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EFFECTS OF CULTIVATION CONDITIONS ON THE QUALITY OF LIAONING SWEET CHERRIES

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Abstract

This study investigated the effects of different cultivation conditions on the quality of Liaoning sweet cherries in China. using the main cultivated variety, 'Hongdeng', as the experimental material, we analyzed how factors such as month, region, greenhouse age, greenhouse film parameters, and different cultivation facilities influence fruit quality. May harvests showed higher sugar (10.48%) and firmness (3.15 kg/cm^2), but lower vitamin C (5.46 mg/100g) and protein (947 µg/g) compared to April. Jinzhou and Zhuanghe regions exhibited optimal total sugar content and nutritional indicators due to fertile soil and suitable temperature differences. The light blue 0.1mm greenhouse film treatment increased sugar content (15.53%) by 36.4% compared to white film, while white film yielded the highest Vitamin C content (7.11 mg/100g). The north-south orientation resulted in yielded 12.3% higher Vitamin C and protein content than east-west orientation, but 18.7% lower sugar content. This study provides optimized cultivation recommendations for Liaoning cherries: white-film solar greenhouses are recommended for early-ripening areas, while light blue-film plastic greenhouses are suitable for late-ripening areas. Harvest timing should be selected based on market demand—April for high-nutrient fruit or May for superior taste. This research offers **s**cientific basis for optimizing sweet cherry cultivation conditions and enhancing quality, and has important implications for guiding local agricultural production and promoting industrial development.

Key words: Sweet cherry; Cultivation conditions; Greenhouse film; Fruit quality; Liaoning Province

Introduction

Sweet cherries (*Prunus avium* L.), a fruit of high economic value, are highly favored by consumers for their distinctive flavor and rich nutritional content. In recent years, driven by increasing market demand, both the planting area and yield of sweet cherries have expanded annually. Particularly in Liaoning Province, sweet cherries have become one of the key economic crops (Zhang *et al*.,2022). However, cherry quality depends on climate, soil, and cultivation practices. Therefore, investigating the effects of different cultivation conditions on cherry quality is crucial for enhancing market competitiveness and economic benefits.

Currently, scholars worldwide have extensively studied factors affecting cherry quality. Research indicates that cherry quality is not only related to varietal characteristics but is also significantly influenced by cultivation environments and management practices (Sønsteby & Heide, 2019). For instance, environmental factors such as light, temperature, moisture, and soil fertility all impact quality indicators like sugar content, acidity, and vitamin C levels. Additionally, cultivation methods (e.g., greenhouse vs. open-field cultivation), tunnel film color, tunnel age, and planting orientation also significantly affect cherry quality. However, research on quality variations of sweet cherries under different cultivation conditions in Liaoning Province, particularly regarding the combined effects of multiple factors, remains limited. This study systematically investigated the effects of various cultivation conditions—including month, region, tunnel age, orientation, tunnel film color and thickness, planting method, and degree of organization—on cherry quality in the Liaoning production area. Through the measurement and analysis of multiple quality indicators—including vitamin C content, soluble sugars, reducing sugars, titratable acidity, protein content, pectin content, solids content, and firmness—this study aims to reveal the specific mechanisms by which different cultivation conditions affect cherry quality. By addressing a gap in regional research, this work offers new insights for the Liaoning production area and a scientific basis for improving cultivation practices and cherry quality.

Materials and Methods

Experimental materials and site overview: This study utilized the "Meizao" sweet cherry variety, the primary cultivar in Liaoning Province. Developed as an early-ripening variety in Washington State, USA, "Meizao" was introduced to Liaoning, China, and through localized adaptation became one of the dominant cultivars on the Liaodong Peninsula (Table 1). It exhibits vigorous growth with an open canopy, reaching 3-4 meters in height at maturity. The variety demonstrates strong adaptability and good cold tolerance, making it well-suited to Liaoning's climate. Individual fruit weight ranges from 10 - 15 grams,

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with a maximum of 18 grams. The fruit shape is broad heart-shaped, featuring deep red to purplish-red skin with high gloss. The flesh is firm and crisp, containing 16%-20% soluble solids, offering a balanced sweet-tart flavor and good storage and transport tolerance.

Table 1. Experimental variety.

Experimental variety	Maturity period	Cold tolerance	Disease resistance
Meizao	Early-maturing variety	Moderate cold tolerance	High

Location: Five representative production areas in Dalian City, Liaoning Province (Jinzhou, Zhuanghe, Lushun, Wafangdian, Pulandian), covering diverse climatic and soil conditions (Tables 2-3).

Climate characteristics: Warm temperate semi-humid monsoon climate, with an average annual temperature of 9~11°C, annual precipitation of 600~800 mm, and a frost-free period of 180~210 days.

Soil characteristics: Primarily brown earth and chernozem soils, pH 6.5~7.5, organic matter content 1.8%~3.2%, with good drainage.

Experimental design: This experiment employed a multi-factor randomized block design. Factors and levels: Month: April, May; Region: 5 production areas (Jinzhou, Zhuanghe, Lushun, Wafangdian, Pulan); Greenhouse age: <5 years, 5~10 years, >10 years; Greenhouse film parameters: Color: White, Blue, Light Blue; Thickness: 0.08 mm, 0.09 mm, 0.1 mm; Cultivation Facility: Solar Greenhouse, Plastic Tunnel; Orientation: North-South, East-West; Organization Level: Individual Farmers, Cooperatives. Zone Grouping: Zones grouped by production area and soil fertility gradient (each area constitutes one zone), with homogeneous environmental conditions (e.g., pH, organic matter) within zones. All treatment combinations randomly assigned within each zone, totaling 324 combinations. Each treatment replicated three times; 10 fruits sampled per replicate, with measured indicators averaged.

Base fertilizer (fall): 45~75 t/ hectare. of well-rotted farmyard manure + 450~750 kg/ hectare. of balanced compound fertilizer (N-P_2O_5-K_2O = 1:1:1). Topdressing: Bud break stage: 150~225kg/ hectare urea (promotes new shoots); post-flowering to hard-kernel stage: 225~300 kg/ hectare balanced compound fertilizer; Fruit enlargement stage: 150~225 kg hectare potassium sulfate (to enhance sugar content). Foliar fertilizer: Spray 0.2% borax during flowering; spray 0.3% calcium chloride before harvest (to prevent fruit cracking).

Method for determining vitamin-C. content: Vitamin C content was determined using the bipyridine colorimetric method. Approximately 1.0 g of fresh ripe fruit was weighed into a mortar, mixed with 5% trichloroacetic acid, ground, centrifuged, and the supernatant adjusted to 10 ml. A 0.3 ml aliquot of the supernatant was mixed with 0.6 ml of 150 mmol NaH_2PO_4 for at least 30 seconds. Sequentially add 0.6 mL of 10% trichloroacetic acid, 0.6 mL of 44% H_3PO_4, 0.6 mL of 4% dipyridine, and 0.3 mL of 3% ferric chloride. Mix thoroughly and maintain at 37°C in a water bath for 1 hour before performing colorimetric measurement (Wojcik *et al*.,2006).

Determination of soluble sugars: Employ the anthrone colorimetric method. Weigh approximately 1.0 g of fresh, mature fruit that has been chopped and thoroughly mixed. Transfer to a 50-mL conical flask,add 10 mL of 80% ethanol, and heat in an 80°C water bath for 40 min with constant stirring. Cool, centrifuge, add 5 mL of 80%ethanol to the residue, repeating the extraction twice in an 80°C water bath. Combine the supernatants, heat in an 80°C water bath for 30 min, filter, and adjust the volume to 25 mL. Pipette 0.2 mL of the sample extract, add 0.8 mL distilled water, mix, then add 5 mL anthrone reagent. Mix thoroughly, boil in a water bath for 10 min, cool, then proceed with colorimetric determination (Radunić *et al*., 2017).

Determination of reducing sugars: Puree the sample using a juicer. Accurately weigh two 20 g portions of the sample into beakers. Add water, transfer, and dilute to 200 mL in a volumetric flask. Filter after timing 30 minutes for reducing sugar determination. Transfer 10 mL of the filtrate to a 100 mL volumetric flask. After water bath treatment, samples should be cooled immediately. Add 4 drops of 0.5% phenolphthalein to each sample, adjust to weakly alkaline with sodium hydroxide, dilute to 100 mL with water, and titrate with Fehling's reagent. The endpoint is reached when the Fehling's reagent changes from blue to pale yellow. Record the volume of reagent consumed

Table 2. Phenological periods of cherry ('Tieton').

Year	Budding month/ Day	Budding month/ Day	Flowering date	Full bloom month/ Day	Harvest date	Leaf fall month/ Day	Growth period (days)
2022	3/15	3/25	4/5	4/10	5/28	11/10	240
2023	3/10	3/20	4/1	4/8	5/25	11/5	235

Table 3. Environmental parameters of experimental sites.

Production area	Soil organic matter (%)	Day-night temperature difference (°C)	Primary facility type
Jinzhou	2.8~3.2	8~10	Solar greenhouses
Plastic greenhouses			
Zhuanghe	2.6~3.0	8~10	Plastic greenhouse
Lushun	2.0~2.5	12~15	Solar greenhouse
Wafangdian	1.8~2.2	10~12	Plastic greenhouse
Pulan	2.2~2.6	9~11	Solar greenhouse

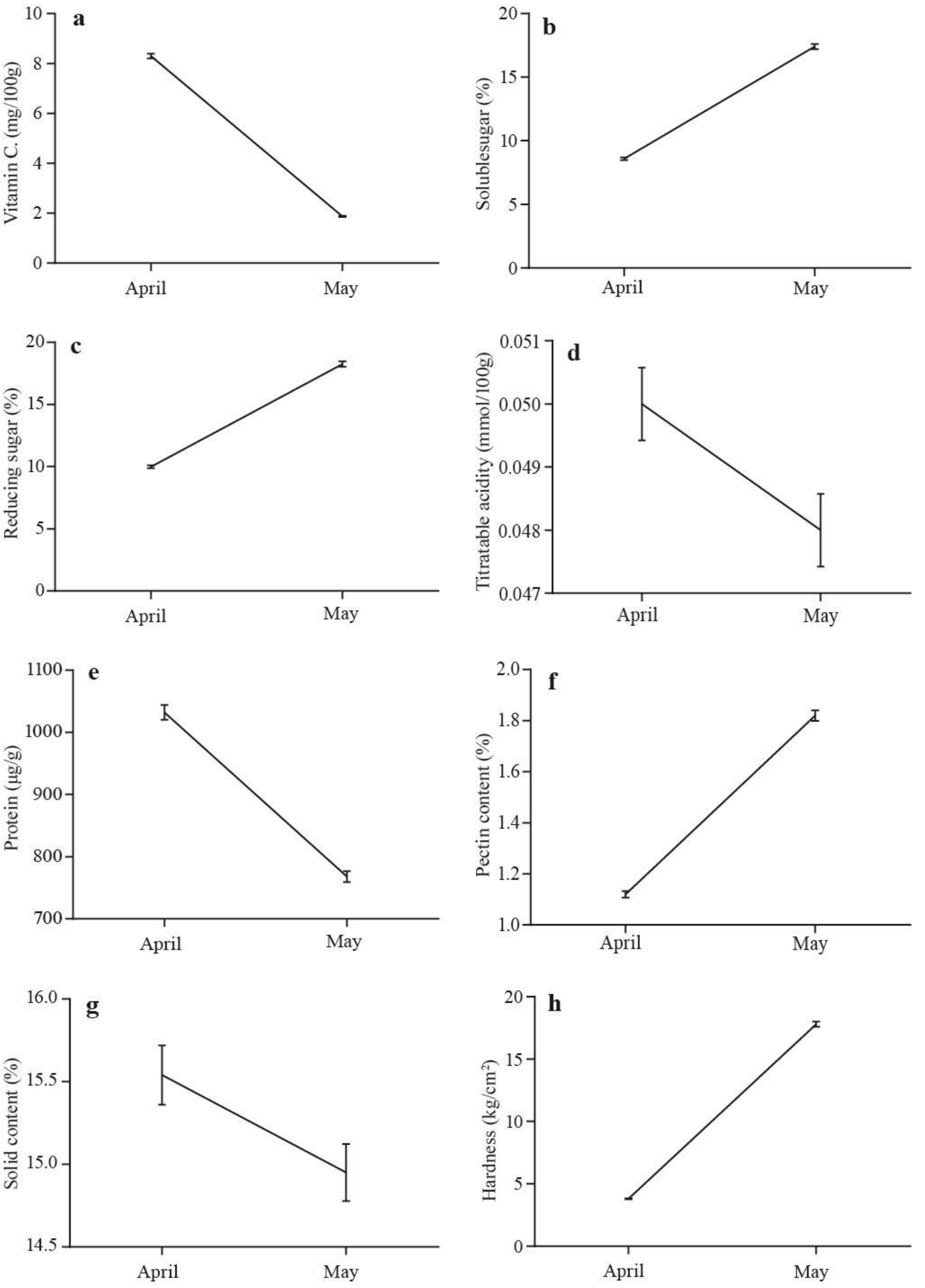

Fig. 1. Influence of different months on cherry quality.
Note: a: Vitamin C. content, b: Soluble sugar content, c: Reducing sugar content, d: titratable acidity, e: Protein content, f: Pectin

content, g: Solid content, h: Hardness.

Determination of titratable acidity: Titratable acid content is determined by acid-base titration. Weigh 0.5 g of cherry sample, grind thoroughly under liquid nitrogen, transfer to a 100 mL volumetric flask, add distilled water to the mark, and shake to dissolve. Filter through filter paper, accurately pipette 20 mL of filtrate into a 100 mL conical flask, and add 2 drops of 1% phenolphthalein indicator. Titrate with calibrated 0.01 mmol/L sodium hydroxide solution to pH 8.0 as the endpoint. Record the volume of sodium hydroxide consumed. Repeat three times and calculate the average. The formula for titratable acid content is as follows: Total Acidity (%) = V × C × N × Conversion Factor × 100 / (W × V × C) v: Total diluted sample volume (ml); V1: Volume of sample taken for titration (mL); C: Milliliters of sodium hydroxide standard solution consumed; N: Molar concentration of sodium hydroxide standard solution; W: Sample weight (g); Conversion factor: Malic acid - 0.067.

Method for determining protein content: Soluble protein content was determined using the Coomassie Brilliant Blue method (PAL *et al*., 2017).

Pectin content determination method: Pectin content was determined using a colorimetric method.

Determination of solids content: Determined using a handheld refractometer.

Hardness determination method: Fruit hardness was measured using an FT-7 non-destructive soft fruit hardness tester (Xie *et al*., 2024).

Statistical analysis: Experimental data were processed and analyzed using Excel 2016 and SPSS 21. Standard deviations were calculated, and multiple comparisons between groups were performed using the Least Significant Difference (LSD) test at a significance level of 0.05. Origin 2018 was used for graphical analysis.

Results

Effects of different months on cherry quality: Fig. 1A shows significant variations in Vitamin C. content across different months, with a decreasing trend throughout the growing season. Fig. 1B indicates a rising trend in soluble sugar content, peaking in May at 8.82% higher than the April average. Fig. 1C reveals an increasing trend in reducing sugar content, with May's content 8.26% higher than April's. Fig. 1D shows titratable acidity gradually decreasing over months. Fig. 1E indicates protein content declining, peaking at 1032 μg/g in April. Fig. 1F reveals pectin content increasing, with May's pectin content exceeding April's by 0.7%. As shown in Fig. 1G, solids content exhibited a gradual decline. As shown in Fig. 1H, firmness showed a rapid increase, peaking in May.

Overall, May cherries exhibited significantly higher total sugar and firmness than April cherries, indicating superior taste in May. However, vitamin C and protein content were substantially lower than in April, suggesting April cherries possessed higher nutritional value.

Influence of different regions on cherry quality: Table 4 indicates significant variations in cherry quality indicators across different regions. The maximum vitamin C. content exceeded the minimum by 40.04%, with significant regional differences in vitamin C. levels. Protein content peaked in Jinzhou, where the maximum value surpassed the minimum by 8.51%. Soluble sugar content reached its highest in Zhuanghe, increasing by 24.71% from the lowest value. Reducing sugar content showed significant regional variation, with the maximum exceeding the minimum by 25.35%. Hardness exhibited significant differences among Lushun, Jinzhou, and Wafangdian, reaching its lowest value in Lushun. Solids content varied significantly across regions, with the maximum exceeding the minimum by 19.44%. Titratable acidity showed significant variation in Lushun and Jinzhou, peaking in Jinzhou, while pectin content did not differ significantly among regions.

Overall, comparing cherry quality samples from five distinct regions in Dalian reveals that Lushun and Jinzhou exhibit relatively higher vitamin C and protein nutritional content. However, Lushun cherries show slightly lower sugar content and firmness compared to the other four regions, resulting in a less sweet and crisp texture. Comprehensive evaluation indicates that cherries from Jinzhou and Zhuanghe regions demonstrate superior taste and richer nutritional composition, performing the best.

Table 4 Effects of growing regions on cherry quality.

Treatment	Vitamin-C content (mg/100g)	Protein content (μg/g)	Soluble sugar (%)	Reducing sugar (%)	Hardness (kg/cm^2)	Solid content (%)	Titratable acidity (mmol/100g)	Pectin content (%)
Lüshun	6.56b	920.00c	10.48e	11.36d	3.15d	17.32a	0.052b	1.16c
Jinzhou	6.31c	956.00a	12.37b	13.42b	9.53c	15.03c	0.061a	1.36b
Wafangdian	4.67e	913.34d	11.83c	13.44b	10.14a	14.92d	0.044c	1.36b
Pulandian	6.60a	881.00e	11.73d	12.47c	9.65b	14.50e	0.042c	1.33b
Zhuanghe	5.46d	947.00b	13.07a	14.24a	9.66b	16.40b	0.044c	1.67a

Note: Different letters indicate significant differences at $p<0.05$

Table 5. Effects of greenhouse age on cherry quality.

Treatment	Vitamin-C content (mg/100g)	Protein content (μg/g)	Soluble sugar (%)	Reducing sugar (%)	Hardness (kg/cm^2)	Solid content (%)	Titratable acidity (mmol/100g)	Pectin content (%)
＜5	7.25b	763.00a	13.98a	15.91a	11.53b	15.81a	0.050a	1.24b
5~10	4.38c	896.27b	13.38b	14.72b	11.93a	15.30c	0.047b	1.59a
＞10	8.16a	1007.06a	9.44c	10.24c	4.29c	15.31b	0.045c	1.06c

Note:<5: Less than 5 years of greenhouse age; 5~10: Greenhouse age between 5 and 10 years; >10: More than 10 years of greenhouse age. Different letters indicate significant differences at $p<0.05$

Effects of different trellis ages on cherry quality: As shown in Table 5, vitamin C content exhibits a trend of first decreasing and then increasing with increasing greenhouse age, reaching its maximum value at >10 years. Protein content shows a gradual upward trend, also peaking at >10 years, with the maximum value increasing by 31.98% compared to the minimum. Soluble sugar content exhibited the opposite trend, peaking at <5 years. Reducing sugar content showed a gradual decline, reaching its maximum at <5 years, with the maximum exceeding the minimum by 55.37%. Firmness reached its minimum at >10 years. Solids content peaked at <5 years. Titratable acidity showed significant differences across different tree ages. Pectin content reached its maximum in the 5~10 year treatment.

Overall, greenhouses older than 10 years yielded higher vitamin C and protein content. Greenhouses under 10 years showed significantly higher sugar content and firmness compared to those over 10 years. This indicates that younger greenhouses produce cherries with better texture, while older greenhouses yield cherries with higher nutritional value.

Effect of orientation on cherry quality: Table 6 indicate that cherry vitamin C content, protein content, and solids reach maximum values under north-south orientation. And soluble sugar content, reducing sugar content, titratable acidity, pectin content, and firmness all reach maximum values under east-west orientation. Overall, cherries grown in a north-south orientation exhibited significantly higher vitamin C. and protein content than those in an east-west orientation. Conversely, cherries in an east-west orientation showed substantially higher sugar content and firmness than those in a north-south orientation.

The variance analysis results indicate planting orientation significantly or extremely significantly influenced all quality indicators of sweet cherries. Cherries grown in a north-south orientation demonstrated superior nutritional quality, with vitamin C content (7.82 mg/100g) and protein content (998.5 μg/g) significantly higher than east-west orientation, while solids content (16.8%) was also significantly higher. This indicates that north-south orientation is more conducive to nutrient accumulation in cherry fruits. Conversely, east-west orientation showed superior sensory quality indicators. Soluble sugar content (13.8%), reducing sugar content (14.5%), and fruit firmness (12.3 kg/cm^2) were extremely significantly higher than north-south orientation, while titratable acidity (0.062 mmol/100g) and pectin content (1.65%) were significantly higher. This indicates that east-west orientation is more conducive to sugar accumulation and improvement in fruit texture.

Effect of different greenhouse film colors on cherry quality: Table 7 shows the trends in different quality indicators under the three colored greenhouse films: Vitamin C content: White > Blue > Light Blue; Total sugar: Light Blue > Blue > White; Protein content: White > Light Blue > Blue; Firmness: Light Blue > Blue > White. Overall analysis: White film yielded the highest Vitamin C. and protein content, offering richer nutritional value; however, its total sugar content and firmness were significantly lower than blue film. For optimal taste, light blue film is recommended; for higher nutritional value, white film is more suitable. Therefore, when balancing both taste and nutritional value, light blue film is the preferred choice.

Effects of different cultivation facilities on cherry quality: Table 8 indicate that cherries grown in greenhouse facilities exhibit significantly higher vitamin C content, protein content, and solids content compared to those grown in plastic tunnels. The cherries from plastic tunnels demonstrate significantly higher soluble sugar content, reducing sugar content, titratable acidity, pectin, and firmness than those from greenhouses. Plastic greenhouses exhibit greater diurnal temperature variation compared to glasshouses, which promotes sugar accumulation in cherries and enhances their flavor profile.

The variance analysis results in Tables 8 indicate that sunlit greenhouse-grown cherries exhibit superior nutritional quality. Their vitamin C content (8.45 mg/100g) and protein content (1025.6 μg/g) are both extremely significantly higher than those of plastic greenhouse cherries, while their solids content (17.2%) is also significantly higher. This indicates that solar greenhouses, with their superior heat retention and stable growing environment, are more conducive to the accumulation and synthesis of nutrients in cherry fruits. In contrast, plastic greenhouses showed clear advantages in sensory quality indicators. Their soluble sugar content (14.2%), reducing sugar content (15.1%), and fruit firmness (13.8 kg/cm^2) were significantly higher than those of sunlit greenhouses. Titratable acidity (0.068 mmol/100g) and pectin content (1.72%) were also significantly higher.

Effect of different greenhouse film thicknesses on cherry quality: As shown in Table 9, different greenhouse film thicknesses significantly affected cherry vitamin C content, with vitamin C. levels increasing as film thickness decreased. Protein content first increased then decreased, peaking at 0.09 mm. Soluble sugar content, reducing sugar content, firmness, titratable acidity, and pectin content all reached maximum values at 0.1 mm. Solids content showed significant differences across treatments.

Overall, for cultivating cherries with sweeter flavor, a 0.1 mm greenhouse film is recommended. For superior nutritional value, a 0.09 mm film is preferred.

Effect of different levels of organization on cherry quality: Table 10 show that cherries grown by cooperatives have higher vitamin C content and solids than those grown by individual farmers. The cherries grown by individual farmers have higher titratable acidity, reducing sugar content, protein content, pectin content, soluble sugar content, and firmness than those grown by cooperatives. Overall, cherries from independent growers exhibited superior taste and slightly higher nutritional content than those from cooperatives.

The ANOVA results in Tables 10 indicate that in terms of nutritional quality, cherries grown by individual farmers demonstrate significant advantages. Their protein content (945.6 μg/g) is extremely significantly higher than that of cooperative-grown cherries. However, in vitamin C content, cooperative-grown cherries (6.85 mg/100g) are significantly higher than those from individual farmers, and the same trend is observed for solids content (15.8%). For sensory quality indicators, cherries from independent growers stood out more prominently, with soluble sugar content (13.8%), reducing sugar content (14.6%), and fruit firmness (11.9 kg/cm^2) all significantly higher than those from the cooperative.

Table 6. Analysis of variance on the influence of different orientations on cherry quality.

Indicators	Treatment	Vitamin-C (mg/100g)	Protein (μg/g)	Soluble sugar (%)	Reducing sugar (%)	Hardness (kg/cm²)	Solid content (%)	Titratable acidity (mmol/100g)	Pectin content (%)
North-South	Mean	7.82	998.5	10.5	11.2	8.7	16.8	0.045	1.28
	SD	0.45	25.6	0.7	0.6	0.5	0.8	0.005	0.12
East-West	Mean	5.94	812.3	13.8	14.5	12.3	14.2	0.062	1.65
	SD	0.38	30.2	0.9	0.8	0.7	0.6	0.006	0.15
F-value		12.45	18.67	15.23	14.56	20.45	9.88	11.34	10.12
P-value		0.003**	0.001***	0.001***	0.002**	0.001***	0.008**	0.004**	0.006**

Note:"*" Indicate significant differences at p<0.05, "**" Indicate significant differences at p<0.01,"***" Indicate significant differences at p<0.001

Table 7. Effects of greenhouse film color on cherry quality.

Treatment	Vitamin-C content (mg/100g)	Protein content (μg/g)	Soluble sugar (%)	Reducing sugar (%)	Hardness (kg/cm²)	Solid content (%)	Titratable acidity (mmol/100g)	Pectin content (%)
Blue	5.20b	803.00b	13.50a	13.52a	11.39a	14.71b	0.041b	1.48a
Light blue	5.21b	803.18b	13.50a	13.51a	11.40a	14.71b	0.041b	1.48a
White	7.11a	990.05a	9.90b	11.13b	6.09b	15.21a	0.048a	1.24b

Note: Different letters indicate significant differences at p<0.05

Table 8. Analysis of variance on the effects of different planting facilities on cherry quality.

Indicators	Treatment	Vitamin C (mg/100g)	Protein (μg/g)	Soluble sugar (%)	Reducing sugar (%)	Hardness (kg/cm²)	Solid content (%)	Titratable acidity (mmol/100g)	Pectin content (%)
Solar greenhouse	Mean	8.45	1025.6	9.8	10.5	7.2	17.2	0.042	1.18
	SD	0.52	28.3	0.6	0.5	0.4	0.7	0.004	0.11
Plastic tunnel	Mean	5.23	785.4	14.2	15.1	13.8	13.5	0.068	1.72
	SD	0.41	32.6	0.8	0.7	0.9	0.5	0.007	0.16
F-value		25.36	32.18	28.45	26.73	35.42	18.67	22.15	19.84
P-value		<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	0.001***	<0.001***	0.001***

Note: "*" Indicate significant differences at p<0.05,"**" Indicate significant differences at p<0.01, "***" Indicate significant differences at p<0.001

Table 9. Effects of greenhouse film thickness on cherry quality.

Treatment	Vitamin-C content (mg/100g)	Protein content (μg/g)	Soluble sugar (%)	Reducing sugar (%)	Hardness (kg/cm²)	Solid content (%)	Titratable acidity (mmol/100g)	Pectin content (%)
0.1mm	3.23c	842.00c	15.53a	17.01a	16.07a	14.91c	0.048a	1.62a
0.09mm	5.87b	971.00a	11.10c	12.07c	1.79c	15.11b	0.045b	1.28c
0.08mm	6.85a	943.00b	11.31b	12.52b	1.87b	15.48a	0.046b	1.41b

Note:0.1mm: The thickness of the greenhouse film is 0.1mm. 0.09mm: The thickness of the greenhouse film is 0.09mm. 0.08mm: The thickness of the greenhouse film is 0.08mm. Different letters indicate significant differences at p<0.05

Table 10. Analysis of variance on the influence of different degrees of organization on cherry quality.

Indicators	Treatment	Vitamin C (mg/100g)	Protein (μg/g)	Soluble sugar (%)	Reducing sugar (%)	Hardness (kg/cm²)	Solid content (%)	Titratable acidity (mmol/100g)	Pectin content (%)
Cooperative	Mean	6.85	865.3	11.2	12.1	9.2	15.8	0.048	1.35
	SD	0.38	24.7	0.5	0.6	0.5	0.6	0.005	0.12
Individual	Mean	5.92	945.6	13.8	14.6	11.9	14.5	0.058	1.62
	SD	0.42	28.9	0.7	0.8	0.8	0.5	0.006	0.14
F-value		8.92	12.45	15.67	14.23	18.34	7.85	11.56	13.78
P-value		0.012*	0.003**	0.001***	0.002**	<0.001***	0.018*	0.004**	0.002**

Note: "*" Indicate significant differences at p<0.05,"**" Indicate significant differences at p<0.01, "***" Indicate significant differences at p<0.001

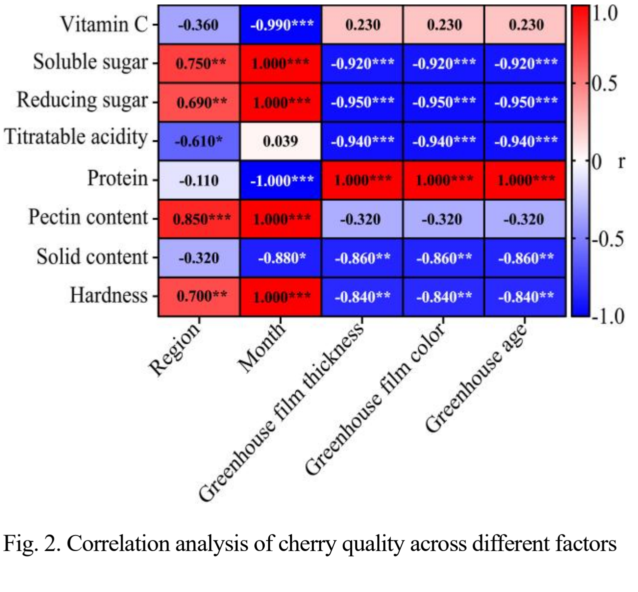

Fig. 2. Correlation analysis of cherry quality across different factors

Note: "*" Indicate significant differences at p<0.05,"**" Indicate significant differences at p<0.01, "***" Indicate significant differences at p<0.001.

Correlation analysis of quality indicators in sweet cherries across factors: To investigate the relationship between different regions, months, greenhouse film thickness, film color, greenhouse age and quality indicators of sweet cherries, correlation analyses were conducted on vitamin C content, soluble sugar content, protein content, reducing sugar content, pectin, solids content, firmness, and titratable acidity of sweet cherries across different regions and months.

As shown in Fig. 2, correlation coefficient analysis indicates that month is positively correlated with soluble sugars (r = 1.0, p<0.001), reducing sugars, firmness (r = 1.0, p<0.01), and pectin content (r = 1.0, p<0.01), indicating that as fruit matures, sugar content and firmness gradually increase, resulting in improved taste. Month showed a highly significant negative correlation with protein and vitamin C content, and a negative correlation with solids content. The correlation analysis indicates that greenhouse film thickness, film color, and greenhouse age exhibit extremely significant negative correlations with soluble sugar, reducing sugar content, and titratable acidity, and significant negative correlations with solids content and firmness. Greenhouse film thickness, film color, and greenhouse age show extremely significant positive correlations with protein content. This may result from long-term cultivation promoting soil organic matter accumulation, which enhances nutrient synthesis.

Discussion

This study systematically investigated the effects of various cultivation conditions on the quality of Liaoning sweet cherries, revealing the differential regulatory mechanisms of different factors on fruit quality traits. Overall, fruit quality attributes exhibited regular variations across months, regions, greenhouse parameters, and cultivation methods, primarily attributable to the integrated regulation of environmental factors such as light, temperature, water, and nutrition, and their interactions, on cherry physiological metabolism.

Dynamic changes and regulatory mechanisms of fruit quality traits: The harvesting month was identified as a key factor influencing core cherry quality indicators. Cherries harvested in May demonstrated significantly higher total sugar content and firmness compared to those in April, whereas April fruits exhibited superior vitamin C and protein levels. This aligns with the physiological patterns of fruit maturation, where sugar accumulation and cell wall synthesis increase with ripening, while some antioxidant compounds decrease due to metabolic consumption. In the Liaoning production area, lower light and temperature conditions in April delay the ripening process, favoring the preservation of substances like vitamin C. Conversely, enhanced sunlight and rising temperatures in May significantly promote sugar synthesis and fruit texture development (Distefano *et al*., 2020). This finding provides direct guidance for producers to precisely determine the harvest timing based on different market positioning (optimal texture for fresh consumption vs. high nutritional value for processing).

Determinative role of regional microenvironments on quality formation: The study confirms that regional microenvironments are central to causing geographical differentiation in quality. Cherries from the Jinzhou and Zhuanghe regions performed best in comprehensive scores of tastes and nutrition, closely associated with their fertile soil, balanced hydrothermal conditions, and moderate diurnal temperature variation (8~10°C) (Ribeiro *et al*., 2019). Suitable temperature differences promote sugar accumulation while avoiding damage to cellular structure (Xin *et al*., 2021). In contrast, excessive temperature fluctuations (12~15°C) in the Lushun region may negatively impact fruit firmness, while areas like Pulandian exhibit weaker soil nutrient retention capacity, indicating a need for enhanced precision water and fertilizer management. These findings elucidate the basis for the formation of regional quality characteristics of Liaoning cherries and point the way for targeted quality improvement in different production areas.

Synergistic effects of greenhouse structure and management: Greenhouse structure and management parameters exert multidimensional and interactive regulatory effects on cherry quality by altering the microclimate within the facilities. A trade-off between "nutrition" and "taste" was observed. Older greenhouses (>10 years) possess higher soil fertility, benefiting nutrient accumulation (Chang *et al*., 2024), while newer greenhouses offer better ventilation and light transmission, more conducive to sugar accumulation and taste enhancement. These jointly regulate light quality and quantity. North-south orientation provides uniform light distribution, favoring vitamin C and protein synthesis. East-west orientation and light blue films significantly promote sugar accumulation and fruit firmness by enhancing the transmission of specific light bands (e.g., red light) (Ricardo-Rodrigues *et al*., 2022; Ateş *et al*., 2022). Film thickness exerts complex effects by influencing UV transmittance and insulation. Thinner films (0.1 mm) are beneficial for increasing sugar, acidity, and firmness, while a specific thickness (0.09 mm) is more favorable for vitamin C synthesis by balancing light and heat (Wang *et al*., 2022; Li *et al*., 2024). Solar greenhouses, with superior insulation, favor the accumulation of protein and vitamin C. Plastic greenhouses, characterized by larger diurnal temperature variations and better ventilation, are more conducive to sugar accumulation and flavor compound formation (Zhang *et al*., 2022; Silva *et al*., 2019). The slightly superior quality from individual farmers compared to cooperative-scale production reflects the importance of management intensity on final quality (Chang *et al*., 2024; Wang *et al*., 2022; Candogan & Yazgan *et al*., 2010; Demirsoy *et al*., 2004; Esen *et al*., 2006; Filiz, 2019).

Practical implications and research prospects: This study provides clear operational pathways for the precision cultivation of Liaoning sweet cherries through multi-factor integrated analysis. Growers can flexibly combine the following strategies based on target markets: selecting April harvest, white film, north-south oriented older solar greenhouses to pursue high nutrition (high VC, protein); or opting for May harvest, light blue film, east-west oriented plastic greenhouses or new greenhouses to pursue superior taste (high sugar, high firmness). This study innovatively explores the combined effects of multiple factors—including month, region, greenhouse parameters, and cultivation methods—simultaneously, which has been less explored in related studies in the Liaoning production area.

It should be noted that this study primarily focused on the 'Hongdeng' variety and two key months (April-May). Future research could expand to more varieties and full growth cycle monitoring to provide more universal cultivation models. Integrating the aforementioned environmental regulation strategies with intelligent greenhouse management systems to achieve dynamic optimization of the growth environment based on quality targets will be a crucial direction for enhancing quality and efficiency in the cherry industry (Demirsoy *et al*., 2004).

Conclusion

This study systematically reveals the influence patterns of different cultivation conditions on the quality of

Liaoning sweet cherries and provides growers with the following precision management strategies: The harvest timing should be flexibly determined based on target markets—May harvesting is recommended for fresh fruit markets prioritizing high sugar content and firm texture, while April harvesting is suitable for processed fruits emphasizing high vitamin C and protein nutritional value. In terms of regional management, optimal production areas such as Jinzhou and Zhuanghe should focus on preserving their existing ecological advantages; early-ripening regions like Lüshun are advised to adopt white-film solar greenhouses to enhance nutritional quality, while late-ripening areas like Zhuanghe are recommended to use light blue-film plastic greenhouses to optimize sugar content and hardness. For facility management, newly constructed greenhouses (<5 years) should implement precise water and fertilizer regulation, whereas older facilities (>10 years) should prioritize ventilation improvements. By integrating the coordinated adjustment of factors such as harvesting month, production region, film parameters, and facility type, targeted enhancement of cherry quality can be achieved, providing actionable pathways for increasing industry efficiency.

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