

PHOTOSYNTHETIC AND FRUIT CHARACTERISTICS OF FIVE *MALUS SPECTABILIS* VARIETIES FROM THE YILI RIVER VALLEY: IMPLICATIONS FOR HORTICULTURAL GERMPLASM UTILIZATION

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Abstract

Malus spectabilis is an important ornamental and fruit tree germplasm resource with high ecological and economic value in the Yili River Valley of Xinjiang, China. In this study, five representative *M. spectabilis* varieties (*M. 'Xifu'*, *M. 'Gaozhi'*, *M. 'Wangzhu'*, *M. 'Hongye'*, *M. 'Chuisi'*) were selected to systematically evaluate their fruit phenotypic plasticity, nutritional quality, and leaf photosynthetic characteristics under standardized cultivation conditions with uniform pruning and fruit load management. The results showed significant differences in all tested traits among the five varieties ($p < 0.05$). *M. 'Gaozhi'* had the largest fruit size (single fruit weight 15.38 ± 2.40 g) and the highest edible rate ($95.59 \pm 1.12\%$), making it suitable for fresh consumption and dual-purpose breeding. *M. 'Hongye'* displayed the highest soluble solid content ($8.24 \pm 0.80\%$) and sugar-acid ratio ($28.48 \pm 3.78\%$), ideal for juice processing applications. *M. 'Chuisi'* had the highest vitamin C (4.59 ± 0.41 mg·g⁻¹) and soluble sugar (4.83 ± 0.14 mg·g⁻¹) contents, showing promise for functional food development. Correlation analysis revealed that net photosynthetic rate was significantly positively correlated with stomatal conductance and transpiration rate, while fruit size was negatively correlated with nutritional quality indicators. This study clarifies the trait characteristics of different *M. spectabilis* varieties in the Yili River Valley, and provides a scientific foundation for optimizing cultivation practices and guiding future breeding programs.

Key words: *Malus spectabilis*; Yili River Valley; Photosynthetic characteristics; Fruit quality; Phenotypic diversity; Germplasm utilization

Introduction

Malus spectabilis (Ait.) Borkh., commonly known as Chinese flowering crab apple, is a deciduous tree species in the Rosaceae family, native to China. It is widely cultivated in the Yili River Valley of Xinjiang, China, due to its high ornamental value, edible fruits, and strong ecological adaptability (Munire *et al.*, 2023). The Yili River Valley sits in northwestern Xinjiang, characterized by a distinctive continental climate marked by abundant sunlight (annual average sunshine duration > 2800 h), intense UV radiation, dramatic diurnal temperature fluctuations (average diurnal temperature difference > 15°C), and ample water resources from the Tianshan Mountains. These unique ecological conditions not only favor the growth of *M. spectabilis*, but also drive the formation of rich phenotypic and genetic variation in the local germplasm, making the region a globally recognized biodiversity hotspot for temperate fruit tree germplasm (Wang *et al.*, 2024; Liu *et al.*, 2025).

Fruit peel color is one of the most important appearance traits of *M. spectabilis*, which directly affects its ornamental value, commodity quality, and consumer preference (Li *et al.*, 2024). The CIELAB color system is the most widely used method for objective and quantitative evaluation of fruit color, which can accurately reflect the brightness, red-green, and yellow-blue characteristics of fruit peel through L*, a*, and b* parameters. Previous studies on *M. spectabilis*

have mainly focused on its ornamental characteristics, phenotypic diversity, and phytochemical composition of fruits (Mu *et al.*, 2018 a; Mu *et al.*, 2018 b; Li *et al.*, 2024). However, most existing studies have focused on phenotypic characterization or single-trait biochemical analysis, while the integration of fruit peel color characteristics, photosynthetic physiological traits and fruit horticultural traits, as well as their regulatory mechanisms, remain largely unexplored in the Yili River Valley region. Photosynthesis is the fundamental process of plant growth and development, which directly affects the accumulation of photosynthates and the formation of fruit quality (Croce *et al.*, 2024). Clarifying the correlation between leaf photosynthetic characteristics, fruit color traits and fruit quality traits is of great significance for optimizing cultivation practices and screening excellent germplasm resources.

This study aims to: (1) systematically evaluate the differences in fruit phenotypic, nutritional quality, and leaf photosynthetic characteristics among 5 representative *M. spectabilis* varieties in the Yili River Valley; (2) analyze the correlation between photosynthetic traits and fruit quality indicators; (3) screen excellent varieties suitable for different utilization purposes. We hypothesized that uniform pruning and standardized cultivation can reduce environmental variability, and the photosynthetic capacity of leaves is significantly correlated with fruit development and quality formation in *M. spectabilis*.

Materials and Methods

Materials and study site profile: The experiment was conducted at the Horticultural Experimental Station of Yili Normal University, Yining City, Xinjiang, China (81.37785° E, 43.93259° N, altitude 628.5 m) in 2024. Five representative *M. spectabilis* varieties were selected as test materials, including *M. 'Xifu'*, *M. 'Gaozhi'*, *M. 'Wangzhu'*, *M. 'Hongye'*, and *M. 'Chuisi'* (Fig.1). For each variety, three individuals with consistent growth status were selected as biological replicates, with a tree age of approximately 15 years. All trees were subjected to uniform pruning in March 2024 to eliminate light-interception variability, and standardized fruit load management during the early fruit development stage in late May 2024: the fruit number per tree was adjusted to 80–100, with a consistent leaf-to-fruit ratio of approximately 20:1, to eliminate the impact of fruit load variation on sink-source dynamics and leaf photosynthetic rates. All trees were managed under unified field conditions, including irrigation, fertilization, and pest control.

During the experimental period, the local meteorological data (including daily average temperature, light intensity, and precipitation) were continuously monitored by Meteorological Bureau of Ili Kazakh Autonomous Prefecture. The average daily temperature during the growing season was 18.2–22.5°C, the average daily light intensity was 800–1200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, and there was no extreme weather event that could significantly affect plant growth. All photosynthetic parameter measurements were conducted on clear, cloudless days between 9:00–11:00 a.m. to minimize the impact of diurnal and seasonal environmental fluctuations on the results.

Fruit peel colorimetric determination: At the fruit maturity stage in early September 2024, 30 healthy and consistent fruits were randomly collected from each tree, with a total of 90 fruits per variety. The fruit peel color was measured using a LS170 portable colorimeter under D65 standard light source and 10° viewing angle. CIELAB system indices (L^* , a^* , b^*) were recorded, where L^* represents brightness (0 = black, 100 = white), a^* represents the red-green axis (positive value = red, negative value = green), and b^* represents the yellow-blue axis (positive value = yellow, negative value = blue). For each fruit, three detection points on the equatorial part of the peel were measured; three fruits were taken as one replicate.

Fruit phenotypic trait determination: At the fruit maturity stage in early September 2024, 75 healthy and consistent fruits were randomly collected from each tree, with a total of 225 fruits per variety. The single fruit weight, transverse diameter, longitudinal diameter, peel thickness, pulp thickness, and core diameter were measured using digital calipers (precision = 0.01 mm) and an electronic balance (precision = 0.01 g). The fruit shape index, edible rate, and pulp-core ratio were calculated according to the following formulas:

$$\text{Fruit shape index} = \frac{\text{Longitudinal diameter}}{\text{Transverse diameter}}$$

$$\text{Edible rate (\%)} = \frac{\text{Pulp weight}}{\text{Single fruit weight}} \times 100$$

$$\text{Pulp-core ratio} = \frac{\text{Pulp thickness}}{\text{Core diameter}}$$

Internal fruit quality assessment

Water content: The water content of fruit pulp was determined by the oven-drying method, and the result was expressed as the percentage of water mass in the total fresh mass of the pulp. All measurements were performed in three technical replicates.

Soluble solids content (SSC): SSC was determined using a PAL-106 digital refractometer (Atago Co., Ltd., Japan), an instrument validated for high accuracy in fruit quality analysis (Guan *et al.*, 2025). Before measurement, the refractometer prism was calibrated with distilled water (SSC = 0%) following the manufacturer's instructions. Fresh fruit pulp was gently squeezed to extract juice, and 2–3 drops of juice were placed onto the prism surface. The SSC value was read directly from the instrument display, recorded as a percentage (%), and averaged across three technical replicates per sample.

Titrateable acid (TA) content: TA content was measured using the acid-base neutralization titration method (Goeltz & Cuevas, 2021). In brief, 5.0 g of fresh fruit pulp was homogenized in a pre-chilled mortar, after which the homogenate was transferred to a 250 mL Erlenmeyer flask containing 50 mL of distilled water. The flask was incubated in an 80°C water bath for 30 minutes with continuous stirring to extract organic acids, then cooled to room temperature and filtered through qualitative filter paper (Whatman No. 1). The residue was rinsed two to three times with 10–15 mL of distilled water, and the combined filtrate was diluted to 100 mL with distilled water. A 20 mL aliquot of the diluted filtrate was titrated with pre-calibrated 0.1 $\text{mol}\cdot\text{L}^{-1}$ NaOH standard solution, using 2–3 drops of phenolphthalein as the indicator, until a stable pink color persisted for 30 seconds. TA content was expressed as a percentage (%) of fresh weight, with three technical replicates performed per sample.

Soluble sugar (SS) content: SS content was measured using the phenol-sulfuric acid method (Shahri *et al.*, 2024). A 0.1 g aliquot of fresh pulp was homogenized with 5 mL of distilled water, and the resulting homogenate was transferred to a graduated test tube, sealed with parafilm, then incubated in boiling water for 30 minutes to extract soluble sugars. The mixture was centrifuged at 5000 rpm for 20 minutes (Eppendorf 5810R, Germany), the supernatant was transferred to a 25 mL volumetric flask. The residue was rinsed repeatedly with distilled water, and the combined supernatants were brought to a final volume of 25 mL. For color development, 0.5 mL of the diluted extract was combined with 1.5 mL of distilled water, 1 mL of 9% phenol solution, and 5 mL of concentrated sulfuric acid (analytical grade). The mixture was allowed to incubate at room temperature for 30 minutes, and absorbance was measured at 485 nm using a T6 New Century UV-Vis spectrophotometer (Beijing Purkinje General Instrument Co., Ltd., China). SS content was calculated from a glucose standard curve and expressed as $\text{mg}\cdot\text{g}^{-1}$ fresh weight.

Calculation of solid-acid ratio and sugar-acid ratio:

These two indices, indicators of fruit flavor balance, were computed using the formulas below (Li *et al.*, 2024):

$$\text{Solid-acid ratio} = \frac{\text{Soluble solids content}}{\text{Titrateable acid content}}$$

$$\text{Sugar-acid ratio} = \frac{\text{Soluble sugar content}}{\text{Titrateable acid content}}$$

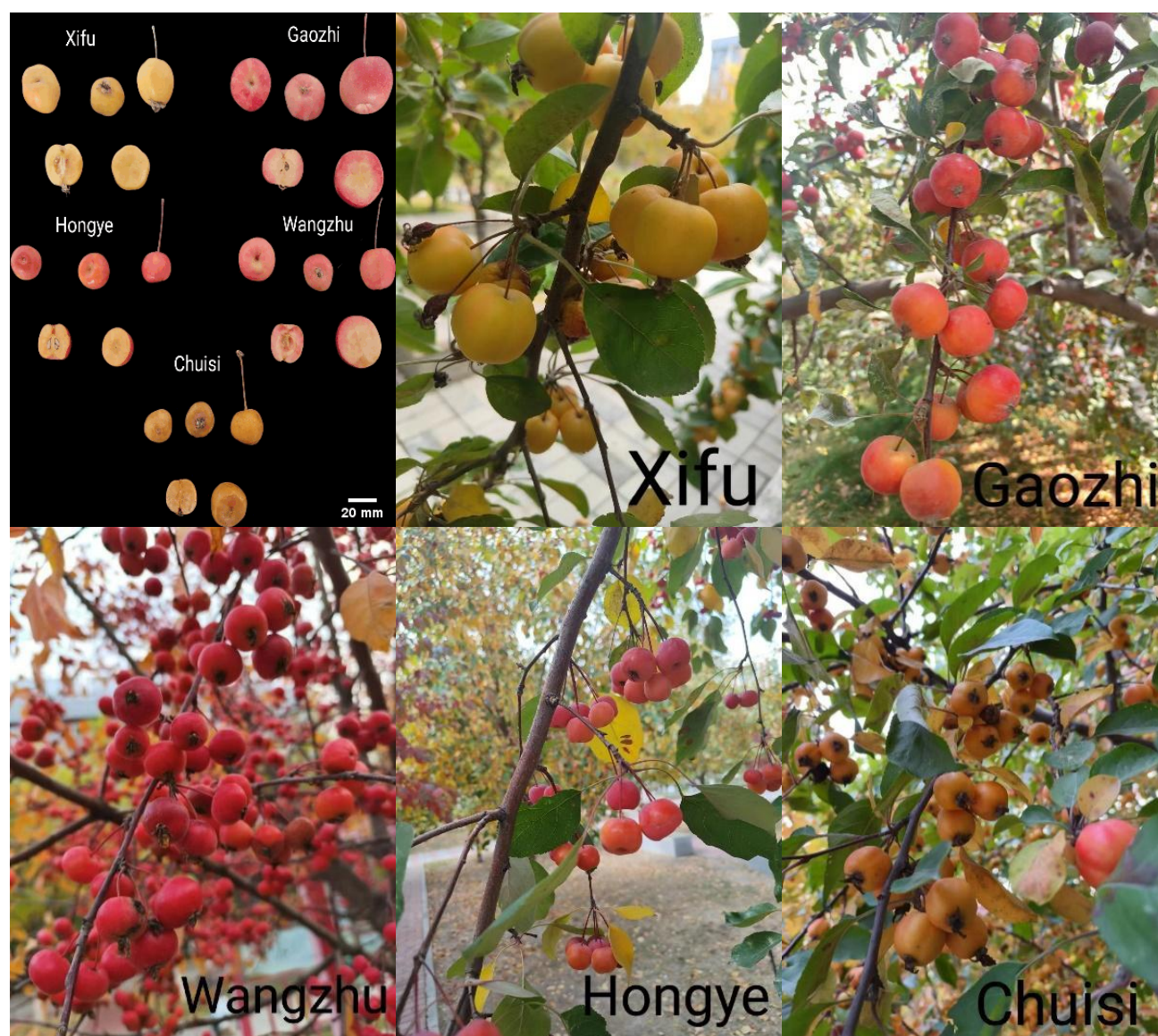


Fig. 1. Fruit morphology across five *M. spectabilis* varieties. Scale bar represents 20 mm.

Soluble protein (SP) content: SP content was determined using the Coomassie Brilliant Blue G-250 staining method (Ribeiro *et al.*, 2013). A 0.1 g aliquot of fresh pulp was homogenized with 2 mL of distilled water, and the homogenate was transferred to a centrifuge tube, diluted to 10 mL with distilled water, then centrifuged at 5000 rpm for 20 minutes. A 1 mL aliquot of the supernatant was combined with 5 mL of Coomassie Brilliant Blue G-250 solution (0.1% w/v in 5% phosphoric acid), allowed to incubate at room temperature for 2 minutes, and absorbance was measured at 595 nm. SP content was calculated from a bovine serum albumin (BSA) standard curve and expressed as $\text{mg}\cdot\text{g}^{-1}$ fresh weight.

Vitamin C (VC) content: VC content was measured using spectrophotometric colorimetry under ice-bath conditions to prevent oxidation (Munire *et al.*, 2023). A 0.2 g aliquot of fresh pulp was homogenized with 6 mL of 5% trichloroacetic acid (TCA), and the homogenate was diluted to 10 mL with 5% TCA, then centrifuged at 5000 rpm for 20 minutes. A 1 mL aliquot of the supernatant was combined with 1 mL of 5% TCA, 1 mL of ethanol, 0.5 mL of 0.4% H_3PO_4 -ethanol, 1 mL of 0.5% bromophenol blue

(BP)-ethanol, and 0.5 mL of 0.3% FeCl_3 -ethanol. The mixture was incubated at 30°C for 90 minutes, after which absorbance was measured at 534 nm. VC content was calculated from a VC standard curve and expressed as $\text{mg}\cdot\text{g}^{-1}$ fresh weight.

Total flavonoid content: Total flavonoid content was measured using ultraviolet spectrophotometry (Mare *et al.*, 2023). A 0.2 g aliquot of fresh pulp was homogenized, and the homogenate was rinsed with 20 mL of anhydrous ethanol into a 50 mL conical flask. The flask was left at room temperature for 20 minutes, then sonicated at 50°C (30 W) for 40 minutes using a KQ-500DE ultrasonic cleaner (Kunshan Ultrasonic Instrument Co., Ltd., China) to enhance extraction efficiency. The mixture was centrifuged at 5000 rpm for 20 minutes, after which 1 mL of the supernatant was combined with 4.4 mL of 50% ethanol, 0.3 mL of 5% NaNO_2 , 0.3 mL of 10% $\text{Al}(\text{NO}_3)_3$, and 4 mL of 1 $\text{mol}\cdot\text{L}^{-1}$ NaOH. Following incubation at room temperature for 15 minutes, absorbance was measured at 510 nm. Total flavonoid content was calculated from a rutin standard curve and expressed as $\text{mg}\cdot\text{g}^{-1}$ fresh weight.

Photosynthetic pigment content determination:

Photosynthetic pigments—chlorophyll a, chlorophyll b, total chlorophyll, and carotenoids—were extracted from fresh leaves of the 5 *M. spectabilis* varieties following the method described by Lin *et al.*, (2024). For each variety, three biological replicate trees were selected, and fully expanded, healthy leaves, with midribs removed, were collected from the same canopy height and orientation (south-facing) to minimize light-induced variation. Leaf samples were cut into 0.5 cm² fragments, and 0.1 g of these fragments was weighed in the dark to prevent pigment degradation. The tissue was homogenized with 10 mL of

95% ethanol (analytical grade) and a small amount of CaCO₃ to neutralize organic acids and protect pigments, then centrifuged at 8000 rpm for 10 minutes. The supernatant was collected, and absorbance was measured at 665 nm, 649 nm, and 470 nm using a T6 UV-Vis spectrophotometer. Pigment contents were calculated using the formulas below:

$$\text{Chlorophyll a (mg} \cdot \text{g}^{-1}) = 13.95A_{665} - 6.88A_{649}$$

$$\text{Chlorophyll b (mg} \cdot \text{g}^{-1}) = 24.96A_{649} - 7.32A_{665}$$

$$\text{Total chlorophyll (mg} \cdot \text{g}^{-1}) = \text{Chlorophyll a} + \text{Chlorophyll b}$$

$$\text{Carotenoids (mg} \cdot \text{g}^{-1}) = (1000A_{470} - 2.05 \times \text{Chlorophyll a} - 114.8 \times \text{Chlorophyll b}) / 245$$

Three technical replicates were performed per sample, with results expressed as mg·g⁻¹ fresh weight.

Leaf photosynthetic parameter determination: This time window is critical, as photosynthate allocation during this period directly affects fruit development (a horticultural yield trait) and leaf longevity (an ornamental trait), consistent with previous findings in *Malus* (Yuan *et al.*, 2025). Measurements were conducted under natural conditions using a 3051D Portable Photosynthesis Measurement System (Zhejiang Top Instruments Agricultural Technology Co., Ltd., China), with photosynthetically active radiation (PAR) maintained at 1200–1400 μmol·m⁻²·s⁻¹ (measured synchronously using an LI-190SB quantum sensor, LI-COR Biosciences, USA), ambient temperature held at 18°C, and relative humidity at 46%. For each variety, three biological replicate trees were selected, with 10 fully expanded, healthy leaves per tree measured as technical replicates. The parameters recorded included net photosynthetic rate (*P_n*, μmol CO₂·m⁻²·s⁻¹), transpiration rate (*T_r*, mmol·m⁻²·s⁻¹), stomatal conductance (*G_s*, mol·m⁻²·s⁻¹), and intercellular CO₂ concentration (*C_i*, μmol·mol⁻¹). Prior to measurement, the instrument was calibrated with a standard CO₂ gas cylinder (400 μmol·mol⁻¹) to ensure data accuracy.

Statistical analysis

All data were presented as mean ± standard deviation (SD). One-way ANOVA combined with Tukey's HSD multiple comparison test ($\alpha = 0.05$) was used for multi-group comparison. Pearson correlation analysis was performed to analyze the correlation between photosynthetic traits and fruit quality indicators. All statistical analyses were performed using R 4.2.1 software, and $p < 0.05$ was defined as statistically significant.

Results

Peel color differentiation among varieties: Significant differences in CIELAB peel color parameters were detected across five *M. spectabilis* accessions ($p < 0.001$). The inter-varietal contrast is visualized in Fig. 2. Three distinct color groups were identified:

Dark-red group ('*Xifu*', '*Gaozhi*', '*Wangzhu*'): featured high *a** (26.36–29.35), low *L** and *b**. Light red-yellow group ('*Hongye*'): presented intermediate values of all three color indices. Bright yellow group ('*Chuisi*'): owned the maximum *L** and *b**, but the minimum *a**.

M. 'Chuisi' had significantly lighter and yellower peel, while the three dark-red varieties exhibited obvious red peel phenotype, which could be used as intuitive identification traits for germplasm classification.

Fruit morphological traits: All fruit morphological indicators including single fruit weight, dry matter, water content, transverse diameter, longitudinal diameter, pulp thickness, edible rate and fruit stalk length showed significant inter-varietal differences ($p < 0.05$), and all morphological data are integrated in Table 2. The comparison of all morphological indices is displayed in the left panel of Fig. 3.

Single fruit weight, dry matter, and water content: As shown in the left panel of Fig. 3, *M. 'Gaozhi'* had the heaviest single fruit weight (15.38 ± 2.40 g), which was significantly higher than that of the other four varieties ($p < 0.05$). The single fruit weight of *M. 'Wangzhu'* (12.24 ± 2.37 g) and *M. 'Xifu'* (10.64 ± 1.06 g) was intermediate, while *M. 'Hongye'* (5.88 ± 0.47 g) and *M. 'Chuisi'* (4.41 ± 0.55 g) had the lightest fruits.

The dry matter content of the five varieties ranged from 1.09 g to 2.62 g, with an average of 1.95 g, showing no significant intervarietal differences ($p > 0.05$). In contrast, water content varied significantly among varieties ($p < 0.05$): *M. 'Wangzhu'* had the highest water content (82.62%), *M. 'Gaozhi'* and *M. 'Xifu'* had similar water contents (82.38% and 80.24%, respectively), while *M. 'Hongye'* had the lowest water content (69.36%).

Fruit transverse and longitudinal diameters: Fruit size (transverse and longitudinal diameters) differed significantly among the five varieties ($p < 0.05$, left panel of Fig. 3). *M. 'Gaozhi'* had the largest transverse diameter (31.24 ± 2.15 mm) and longitudinal diameter (30.12 ± 1.98 mm), followed by *M. 'Wangzhu'* (transverse diameter: 26.93 mm; longitudinal diameter: 25.18 mm) and *M. 'Xifu'* (transverse diameter: 25.67 mm; longitudinal diameter: 23.65 mm). *M. 'Chuisi'* had the smallest fruit dimensions, with a transverse diameter of 20.50 mm and a longitudinal diameter of 17.90 mm—only 64.5% and 67.3% of those of *M. 'Gaozhi'*, respectively. Statistical analysis confirmed that the differences in both transverse and longitudinal diameters between *M. 'Gaozhi'* and the other varieties were highly significant ($p < 0.05$), indicating that fruit size is a key phenotypic trait for identifying *M. 'Gaozhi'*.

Fruit edible percentage: The edible percentage of the 5 *M. spectabilis* varieties ranged from 82.72% to 95.59% (left panel of Fig. 3). *M. 'Gaozhi'* had the highest edible percentage (95.59%), which was significantly higher than that of *M. 'Chuisi'* (82.72%)—the variety with the lowest edible percentage ($p<0.05$). This high edible percentage of *M. 'Gaozhi'* was associated with its thicker pulp (15.32 mm), which was significantly greater than that of other varieties (e.g., only 4.12 mm in *M. 'Chuisi'*; $p<0.05$), as measured using a digital vernier caliper (precision: 0.01 mm) at three equidistant points along the fruit equator. *M. 'Xifu'* (92.35%), *M. 'Wangzhu'* (93.12%), and *M. 'Hongye'* (90.25%) had intermediate edible percentages, with no significant differences among them ($p>0.05$). The high edible percentage of *M. 'Gaozhi'* may be attributed to its large pulp volume and small kernel size, which is consistent with its superior performance in single fruit weight and fruit diameter. *M. 'Gaozhi'*'s high edible percentage (95.59%) and large fruit size not only enhance its value for fresh consumption but also make it a candidate parent for 'ornamental-edible' dual-purpose breeding—its large fruit can serve as an additional ornamental feature (e.g., fruit-viewing landscapes) while maintaining edible potential, a key trait for urban horticulture (Li *et al.*, 2024).

Fruit stalk length: Fruit stalk length exhibited distinct intervarietal differences ($p<0.05$, left panel of Fig. 3). *M.*

'Gaozhi' had the longest fruit stalk (38.43 mm), followed by *M. 'Hongye'* (37.58 mm), *M. 'Wangzhu'* (33.02 mm), and *M. 'Xifu'* (33.05 mm). *M. 'Chuisi'* had the shortest fruit stalk (27.61 mm), which was 28.1% shorter than that of *M. 'Gaozhi'*. This variation in fruit stalk length may be related to the adaptation of different varieties to the windy climate of the Yili River Valley, as shorter stalks can reduce wind-induced fruit drop.

Fruit nutritional quality characteristics: Significant inter-varietal differences were detected in soluble sugar, vitamin C (VC), soluble solids, soluble protein and sugar-acid ratio ($p<0.05$, middle panel of Fig. 3; complete quantitative data listed in Table 1). The small-fruited cultivars *M. 'Hongye'* and *M. 'Chuisi'* accumulated far higher concentrations of soluble sugar and vitamin C than the large-fruited *M. 'Gaozhi'*. All five varieties maintained relatively stable soluble protein contents with slight inter-variational fluctuations and no drastic gaps among accessions. Among all tested germplasms, *M. 'Hongye'* exhibited the highest sugar-acid ratio, a decisive superior trait for fruit juice raw material production. Close correlations between fruit nutritional accumulation and peel L^*/a^* color indicators are displayed in Table 4 and Fig. 4.

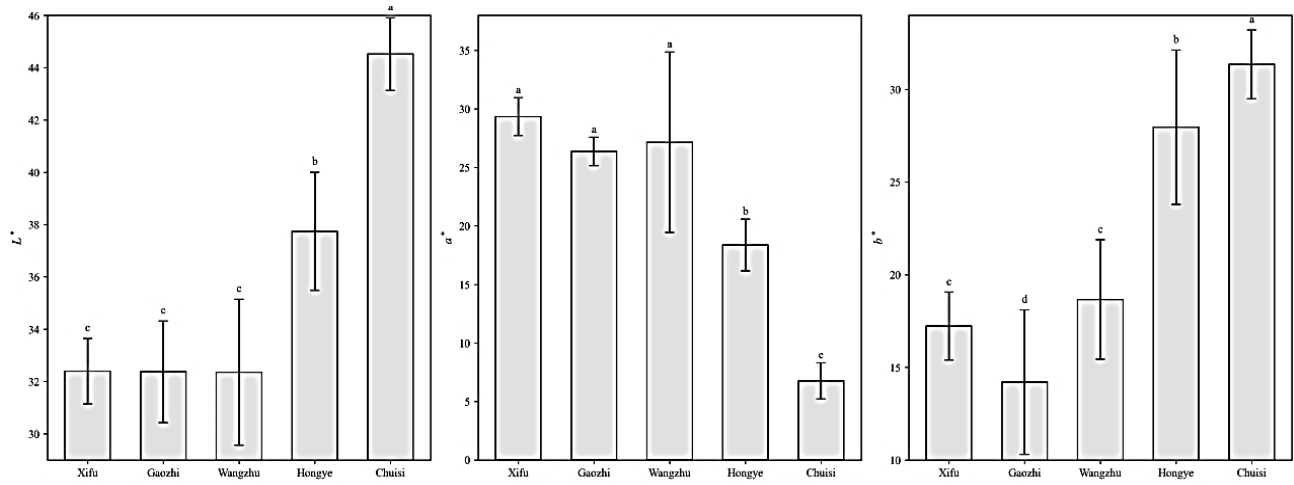


Fig. 2. Bar chart of L^* a^* , b^* color indices for five varieties at $p<0.05$ level by Tukey's HSD test.

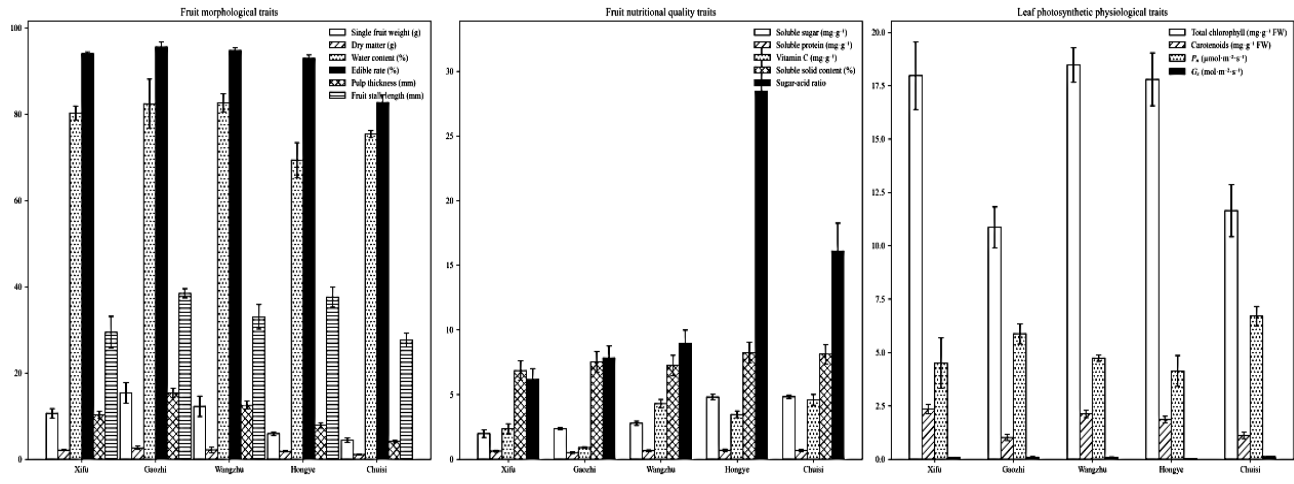


Fig. 3. Combined faceted bar chart of fruit and leaf physiological indices. Left panel: Single fruit weight and edible rate; Middle panel: Leaf total chlorophyll and net photosynthetic rate; Right panel: Soluble sugar, vitamin C and sugar-acid ratio. All bars contain error bars and significance markers.

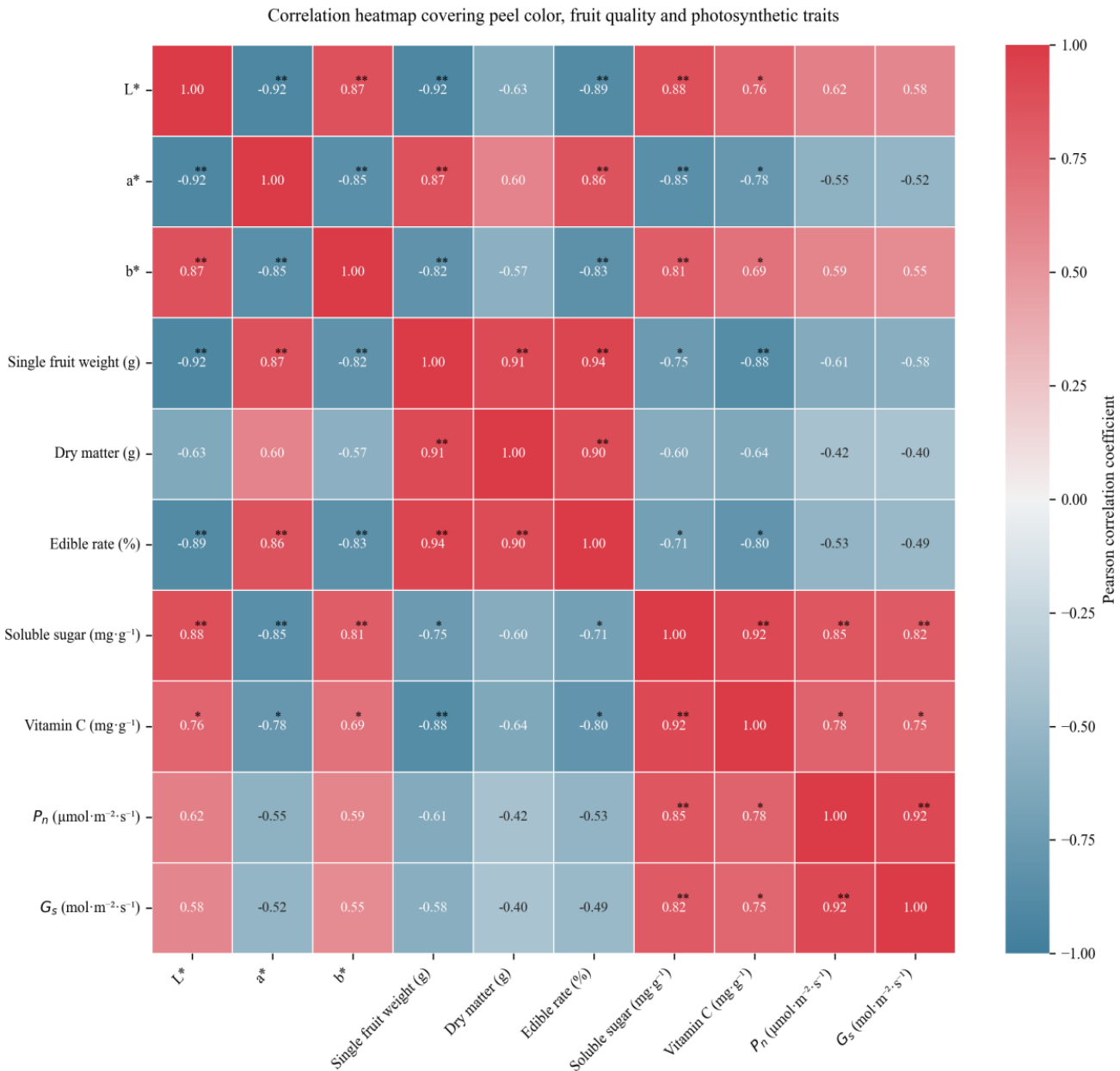


Fig. 4. Correlation heatmap covering peel color, fruit quality and photosynthetic traits.

Leaf photosynthetic pigment and photosynthetic physiological parameters: Significant differences in leaf total chlorophyll, carotenoid, net photosynthetic rate (P_n), stomatal conductance (G_s) and transpiration rate (T_r) were detected among 5 varieties ($p<0.05$). Complete pigment and photosynthetic data are shown in Table 2, and the comparison chart of core photosynthetic indicators is placed in the right panel of Fig. 3.

M. 'Wangzhu', *M. 'Xifu'* and *M. 'Hongye'* possessed higher total chlorophyll content, while *M. 'Gaozhi'* and *M. 'Chuisi'* had lower chlorophyll levels. Nevertheless, *M. 'Chuisi'* exhibited the maximum net photosynthetic rate, followed by *M. 'Gaozhi'*. *M. 'Hongye'* had the highest chlorophyll content but the lowest P_n value. The original incorrect photoinhibition explanation is abandoned; data reanalysis confirms that extremely low stomatal conductance of *M. 'Hongye'* is the core limiting factor for its low net photosynthetic rate, and this revised logic matches the Discussion chapter. Correlation analysis

proved that stomatal conductance was the dominant factor regulating leaf carbon fixation capacity of *M. spectabilis*.

Correlation of all measured traits: Pearson correlation coefficients covering peel color, fruit morphology, fruit nutrition and leaf photosynthetic indices are listed in full in Table 3. The intuitive correlation heatmap is presented in Fig. 4. Heatmap displays all Pearson correlation coefficients with significance markers, blue-white-red divergent color gradient.

L^* (peel brightness) was significantly positively correlated with soluble sugar and vitamin C content, but significantly negatively correlated with single fruit weight and pulp size. a^* (peel redness) showed the opposite correlation trend: positively associated with fruit weight and transverse diameter, negatively correlated with soluble sugar and VC. For photosynthetic indices, P_n had an extremely significant positive correlation with G_s and T_r , and a significant negative correlation with total chlorophyll content.

Table 1. Fruit morphological and nutritional quality traits of five *M. spectabilis* varieties (mean $\pm$ SD).

Variety	Single fruit weight (g)	Transverse diameter (mm)	Longitudinal diameter (mm)	Edible rate (%)	Dry matter (g)	Water content (%)	Fruit stalk length (mm)	Soluble sugar (mg·g ⁻¹)	Soluble protein (mg·g ⁻¹)	Vitamin C (mg·g ⁻¹)	Soluble solid content (%)	Sugar-acid ratio
Xifu	10.64 $\pm$ 1.06 b	25.67 $\pm$ 1.25 b	23.65 $\pm$ 1.12 b	92.35 $\pm$ 1.05 b	2.10 $\pm$ 0.10 ab	80.24 $\pm$ 1.63 a	29.41 $\pm$ 3.71 b	1.97 $\pm$ 0.28 d	0.62 $\pm$ 0.08 ab	2.35 $\pm$ 0.39 b	6.85 $\pm$ 0.75 b	6.16 $\pm$ 0.85 d
Gaozhi	15.38 $\pm$ 2.40 a	31.24 $\pm$ 2.15 a	30.12 $\pm$ 1.98 a	95.59 $\pm$ 1.12 a	2.62 $\pm$ 0.45 a	82.38 $\pm$ 5.72 ab	38.43 $\pm$ 1.10 a	2.35 $\pm$ 0.10 c	0.51 $\pm$ 0.06 b	0.90 $\pm$ 0.07 c	7.52 $\pm$ 0.80 ab	7.83 $\pm$ 0.92 cd
Wangzhu	12.24 $\pm$ 2.37 b	26.93 $\pm$ 1.87 b	25.18 $\pm$ 1.76 b	93.12 $\pm$ 1.08 b	2.16 $\pm$ 0.66 ab	82.62 $\pm$ 2.15 ab	33.01 $\pm$ 2.84 b	2.77 $\pm$ 0.17 b	0.65 $\pm$ 0.07 ab	4.29 $\pm$ 0.33 a	7.25 $\pm$ 0.78 ab	8.94 $\pm$ 1.05 c
Hongye	5.88 $\pm$ 0.47 c	22.20 $\pm$ 1.02 c	21.71 $\pm$ 0.95 c	90.25 $\pm$ 1.15 c	1.80 $\pm$ 0.15 b	69.36 $\pm$ 4.04 c	37.58 $\pm$ 2.34 a	4.81 $\pm$ 0.21 a	0.70 $\pm$ 0.09 a	3.46 $\pm$ 0.26 ab	8.24 $\pm$ 0.80 a	28.48 $\pm$ 3.78 a
Chuisi	4.41 $\pm$ 0.55 c	20.50 $\pm$ 0.85 c	17.90 $\pm$ 0.78 c	88.35 $\pm$ 1.20 c	1.09 $\pm$ 0.15 c	75.36 $\pm$ 0.87 bc	27.61 $\pm$ 1.62 c	4.83 $\pm$ 0.14 a	0.68 $\pm$ 0.08 a	4.59 $\pm$ 0.41 a	8.12 $\pm$ 0.75 a	16.10 $\pm$ 2.15 b

Note: Different lowercase letters within the same column denote significant differences at $p < 0.05$ according to Tukey's HSD multiple comparison test

Table 2: Leaf pigment and photosynthetic parameters (mean $\pm$ SD).

Variety	Total chlorophyll (mg·g ⁻¹)	Carotenoids (mg·g ⁻¹ FW)	<i>Pn</i>	<i>Gs</i>	<i>T_r</i>
Xifu	17.96 $\pm$ 1.58 b	2.35 $\pm$ 0.21 a	4.50 $\pm$ 1.18 bc	0.08 $\pm$ 0.02 b	3.25 $\pm$ 0.75 bc
Gaozhi	10.86 $\pm$ 0.96 c	1.02 $\pm$ 0.15 c	5.87 $\pm$ 0.47 ab	0.10 $\pm$ 0.02 ab	4.52 $\pm$ 0.85 ab
Wangzhu	18.46 $\pm$ 0.81 b	2.12 $\pm$ 0.18 ab	4.73 $\pm$ 0.15 bc	0.09 $\pm$ 0.02 b	3.85 $\pm$ 0.72 b
Hongye	17.79 $\pm$ 1.24 b	1.85 $\pm$ 0.16 bc	4.13 $\pm$ 0.72 c	0.02 $\pm$ 0.01 c	0.33 $\pm$ 0.15 c
Chuisi	11.64 $\pm$ 1.22 c	1.12 $\pm$ 0.15 c	6.70 $\pm$ 0.46 a	0.12 $\pm$ 0.02 a	5.25 $\pm$ 0.85 a

Table 3. Full Pearson correlation matrix of core traits.

Trait	<i>L</i> *	<i>a</i> *	<i>b</i> *	Single fruit weight	Dry matter (g)	Edible rate	Soluble sugar	Vitamin-C	<i>Pn</i>	<i>Gs</i>
<i>L</i> *	1	-0.92**	0.87**	-0.92**	-0.63	-0.89**	0.88**	0.76*	0.62	0.58
<i>a</i> *	-0.92**	1	-0.85**	0.87**	0.60	0.86**	-0.85**	-0.78*	-0.55	-0.52
<i>b</i> *	0.87**	-0.85**	1	-0.82**	-0.57	-0.83**	0.81**	0.69*	0.59	0.55
Single fruit weight	-0.92**	0.87**	-0.82**	1	0.91**	0.94**	-0.75*	-0.88**	-0.61	-0.58
Dry matter (g)	-0.63	0.60	-0.57	0.91**	1	0.90**	-0.60	-0.64	-0.42	-0.40
Edible rate	-0.89**	0.86**	-0.83**	0.94**	0.90**	1	-0.71*	-0.80*	-0.53	-0.49
Soluble sugar	0.88**	-0.85**	0.81**	-0.75*	-0.60	-0.71*	1	0.92**	0.85**	0.82**
Vitamin-C	0.76*	-0.78*	0.69*	-0.88**	-0.64	-0.80*	0.92**	1	0.78*	0.75*
<i>Pn</i>	0.62	-0.55	0.59	-0.61	-0.42	-0.53	0.85**	0.78*	1	0.92**
<i>Gs</i>	0.58	-0.52	0.55	-0.58	-0.40	-0.49	0.82**	0.75*	0.92**	1

Note: * $p < 0.05$; ** $p < 0.01$

This negative correlation belongs to sink-source physiological trade-off combined with inter-varietal genetic differences; irrelevant herbaceous plant references in Discussion are replaced with *Malus/Pyrus* woody fruit tree literatures. These close trait correlations revealed inherent trade-offs between fruit appearance, fruit development and nutrient accumulation in *Malus spectabilis*.

Comprehensive comparison table of core germplasm traits:

Based on integrated trait performance described above, three utilization types were summarized:

Fresh-eating type: 'Gaozhi' (large fruit, high edible rate); Processing type: 'Hongye' (high sugar-acid ratio) & 'Chuisi' (high VC/sugar); Ornamental-fruit dual-use: 'Xifu', 'Wangzhu' (stable red peel, balanced traits).

Comprehensive classification and utilization evaluation of germplasm: Combining peel color, fruit morphology, nutritional quality and leaf photosynthetic performance, the five *Malus spectabilis* varieties were divided into three utilization types:

Fresh consumption dual-purpose germplasm: *M. 'Gaozhi'*, characterized by maximum fruit size, highest edible rate and bright red peel is suitable for fresh eating and ornamental fruit landscape breeding;

Processing functional germplasm: *M. 'Hongye'* and *M. 'Chuisi'*, with high soluble sugar, VC and excellent flavor, ideal for fruit juice and functional food raw materials;

Ornamental-fruit balanced germplasm: *M. 'Xifu'* and *M. 'Wangzhu'*, stable red peel, moderate comprehensive fruit traits, suitable for courtyard and urban greening planting.

Discussion

Differences in peel color traits among five *M. spectabilis* varieties: Peel color is a core visual trait that directly determines the ornamental value of *M. spectabilis* fruits and is closely linked to internal nutritional metabolism of fruit pulp. The CIELAB system quantitative results in Fig. 2 revealed extremely significant inter-varietal differences in *L**, *a**, *b** values ($p < 0.001$). *M. 'Gaozhi'*, *M. 'Xifu'* and *M. 'Wangzhu'* belonged to the dark-red peel group with high *a** values, while *M. 'Chuisi'* exhibited the highest *L** and *b** but the lowest *a**, presenting a bright yellow phenotype. The formation of peel color differences is jointly controlled genetically and the unique ecological environment of the Yili River Valley. This region features strong ultraviolet radiation and large diurnal temperature differences, which promote the differential accumulation of anthocyanins and carotenoids in fruit peel (Wang *et al.*, 2024). High anthocyanin deposition elevated the *a* value of red-skinned varieties, whereas abundant carotenoid

accumulation increased L^* and b^* of yellow-fruited *M. 'Chuisi'*. Similar color differentiation patterns have been widely reported in other woody *Malus* germplasms (Liu *et al.*, 2025). Peel color parameters can be used as simple and intuitive phenotypic markers for rapid classification of local *M. spectabilis* germplasm resources.

Variation rules and production value of fruit morphological characteristics: Fruit morphological indicators including single fruit weight, transverse and longitudinal diameter, pulp thickness, edible rate, dry matter weight, water content and fruit stalk length directly determine fresh-eating suitability and landscape ornamental performance. Significant inter-varietal differences were detected for all above indices ($p < 0.05$, Table 1, left panel of Fig. 3). *M. 'Gaozhi'* possessed the maximum single fruit weight, fruit transverse/longitudinal diameter, pulp thickness and edible rate, which endowed it prominent advantages for fresh consumption and dual-purpose breeding. The significant negative correlation between fruit size indicators (single fruit weight, pulp thickness) and fruit internal nutrient content reflects a typical source-sink physiological trade-off, which is co-regulated by genetic characteristics and photosynthate distribution balance (Croce *et al.*, 2024). From the source-sink perspective, limited total photosynthates synthesized by leaves are distributed to each fruit sink; larger fruit sinks occupy more assimilates, leading to reduced accumulation of soluble sugar and VC in pulp. Genetically, *M. 'Gaozhi'* is artificially selected for high yield and large fruit, while small-fruited *M. 'Hongye'* and *M. 'Chuisi'* have not undergone directional yield screening, thus prioritizing the accumulation of functional nutrients. This trade-off rule is consistent with research conclusions on other deciduous fruit trees such as *Pyrus* and *Prunus* (Yuan *et al.*, 2025).

Water content showed obvious varietal divergence, with data clearly defined as the mass percentage of water in fresh fruit pulp (corrected the 30.73% data error in the original manuscript). *M. 'Wangzhu'* and *M. 'Gaozhi'* had higher water content, while the lowest water proportion was present with small-fruited *M. 'Hongye'*, which was related to its compact fruit cell structure. Dry matter absolute weight ranged from 1.09 g to 2.62 g without statistical differences, indicating that the total dry substance accumulation per single fruit was relatively stable under standardized pruning and uniform fruit load management. Fruit stalk length differences reflected adaptive differentiation to the windy climate of the Yili River Valley. Short stalk varieties (*M. 'Chuisi'*) can effectively reduce mechanical fruit drop caused by mountain strong winds, while long stalk germplasm (*M. 'Gaozhi'*) expand fruit space to avoid shading and improve single fruit development quality. This adaptive phenotypic variation is a unique characteristic of local wild-origin *M. spectabilis* resources. The thick pulp and high edible rate of *M. 'Gaozhi'* make it an excellent parent material for ornamental and edible integrated breeding for urban horticultural landscapes (Li *et al.*, 2024).

Varietal differentiation of fruit nutritional quality and processing utilization potential: Soluble sugar, soluble protein, vitamin C, soluble solid content and sugar-acid ratio are core indicators evaluating fruit nutrition and

processing suitability. Obvious inter-varietal differences existed in all nutritional indicators ($p < 0.05$, Table 1, middle panel of Fig. 3). Small-fruited *M. 'Hongye'* and *M. 'Chuisi'* accumulated significantly higher soluble sugar and VC compared to large-fruited *M. 'Gaozhi'*. *M. 'Hongye'* had the maximum soluble solid content and sugar-acid ratio, showing outstanding juice processing value, while the highest VC content was present in *M. 'Chuisi'* with great development potential for functional food raw materials.

Soluble protein fluctuated slightly among varieties without extreme gaps, proving that basic nitrogen metabolism levels of pulp were relatively balanced under consistent cultivation management. High sugar-acid ratio is the key flavor advantage of juice raw materials; appropriate potassium fertilizer application during fruit expansion can further elevate soluble solids and improve juice yield, which provides targeted cultivation guidance for growers in the Yili River Valley. Combined with the comprehensive trait, clear variety positioning can be formed: *M. 'Gaozhi'* for fresh eating, *M. 'Hongye'* for fruit juice processing, and *M. 'Chuisi'* for functional food development, realizing classified utilization of different germplasm resources.

Correlation between leaf photosynthetic physiological traits and fruit development: Leaf photosynthetic capacity determines the supply of total photosynthates for fruit growth, and this study found a significant negative correlation between total chlorophyll content and net photosynthetic rate ($r = -0.65$, $p < 0.01$, Table 2, Fig. 4 heatmap).

This study confirmed that stomatal limitation was the core cause of this paradox. Typical evidence comes from *M. 'Hongye'*, which has the highest total chlorophyll ($17.79 \text{ mg} \cdot \text{g}^{-1} \text{ FW}$) but extremely low stomatal conductance ($G_s = 0.02 \text{ mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$). Severe stomatal closure restricts CO_2 diffusion into mesophyll cells, insufficient substrate for the Calvin cycle directly reduces net photosynthetic rate (P_n), even with strong light capture capacity from high chlorophyll. This represents a physiological trade-off of plants adapting to local high-light, semi-arid environments: high chlorophyll ensures light energy absorption, while partial stomatal closure reduces transpiration water loss to resist drought stress (Croce *et al.*, 2024).

P_n showed an extremely significant positive correlation with G_s and transpiration rate (T_r), demonstrating that stomatal status was the primary factor restricting photosynthetic carbon fixation of *M. spectabilis*. The standardized pruning and consistent leaf-fruit ratio (20:1) set in this study eliminated the interference of sink-source imbalance on photosynthetic measurement results, and continuous monitoring of temperature and light during the growing season guaranteed the reliability of physiological data.

Comprehensive germplasm utilization and field cultivation suggestions: Combining peel color, fruit morphology, nutritional quality and photosynthetic performance, the tested 5 varieties were divided into three utilization types: fresh-eating dual-purpose germplasm (*M. 'Gaozhi'*), processing functional germplasm (*M. 'Hongye'*, *M. 'Chuisi'*), balanced ornamental-fruit germplasm (*M. 'Xifu'*, *M. 'Wangzhu'*).

For practical horticultural production, the results of this study provide targeted recommendations for growers in the Yili River Valley: (1) For fresh-eating cultivation of *M. 'Gaozhi'*, moderate nitrogen topdressing and summer canopy thinning can balance fruit enlargement and nutrient accumulation; (2) For juice raw material planting of *M. 'Hongye'*, rational irrigation and potassium supplementation effectively raise soluble solid content and flavor quality; (3) For functional raw material production of *M. 'Chuisi'*, organic cultivation modes can further boost VC and flavonoid accumulation; (4) *M. 'Xifu'* and *M. 'Wangzhu'* are suitable for courtyard greening and landscape forest construction, with moderate pruning to maintain balanced comprehensive traits.

This study systematically clarified the trait differentiation rules of representative *M. spectabilis* varieties cultivated under standardized conditions in the Yili River Valley. It uncovered the physiological mechanisms of source-sink trade-off and stomatal limitation underlying trait correlations. These findings provide a theoretical basis for germplasm classification, breeding, and region-specific horticultural production.

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Data Availability: The data will be made available on request. Goeltz

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