell solar greenhouses in tomato overwintering production in North China. Through dynamic environmental monitoring and multi-cultivar comparative trials, it confirms that soft-shell greenhouses significantly address the limitations of traditional solar greenhouses under extreme low temperatures through optimized light–temperature–humidity synergistic regulation. Results show that soft-shell greenhouses increased average daily temperature by 10–15 °C, reduced low-temperature stress duration by 25%, improved light saturation compliance to 82%, and minimized humidity fluctuations by 23%, providing a stable growth environment for all tomato growth stages, especially flowering–fruiting and fruit expansion phases. Cultivar response analysis indicates early-maturing cherry tomato varieties exhibit high-yield advantages at middle fruit clusters (2nd–4th clusters) with yields of 0.52–0.55 t ha^{−1}, while different tomato types and varieties achieve superior net economic returns through high yields and combinatorial sales models, highlighting cultivar–market strategy alignment. Physiologically, light intensity positively correlates with acid accumulation while humidity negatively impacts yield significantly, providing a theoretical basis for precise environmental regulation. Economic verification validates the feasibility of the “variety optimization + scenario-based sales” model where differentiated sales (gift boxes accounting for 50%) effectively mitigate market price volatility, offering replicable income enhancement pathways for smallholder farmers. PLS-PM path analysis quantifies the impacts of light intensity, temperature, and humidity on yield and quality across tomato types, providing theoretical guidance for environment-driven production optimization. Compared to previous single-factor studies, this research innovates by integrating environment–cultivar–market multidimensional data to construct a dynamically adaptive production system, filling knowledge gaps in soft-shell greenhouse microclimate–crop response mechanisms and providing practical examples for low-carbon transitions in regional protected agriculture (reducing carbon footprints of traditional greenhouse materials). Future research should explore cross-climatic adaptability and lifecycle ecological benefit assessments to deepen integration of dual carbon goals with rural revitalization.

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References

1. FAO. FAOSTAT Database 2023. Available online: <http://www.fao.org/statistics/en> (accessed on 1 March 2025).

2. World Processing Tomato Council. Tomato News 2021. Available online: http://www.tomatonews.com/en/wptc_3_411002.html (accessed on 1 March 2025).
3. Cammarano, D.; Jamshidi, S.; Hoogenboom, G.; Alex, C.R.; Niyogi, D.; Ronga, D. Processing tomato production is expected to decrease by 2050 due to the projected increase in temperature. *Nat. Food* **2022**, *3*, 437–444. [CrossRef] [PubMed]
4. Yu, J.Q.; Zhou, J. Progress in protected vegetable production and research during China’s 12th. *China Veg.* **2016**, *9*, 18–30. [CrossRef]
5. Li, J.G.; Liu, H.B.; Wang, H.Y.; Luo, J.F.; Zhang, X.J.; Liu, Z.H. Managing irrigation and fertilization for the sustainable cultivation of greenhouse vegetables. *Agric. Water Manag.* **2018**, *210*, 354–363. [CrossRef]
6. Li, Y.; Xue, X.; Xu, F.; Guo, W.; Duan, M.; Lin, S. Negative-pressure irrigation improves water and fertilizer use efficiencies and fruit yield of greenhouse tomato on the North China Plain. *Irrig. Drain.* **2021**, *70*, 1027–1038. [CrossRef]
7. Liu, H.; Shao, M.; Yang, L. Photosynthesis Characteristics of Tomato Plants and Its’ Responses to Microclimate in New Solar Greenhouse in North China. *Horticulturae* **2023**, *9*, 197. [CrossRef]
8. Niu, Y.; Wang, X.J.; Chen, X.; Yan, Y.; Wang, J.S. Current situation, problems and countermeasures of tomato industry development in China and achievements of tomato industry development in Ningxia. *Heilongjiang Agric. Sci.* **2022**, *12*, 70–74.
9. Wang, L.; Yu, X.; Guo, B.; Li, Q.; Lai, K.; Wang, X. Fruit rot on tomatoes caused by *Talaromyces stipitatus* newly reported in China. *Crop Prot.* **2024**, *181*, 106698. [CrossRef]
10. Li, M.; Chen, S.; Liu, F. A risk management system for meteorological disasters of solar greenhouse vegetables. *Precis. Agric.* **2017**, *18*, 997–1010. [CrossRef]
11. IPCC. Climate Change 2023 Synthesis Report. 2023. Available online: <https://www.ipcc.ch/report/sixth-assessment-report-cycle/> (accessed on 5 March 2025).
12. Ballesta, M.; Egea, I.; Estrada, Y.; Morales, M.B.; Egea-Fernández, J.M.; Bolarín, M.C. Interest of traditional tomato cultivars adapted to the Mediterranean environmental constraints for their improvement of fruit quality under high temperatures and water scarcity conditions. *Acta Hort.* **2023**, *1372*, 43–50. [CrossRef]
13. U.S. Department of Agriculture (USDA). U.S. Agricultural Trade Data. 2023. Available online: <https://www.ers.usda.gov/topics/international-markets-u-s-trade/u-s-agricultural-trade/data/> (accessed on 6 March 2025).
14. Fu, D.; Ding, Y. The study of changing characteristics of the winter temperature and extreme cold events in China over the past six decades. *Int. J. Climatol.* **2021**, *41*, 2480–2494. [CrossRef]
15. Zhang, P.; Zhang, Z.; Xiao, M.; Chao, J.; Dai, Y.; Liu, G. Effects of organic mulching on moisture and temperature of soil in greenhouse production of tomato under unheated greenhouse cultivation in the cold zone of China. *Food Sci. Nutr.* **2023**, *11*, 4829–4842. [CrossRef] [PubMed]
16. Chu, X.L.; Zheng, L.X.; Ye, G.S. Comparison of greenhouse gas emissions between open field and facility tomato production in China. *J. Agro-Environ. Sci.* **2023**, *42*, 1870–1881.
17. Doddrell, N.H.; Lawson, T.; Raines, C.A.; Wagstaff, C.; Simkin, A.J. Feeding the world: Impacts of elevated [CO₂] on nutrient content of greenhouse grown fruit crops and options for future yield gains. *Hortic. Res.* **2023**, *10*, uhad026. [CrossRef]
18. NBS. *China Statistical Yearbook*; China Statistical Press: Beijing, China, 2023. Available online: <https://www.stats.gov.cn/sj/ndsj/2023/indexch.htm> (accessed on 10 March 2025).
19. Jiang, Z.; Jing, G.; He, M. Development Status, Problems and Countermeasures of Facility Agriculture in Beijing. In Proceedings of the 2016 International Conference on Material, Energy and Environment Engineering (ICM3E 2016), Beijing, China, 1–5 October 2016; pp. 551–556.
20. Wang, Y.; Wang, H.R. Sustainable use of water resources in agriculture in Beijing: Problems and countermeasures. *Water Policy* **2005**, *7*, 345–357. [CrossRef]
21. Wu, Y.; Wang, Y.; Wang, K.; Tian, J.; Chen, Y.; Zou, G. Pollution Characteristics and Potential Sources of Microplastics in Facility Agricultural Soil in Beijing. *Asian J. Ecotoxicol.* **2022**, *17*, 333–344. [CrossRef]
22. Xie, Y.L.; Qi, C.J. Supply and Demand Adaptation of “Vegetable Basket” Products: Mechanism, Effect and Governance Path. *Econ. Probl. Agric.* **2021**, *42*, 55–68.
23. Beijing Municipal People’s Government. Beijing 14th Five-Year Rural Revitalization Plan. 2021. Available online: https://www.gov.cn/xinwen/2021-08/12/content_5630961.htm (accessed on 10 March 2025).
24. Li, Y.D.; Miao, T.; Zhu, C.; Ji, J.W. The design and implementation of intelligent monitoring system of the northern greenhouse. *J. Agric. Sci. Technol.* **2016**, *18*, 94–101. [CrossRef]
25. Tian, D.; Li, Y.; Zhao, S.; Wu, Q.; Ma, C.; Song, W. An Analysis of the Influence of Construct Parameters on the Solar Radiation Input in an Insulated Plastic Greenhouse. *Agronomy* **2024**, *14*, 510. [CrossRef]
26. Hou, Y.; Li, A.; Li, Y.; Jin, D.C.; Tian, Y.; Zhang, D.; Wu, D.M.; Zhang, L.H.; Lei, W.J. Analysis of microclimate characteristics in solar greenhouses under natural ventilation. *Build. Simul.* **2021**, *14*, 1811–1821. [CrossRef]
27. Luo, G.L.; Cheng, R.F.; Zhang, Y.; Fang, H.; Li, D.; Zhang, J.F.; Song, G.X. Sunlight greenhouse active heat storage system optimization. *Trans. Chin. Soc. Agric. Eng.* **2020**, *36*, 8. [CrossRef]

28. Li, H.; Lu, J.R.; He, X.Y.; Zong, C.J.; Song, W.T.; Zhao, S.M. Effect of installation factors on the environment uniformity of multifunctional fan-coil unit system in Chinese solar greenhouse. *Case Stud. Therm. Eng.* **2024**, *60*, 104818. [\[CrossRef\]](#)
29. He, M.; Wan, X.C.; Liu, H.L.; Xia, T.Y.; Gong, Z.R.; Li, Y.M.; Liu, X.G.; Li, T.L. Theory and application of sustainable energy-efficient solar greenhouse in China. *Energy Convers. Manag.* **2025**, *352*, 119394. [\[CrossRef\]](#)
30. Wang, Y.F.; Lei, X.H.; Li, W.; Niu, M.L.; Wang, B.H.; Wang, F.D. Application Status and Development Suggestions for Greenhouse with Flexible Thermal Insulation Wall in Beijing. *China Veg.* **2023**, *1*, 11–16. [\[CrossRef\]](#)
31. Li, L.B.; Wang, Z.R.; Zhang, D.; Zhou, Z.C.; Li, X.G.; Qu, W.M. Research on winter temperature field distribution of a new flexible wall solar greenhouse. *Agric. Sci. Eng. China* **2023**, *35*, 36–41. [\[CrossRef\]](#)
32. Abdelghany, A.E.; Dou, Z.Y.; Alashram, M.G.; Eltohamy, K.M.; Elrys, A.S.; Liu, X.Q.; Wu, Y.; Cheng, M.H.; Fan, J.L.; Zhang, F.C. The joint application of biochar and nitrogen enhances fruit yield, quality and water-nitrogen productivity of water-stressed greenhouse tomato under drip fertigation. *Agric. Water Manag.* **2023**, *290*, 108605. [\[CrossRef\]](#)
33. Ruizendaal, J.; Polder, G.; Kootstra, G. Automated and non-destructive estimation of soluble solid content of tomatoes on the plant under variable light conditions. *Biosyst. Eng.* **2024**, *242*, 80–90. [\[CrossRef\]](#)
34. Rivelli, A.R.; Castronuovo, D.; Gatta, B.L.; Liberatore, M.T.; Libutti, A. Qualitative Characteristics and Functional Properties of Cherry Tomato under Soilless Culture Depending on Rootstock Variety, Harvesting Time and Bunch Portion. *Foods* **2024**, *13*, 1450. [\[CrossRef\]](#)
35. Liu, H.; Tian, Y.; Zhao, H.; Liu, S.; Zhu, N.; Wang, Y.; Li, W.; Sun, D.; Wang, T.; Li, L. Decoding the Secrets of Agricultural Light, Heat, and Water Resources in Beijing Under Climate Change: Spatio-Temporal Variations on a Small Scale and Future Prospects. *Agriculture* **2025**, *15*, 371. [\[CrossRef\]](#)
36. Dai, Y.T.; Hu, B.; Feng, B.J.; Li, M.B.; Jia, D.Z.; Yang, M.Y.; Wang, T.C. High yield cultivation technology of high-quality tomato in the long winter season in solar greenhouse. *China Veg.* **2025**, *2*, 172–175. [\[CrossRef\]](#)
37. Lee, S.K.; Chiang, M.S.; Hseu, Z.Y.; Kuo, C.H.; Liu, C.T. A photosynthetic bacterial inoculant exerts beneficial effects on the yield and quality of tomato and affects bacterial community structure in an organic field. *Front. Microbiol.* **2022**, *13*, 959080. [\[CrossRef\]](#)
38. Dong, S.C.; Zhang, J.W.; Ling, J.Y.; Xie, Z.X.; Song, L.X.; Wang, Y.L.; Zhao, L.P.; Zhao, T.M. Comparative analysis of physical traits, mineral compositions, antioxidant contents, and metabolite profiles in five cherry tomato cultivars. *Food Res. Int.* **2024**, *194*, 114897. [\[CrossRef\]](#) [\[PubMed\]](#)
39. Zhang, Z.Y.; Zhu, Y.B.; Guo, Y.B.; Li, P.; Cheng, J.Y.; Zhao, S.M.; Sun, G.Z.; Wei, M. Distribution characteristics and improvement measures of light environment of flexible thermal insulation solar greenhouse. *J. China Agric. Univ.* **2025**, *30*, 197–205.
40. Matsuda, R.; Ozawa, N.; Fujiwara, K. Leaf photosynthesis, plant growth, and carbohydrate accumulation of tomato under different photoperiods and diurnal temperature differences. *Sci. Hortic.* **2014**, *170*, 150–158. [\[CrossRef\]](#)
41. Ruiz-Nieves, J.M.; Ayala-Garay, O.J.; Serra, V.; Dumont, D.; Vercambre, G.; Génard, M.; Gautier, H. The effects of diurnal temperature rise on tomato fruit quality. Can the management of the greenhouse climate mitigate such effects? *Sci. Hortic.* **2021**, *278*, 109836. [\[CrossRef\]](#)
42. Cao, K.; Xu, H.J.; Zhang, R.; Xu, D.W.; Yan, L.L.; Sun, Y.C.; Xia, L.R.; Zhao, J.T.; Zou, Z.R.; Bao, E.C. Renewable and sustainable strategies for improving the thermal environment of Chinese solar greenhouses. *Energy Build.* **2019**, *202*, 109414. [\[CrossRef\]](#)
43. Argento, S.; Garcia, G.; Treccarichi, S. Sustainable and Low-Input Techniques in Mediterranean Greenhouse Vegetable Production. *Horticulturae* **2024**, *10*, 997. [\[CrossRef\]](#)
44. Liu, R.; Shi, Y.; Bournet, P.-E.; Liu, K. Development of a Machine Learning Natural Ventilation Rate Model by Studying the Wind Field Inside and Around Multiple-Row Chinese Solar Greenhouses. *Horticulturae* **2024**, *10*, 1226. [\[CrossRef\]](#)
45. Chen, F.C.; Zhang, Z.S.; Omer, A.A.A.; Zhang, F.X.; Fan, L.L.; Ma, H.Y.; Lu, H.; Li, M.; Zhang, X.Y.; Liu, W. Photon management heightens the energy use efficiency of greenhouses through the integration of photovoltaic systems and supplemental lighting. *Renew. Energy* **2025**, *247*, 123009. [\[CrossRef\]](#)
46. Guo, J.J.; Zhang, B.B.; Lin, L.J.; Xu, Y.D.; Zhou, P.; Luo, S.W.; Zhuo, Y.H.; Ji, J.Y.; Luo, Z.J.; Hassan, S.G. Multi-model fusion method for predicting CO₂ concentration in greenhouse tomatoes. *Comput. Electron. Agric.* **2024**, *227*, 2. [\[CrossRef\]](#)
47. Zhu, Z.; Miller, S.A. Greenhouse gas emissions of tomato production and supply: A systematic review. *Resources. Conserv. Recycl.* **2025**, *218*, 108236. [\[CrossRef\]](#)
48. Shamshiri, R.R.; Jones, J.W.; Thorp, K.R.; Ahmad, D.; Man, H.C.; Taheri, S. Review of optimum temperature, humidity, and vapour pressure deficit for microclimate evaluation and control in greenhouse cultivation of tomato: A review. *Int. Agrophys.* **2018**, *32*, 287–302. [\[CrossRef\]](#)
49. Mao, Q.J.; Peng, Y.; Ji, C.C.; Li, H.W.; Li, T. Effect of external shading on the temperature distribution performance of glass greenhouse in Wuhan region. *Case Stud. Therm. Eng.* **2024**, *61*, 104879. [\[CrossRef\]](#)
50. Lin, Y.; Jen, L. The impact of consumer heterogeneity in the product life cycle on the diffusion patterns of user reviews and sales. *J. Retail. Consum. Serv.* **2024**, *76*, 103558. [\[CrossRef\]](#)

51. Li, J.; Liu, F.H.; Wu, Y.; Tang, Z.Q.; Zhang, D.; Lyu, J.; Khan, K.S.; Xiao, X.M.; Yu, J.H. Evaluation of nutritional composition, biochemical, and quality attributes of different varieties of tomato (*Solanum lycopersicum* L.). *J. Food Compos. Anal.* **2024**, *132*, 106384. [\[CrossRef\]](#)
52. Saavedra, F.M.; Villanueva, G.; Gramazio, P.; Vilanova, S.; Mauceri, A.; Abenavoli, M.R.; Sunseri, F.; Prohens, J.; Plazas, M. Nitrogen use efficiency, growth and physiological parameters in different tomato genotypes under high and low N fertilisation conditions. *Plant Physiol. Biochem.* **2024**, *208*, 108447. [\[CrossRef\]](#)
53. Xia, J.; Huang, W.T.; Wang, X.; Zhu, Z.Q.; Zhang, M.J.; Zhang, X.S. Flexible sensing technology for fruit quality control in the cold chain: Characterization, application, and improvement. *Food Control* **2023**, *154*, 109976. [\[CrossRef\]](#)
54. Slapø, H.; Bugge, A.B.; Sandaker, I.; Lekhal, S. Can in-store interventions reduce the socioeconomic gap in fruit and vegetable purchases in grocery stores? A descriptive study of volume sales from 2012 to 2020 in Norway's largest grocery store chain. *Appetite* **2022**, *176*, 106100. [\[CrossRef\]](#)
55. Peña, A.; Rovira-Val, M.R.; Mendoza, J.M.F. Life cycle cost analysis of tomato production in innovative urban agriculture systems. *J. Clean. Prod.* **2022**, *367*, 133037. [\[CrossRef\]](#)

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