

## METHOD FOR DETERMINING THE OPTIMAL HARVEST PERIOD OF LYCIUM BARBARUM L.

### 枸杞最佳采收周期判定方法

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#### ABSTRACT

To determine the optimal harvesting period for mechanized harvesting of *Lycium barbarum* L. (*L. barbarum*), fruits from different harvest batches within the same harvesting season were used as the experimental materials, and a comprehensive evaluation was conducted based on fresh-fruit ripeness and damage resistance. Fruit weight, fruit–pedicel detachment force, firmness, soluble solids content, color difference, moisture content, and damage rate were measured on different sampling dates in two consecutive harvest batches (HP<sub>1</sub> and HP<sub>2</sub>). Their variation patterns were analyzed, and a comprehensive evaluation model was established based on correlation analysis and principal component analysis to rank and optimize fruit quality across different sampling dates. The results showed that, with the progression of sampling dates, the ripeness of fresh *L. barbarum* fruit gradually increased, whereas damage resistance exhibited a stage-dependent variation pattern, and significant correlations were observed among the measured indicators. The dual-index weighted comprehensive evaluation indicated that the optimal harvesting period for both harvest batches was day 7, corresponding to an appropriate harvesting interval of 7 d. These results provide a theoretical basis for determining the harvesting period for mechanized *L. barbarum* harvesting.

#### 摘要

为明确适宜机械化采收的枸杞最佳采收周期, 本研究以同一采收季节内不同茬次的枸杞果实为试验对象, 围绕鲜果成熟度与抗损伤能力开展综合评价。通过测定连续两茬 (HP<sub>1</sub> 与 HP<sub>2</sub>) 不同采样日期果实的重量、果实-果柄结合力、硬度、糖度、色差值、含水率及损伤率等指标, 分析其变化规律, 并结合相关性分析和主成分分析构建综合评价模型, 对不同采样日期果实品质进行排序与优选。结果表明, 随着采样日期推进, 枸杞鲜果成熟度逐步提高, 而抗损伤能力呈阶段性变化特征, 不同指标间存在较显著的相关性。双指标加权综合评价结果表明, 两茬果实的最佳采收周期均为第7天, 即适宜采收间隔为7d, 为枸杞机械化采收周期的判定提供了理论依据。

#### INTRODUCTION

*L. barbarum* is an indeterminate inflorescence crop with continuous flowering and fruiting, and its fruit-bearing branches simultaneously bear ripe fruits, semi-ripe fruits, unripe fruits, flowers, and leaves (Kulczyński & Gramza-Michałowska, 2016; Yu et al., 2023; Liang et al., 2024). Therefore, multiple harvests are usually required during the ripening period. Fresh *L. barbarum* fruit is a berry-type fruit, and under ambient conditions without any postharvest treatment, the probability of mildew within three days after harvest can reach 50%–80% (Wan et al., 2020). As a result, drying is currently the dominant processing method for fresh *L. barbarum* fruit, accounting for more than 95% of production and processing practices (Chen et al., 2010). Harvesting is the final key step in *L. barbarum* field production, and its timing directly affects fruit quality and economic returns (Ma et al., 2022; Mei et al., 2024; Cao et al., 2024; Y. Liu et al., 2025). If harvesting is delayed, the fruit becomes overripe, the berry tissue softens, some nutritional and bioactive components decline, and the resistance of fresh fruit to mechanical damage decreases, making the fruit more susceptible to damage and adhesion during postharvest handling and drying, thereby reducing the quality of the final product (Cañete et al., 2015; Mineață et al., 2024). In contrast, if harvesting is carried out too early, the fruit is not fully mature and is characterized by smaller size, firmer flesh, and incomplete accumulation and transformation of internal nutrients, which not only reduces yield but also diminishes its marketability and economic value (Fan et al., 2019; Sun et al., 2023). Therefore, timely harvesting is an important prerequisite for obtaining high-quality *L. barbarum*, and research on the optimal harvesting period of *L. barbarum* is of great practical significance.

During fruit ripening, a series of complex physiological and biochemical changes occur. In addition to alterations in external appearance, the internal tissue structure and compositional profile are continuously adjusted, ultimately jointly affecting quality characteristics such as fruit firmness, flavor, and aroma (Mocan *et al.*, 2019; Rajkowska *et al.*, 2023). In recent years, considerable research has been conducted on the optimal harvesting period of fruits. These studies generally determine the optimal harvest time by measuring the contents of nutritional components and other quality-related indicators at different stages of fruit growth and development, and then evaluating overall fruit quality using statistical analysis methods (Giongo *et al.*, 2022; Zhou *et al.*, 2023; Liu D. *et al.*, 2024; Zhang *et al.*, 2025). Guevara-Terán *et al.* (2022) compared the chemical composition, antioxidant capacity, and antibacterial activity of wild Andean blueberries at different maturity stages, and found that bioactive compounds such as phenolics and anthocyanins changed continuously during ripening, indicating that these functional traits can serve as indicators of fruit maturity and quality. Hu *et al.* (2022) measured soluble sugar, titratable acid, sugar–acid ratio, total phenols, glucose, fructose, sucrose, oxalic acid, tartaric acid, quinic acid, and malic acid in Merlot and Marselan grapes at different harvest stages, and combined principal component analysis (PCA) with cluster analysis (CA) for comprehensive evaluation, thereby determining the optimal harvesting period for each cultivar. Poggioni *et al.* (2022) determined the appropriate harvest time for *L. barbarum* by comparing changes in polyphenols, carotenoids, flavonoids, and other components over two harvest seasons in combination with environmental and climatic factors. Fatchurrahman *et al.* (2022) characterized *L. barbarum* fruit at different ripening stages in terms of color, firmness, chemical composition, and metabolic behavior, and further analyzed its postharvest quality changes. Zhao *et al.* (2023) established a comprehensive quality evaluation model for blueberry wine based on multiple physicochemical indicators, including total sugars, organic acids, total esters, total phenols, anthocyanins, and color characteristics, combined with principal component analysis.

Although existing studies have provided important references for determining the optimal harvesting period of fruits, most have mainly focused on fresh-eating quality, nutritional composition, or postharvest storage characteristics, while relatively limited attention has been paid to fruit damage resistance under mechanized harvesting conditions and its coordinated variation with ripeness. Therefore, in this study, fruits from different harvest batches within the same harvesting season of *L. barbarum* were used as experimental materials. A comprehensive evaluation was conducted based on fresh-fruit ripeness and damage resistance, and statistical analysis methods were further applied to determine the optimal harvesting period suitable for mechanized harvesting.

## MATERIALS AND METHODS

### *Experimental conditions*

The experiments in this study were conducted at the *L. barbarum* planting base located in Guyuan City (106°15'25"E, 36°00'36"N), Ningxia Hui Autonomous Region, China. At this site, *L. barbarum* fruits typically enter the ripening stage in July each year, and the ripening period lasts for approximately one month, during which multiple harvest rounds are required. The base primarily focuses on the processing and marketing of dried *L. barbarum* products and has established a large-scale planting base, forming a relatively complete production chain encompassing "cultivation-harvesting-drying and processing". The base commonly adopts a double-layer trellis cultivation system with standardized field management, including regulated row and plant spacing. Moreover, mature standardized procedures are implemented for base management, harvest organization, and drying/processing, ensuring consistent field management throughout the experimental period and enabling continuous sample collection (Fig. 1).



Fig. 1 - *L. barbarum* cultivation base

### Experimental materials

The base cultivates a wide range of *L. barbarum* cultivars, mainly including “Ningqi No.1, 5, 6, 7” and 10, “Keqi No.1 and 2”, and “Ningnongqi”. Among them, Ningqi No.7 exhibits rapid growth and strong stress tolerance, enabling stable performance across diverse environments, particularly under unfavorable climatic conditions such as drought and cold. It also shows high resistance to diseases and pests, with a high proportion of premium-grade fruits and notable economic value. In addition, Ningqi No.7 produces relatively large fruits and is suitable for multiple utilization routes, including fresh consumption, drying, juice/pulp processing, and health-related products. Owing to its strong market adaptability and broad application prospects, this cultivar has been widely promoted and cultivated in major *L. barbarum* producing regions of China, including Ningxia, Gansu, Qinghai, and Xinjiang.

Therefore, field experiments were conducted in July 2023 using Ningqi No.7 plants aged 4-5 years. The orchard adopted a double-layer trellis cultivation system, with an agronomic row spacing of approximately 3 m and a plant spacing of approximately 1 m. The plants were cultivated in open fields and covered with bird-proof nets to reduce fruit damage caused by bird pecking.

### Experimental methods

#### Measurements and methods

Fruit weight was measured using a 8028 high-precision electronic balance (measurement range: 0-100 g; accuracy: 0.001 g; Shenzhen Diheng Electronics Co., Ltd., China); Fruit-pedicel detachment force and fruit firmness were determined using an SF-30 Aireup digital force gauge/hardness tester (measurement range: 0-30 N; accuracy: 0.01 N; Probe diameter: 3.5 mm, Zhejiang Aireup Instrument Co., Ltd., China); Color parameters were measured using an SR-64 portable spectrophotometer (aperture: 4 mm; repeatability:  $\leq 0.08 \Delta E^*ab$ ; 3nh Technology Co., Ltd., Guangdong, China). To characterize the relative red to yellow color variation of the fruit samples and to reduce the influence of illumination disturbances on a single chromatic component, the ratio of  $a^*$  to  $b^*$  ( $a^*/b^*$ ) was used in this study as a composite color indicator. Soluble solids content was measured using a BM-06S digital refractometer (measurement range: 0-55 °Brix; accuracy: 0.1%; Tianjin Liaowang Optoelectronics Technology Co., Ltd., China). Moisture content was determined using a 101-00BS constant-temperature forced-air drying oven (temperature control range: 10-300 °C; accuracy: 0.1 °C; Shaoxing Super Instrument Co., Ltd., China), and fruit damage rate was recorded accordingly.

#### Screening test for ripeness evaluation indicators of fresh *L. barbarum* fruit

To screen relevant indicators for determining the ripeness of fresh *L. barbarum* fruit, ten fruit-bearing branches were randomly selected during the peak fruiting stage. The selected branches were required to cover a relatively complete range of ripeness levels, with the ripeness distribution along the branch following the commonly observed pattern. Based on fruit surface color, samples were classified into four ripeness grades: red fruit (peak fruiting stage), red-yellow fruit (late yellowing stage), yellow-green fruit (early yellowing stage), and green fruit, as shown in Fig. 2.

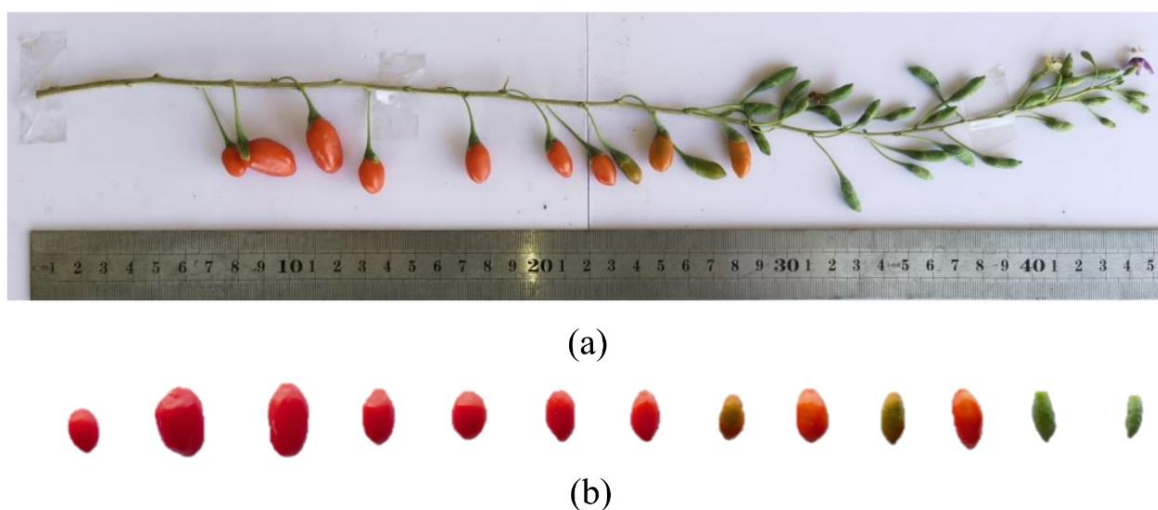


Fig. 2 - Schematic diagram of fruit maturity distribution on a fruit-bearing branch and sample grading

(a) Schematic diagram of sampling and distance measurement on a fruit-bearing branch;

(b) Fruit samples at different ripeness levels

For each branch, sampling was conducted sequentially along the branch axis. Taking the branch base as the zero-distance reference point, the spatial position (distance) and ripeness grade (red, red-yellow, yellow-green, and green) of each sampled fruit were recorded to establish a “position-ripeness-indicator” correspondence. Subsequently, each fruit sample was measured for weight, fruit-pedicle detachment force, firmness, soluble solids content (SSC), and color parameters. After data compilation, statistical analyses were performed to evaluate the correlations between each indicator and ripeness grade (or positional distance). Considering both correlation strength and the discriminative ability among ripeness grades, the indicators most suitable for ripeness determination of fresh *L. barbarum* fruit were selected.

#### **Optimal harvest period determination experiment**

The experimental site was the same as described above. During the July ripening season, *L. barbarum* typically requires four harvesting rounds. Considering that the first round occurs at the initiation of harvesting, when the spatial distribution of fruit ripeness along branches is often not yet stable, and that the final round is more susceptible to short-term meteorological fluctuations and late-season physiological decline of the plants, which increases the dispersion of fruit quality and damage outcomes, this study selected the adjacent second and third harvesting rounds as the experimental targets. Continuous full-cycle monitoring and measurements were conducted for these two rounds to determine the optimal harvest period, thereby improving representativeness while enhancing comparability and statistical robustness of the data.

Specifically, after completion of the first harvesting round and upon entering a stable harvesting stage, two consecutive stable rounds from July 5 to July 20, 2023 were selected. Sampling was performed once per day, and each round was monitored continuously for 8 days to cover the typical self-determined harvesting cycle adopted by local growers. The two harvesting periods were coded as follows: July 5-12 (second round, HP<sub>1</sub>) and July 13-20 (third round, HP<sub>2</sub>). The selected plots had consistent irrigation and fertilization conditions and were managed under identical field practices. During sampling, fresh fruits with the highest ripeness on that day were randomly collected, excluding fruits with rot, mildew, or obvious mechanical damage. All samples were collected by the same person between 09:00 and 10:00 each day to minimize operator- and time-related bias. For each indicator, 60 fresh fruits were measured.

#### **Data processing and analysis**

All experimental data were statistically analyzed using IBM SPSS Statistics 27.0. One way analysis of variance followed by Tukey's test was used to evaluate significant differences at ( $P < 0.05$ ). Pearson correlation analysis was performed to assess relationships among variables. Principal component analysis was applied to calculate ripeness scores for different sampling dates within the same harvesting period, and the comprehensive score was then obtained by combining the ripeness score with the resistance-to-damage score. Results are presented as mean  $\pm$  standard deviation.

## **RESULTS AND DISCUSSION**

### **Results of the screening test for ripeness evaluation indicators of fresh *L. barbarum* fruit**

Owing to the indeterminate inflorescence and continuous flowering-fruiting habit of *L. barbarum*, fruit ripeness on a single fruit-bearing branch typically shows a decreasing gradient from the upper to the lower part of the branch, sequentially presenting as red fruit, red-yellow fruit, yellow-green fruit, and green fruit. Considering that green fruit are relatively small and that some indicators are difficult to obtain reliably, the accuracy and repeatability of the measurements may be compromised. Therefore, this study focused on three ripeness grades: red fruit, red-yellow fruit, and yellow-green fruit, and measured their fruit weight, fruit-pedicle detachment force, firmness, soluble solids content (SSC), and color parameters.

Table 1 presents the fruit-by-fruit measurements along the branch axis for one representative fruit-bearing branch, providing a direct illustration of how each indicator varied with ripeness. Data from the remaining branches were used for subsequent statistical analyses and for screening ripeness evaluation indicators.

Table 1

Measurement results of fruit parameters at different ripeness levels on a fruit-bearing branch

No.	Ripeness	Distance [mm]	Weight [g]	Fruit-pedicel attachment force [N]	Firmness [ $10^5$ Pa]	SSC [ $^{\circ}$ Brix]	Color difference
1	Red fruit	66	0.416	0.60	2.85	17.1	1.33
2	Red fruit	78	1.798	0.28	2.28	17.7	1.47
3	Red fruit	96	1.452	0.59	2.06	16.6	1.50
4	Red fruit	132	0.678	0.69	2.01	16.0	1.42
5	Red fruit	160	0.641	0.87	2.57	16.1	1.39
6	Red fruit	185	0.548	0.21	3.67	14.7	1.36
7	Red fruit	202	0.477	0.90	3.06	13.6	1.38
8	Yellow-green fruit	217	0.319	1.85	5.59	/	0.18
9	Red-yellow fruit	233	0.602	1.34	4.14	/	0.79
10	Yellow-green fruit	251	0.319	1.78	7.74	/	0.32
11	Red-yellow fruit	259	0.501	1.21	4.02	/	0.65

The correlation analysis results are presented in Table 2. Fruit ripeness showed significant correlations with fruit weight, fruit–pedicel detachment force, firmness, and color parameters, indicating that these indicators can effectively reflect the physiological and visual changes associated with the ripening process. It should be noted that, for semi-ripe fruit (red-yellow and yellow-green), the determination of soluble solids content and moisture content was affected by insufficient juice yield and tissue heterogeneity, resulting in poor measurement stability. Therefore, the correlations between these two variables and fruit ripeness could not be reliably assessed based on the obtained data. Nevertheless, the commercial quality of dried *L. barbarum* is largely influenced by sugar accumulation, and total sugar content is an important internal quality basis of *L. barbarum* (Fatchurrahman et al., 2022). Accordingly, soluble solids content was retained as a key quality indicator for ripeness determination. In addition, moisture content directly affects drying efficiency and the texture of the dried product, and it is also an important parameter reflecting both fruit ripeness and processing suitability.

Considering both the correlation results and the requirements of dried-product processing, six indicators were ultimately selected in this study, including fruit weight, fruit-pedicel detachment force, soluble solids content, firmness, color parameters, and moisture content, to determine and comprehensively evaluate the ripeness of fresh *L. barbarum* fruit. On this basis, to meet the low-damage requirement of mechanized harvesting, fruit damage rate was further introduced to characterize resistance to mechanical injury and was used together with the comprehensive ripeness score for determining the optimal harvest period.

Table 2

Correlation between maturity indicator (distance) and evaluation indices

Correlation	Distance	Weight	Fruit-pedicel attachment force	Color difference	Firmness
Distance	1	-0.629*	0.731*	-0.747**	0.720*
Weight	-0.629*	1	-0.579	0.548	-0.564
Fruit-pedicel attachment force	0.731*	-0.579	1	-0.921**	0.807**
Color difference	-0.747**	0.548	-0.921**	1	-0.892**
firmness	0.720*	-0.564	0.807**	-0.892**	1

Note: \* indicates a significant correlation at  $P < 0.05$ ; \*\* indicates a highly significant correlation at  $P < 0.01$ .

### Results of the optimal harvest period determination experiment

#### Analysis of indicator variation patterns within the harvesting period

Fruit weight, fruit-pedicel detachment force, color parameters, soluble solids content, firmness, moisture content, and damage rate of fresh *L. barbarum* fruit were measured within the same harvesting period.

The results were summarized, and the mean values and standard deviations were calculated, as shown in Tables 3 and 4. Overall, although the absolute values of the indicators differed to some extent between the two harvesting periods (HP<sub>1</sub> and HP<sub>2</sub>), their general temporal trends were essentially consistent.

Within a single harvesting period from Day 1 to Day 8, fruit weight exhibited a monotonic increasing trend. The fruit expanded rapidly at the early stage, whereas the increment gradually decreased and became stable at the late stage. Fruit-pedicle detachment force decreased steadily, indicating a progressive weakening of the attachment tissue between the fruit and pedicle during ripening and, consequently, a reduced difficulty of fruit detachment. Color parameters showed an overall increasing trend with relatively smooth variation. The color change was faster at the early stage, and the rate of change decreased after entering the ripening stage. Soluble solids content increased steadily, suggesting continuous accumulation of soluble solids during ripening. Firmness generally declined, and the decrease accelerated from the middle stage before becoming relatively stable, reflecting the stage dependent characteristics of fruit softening. Moisture content fluctuated only slightly.

Although the difference between the beginning and end was limited, a slow increasing tendency was still observed. Damage rate increased over time and showed a more pronounced jump in the middle stage, indicating that, as the fruit further ripened and softened, its resistance to mechanical injury decreased and the risk of damage during mechanized harvesting increased significantly.

Table 3

Test results of various indicators for the first harvesting period (HP<sub>1</sub>)

No.	Fresh fruit ripeness						Damage rate [%]
	Weight [g]	Fruit-pedicle attachment force [N]	Color difference	SSC [°Brix]	Firmness [10 <sup>5</sup> Pa]	Moisture content [%]	
HP <sub>1-1</sub>	0.738±0.106 <sup>d</sup>	0.86±0.38 <sup>a</sup>	1.26±0.05 <sup>c</sup>	18.0±1.2 <sup>c</sup>	2.56±0.38 <sup>a</sup>	74.20±2.10 <sup>c</sup>	10.00±8.66 <sup>f</sup>
HP <sub>1-2</sub>	0.763±0.075 <sup>d</sup>	0.67±0.21 <sup>ab</sup>	1.27±0.09 <sup>c</sup>	18.3±0.9 <sup>bc</sup>	2.55±0.47 <sup>a</sup>	74.48±2.01 <sup>c</sup>	15.56±10.14 <sup>ef</sup>
HP <sub>1-3</sub>	0.827±0.096 <sup>d</sup>	0.60±0.14 <sup>b</sup>	1.29±0.05 <sup>bc</sup>	18.3±1.1 <sup>bc</sup>	2.41±0.45 <sup>ab</sup>	75.65±3.70 <sup>c</sup>	22.22±13.02 <sup>def</sup>
HP <sub>1-4</sub>	0.986±0.090 <sup>c</sup>	0.55±0.13 <sup>b</sup>	1.37±0.05 <sup>b</sup>	18.7±1.2 <sup>bc</sup>	2.21±0.38 <sup>bc</sup>	77.55±1.40 <sup>b</sup>	30.00±7.07 <sup>cde</sup>
HP <sub>1-5</sub>	1.064±0.119 <sup>bc</sup>	0.52±0.12 <sup>b</sup>	1.46±0.09 <sup>a</sup>	18.7±1.0 <sup>bc</sup>	2.19±0.37 <sup>bc</sup>	77.59±3.19 <sup>b</sup>	36.67±10.14 <sup>bcd</sup>
HP <sub>1-6</sub>	1.079±0.120 <sup>bc</sup>	0.51±0.09 <sup>b</sup>	1.48±0.05 <sup>a</sup>	19.0±1.4 <sup>b</sup>	2.16±0.35 <sup>c</sup>	77.62±1.24 <sup>b</sup>	38.89±8.82 <sup>bc</sup>
HP <sub>1-7</sub>	1.097±0.128 <sup>b</sup>	0.49±0.12 <sup>b</sup>	1.49±0.03 <sup>a</sup>	20.2±1.9 <sup>a</sup>	2.09±0.37 <sup>c</sup>	77.75±0.80 <sup>b</sup>	45.56±13.23 <sup>b</sup>
HP <sub>1-8</sub>	1.202±0.132 <sup>a</sup>	0.46±0.09 <sup>b</sup>	1.54±0.04 <sup>a</sup>	21.0±1.6 <sup>a</sup>	2.08±0.33 <sup>c</sup>	79.72±1.09 <sup>a</sup>	61.11±10.93 <sup>a</sup>

Note: Lowercase letters (a, b, c, etc.) indicate significant differences among different sampling dates for the same indicator ( $P < 0.05$ ). The same below.

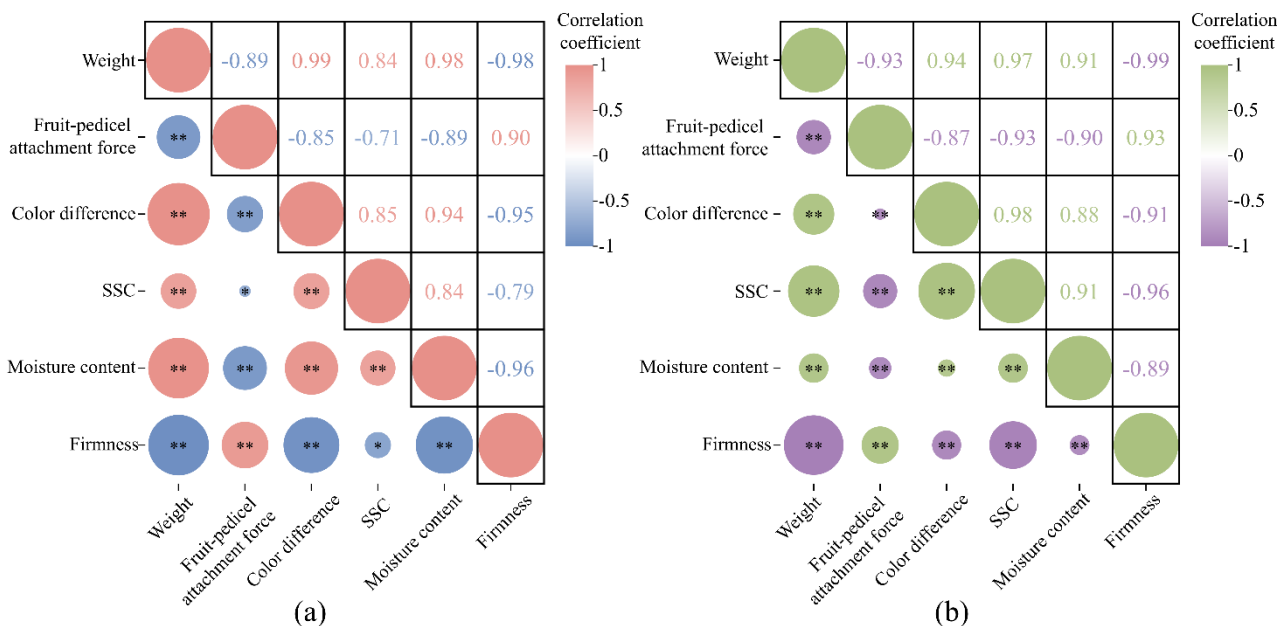
Table 4

Test results of various indicators for the first harvesting period (HP<sub>2</sub>)

No.	Fresh fruit ripeness						Damage rate [%]
	Weight [g]	Fruit-pedicle attachment force [N]	Color difference	SSC [°Brix]	Firmness [10 <sup>5</sup> Pa]	Moisture content [%]	
HP <sub>2-1</sub>	0.557±0.068 <sup>d</sup>	0.81±0.14 <sup>d</sup>	1.26±0.09 <sup>c</sup>	14.1±1.4 <sup>f</sup>	3.25±0.47 <sup>c</sup>	76.44±1.17 <sup>c</sup>	23.33±12.25 <sup>c</sup>
HP <sub>2-2</sub>	0.777±0.091 <sup>bcd</sup>	0.71±0.18 <sup>d</sup>	1.29±0.06 <sup>c</sup>	15.5±1.3 <sup>e</sup>	2.83±0.40 <sup>c</sup>	77.76±1.73 <sup>abc</sup>	38.89±9.28 <sup>bc</sup>
HP <sub>2-3</sub>	0.831±0.117 <sup>bc</sup>	0.70±0.13 <sup>cd</sup>	1.40±0.18 <sup>b</sup>	18.3±1.3 <sup>d</sup>	2.81±0.38 <sup>c</sup>	77.99±2.21 <sup>abc</sup>	40.00±11.18 <sup>bc</sup>
HP <sub>2-4</sub>	0.960±0.116 <sup>abc</sup>	0.68±0.11 <sup>bc</sup>	1.41±0.05 <sup>b</sup>	19.1±1.2 <sup>cd</sup>	2.42±0.49 <sup>c</sup>	78.58±1.00 <sup>bc</sup>	42.22±10.93 <sup>ab</sup>
HP <sub>2-5</sub>	0.972±0.149 <sup>abc</sup>	0.64±0.11 <sup>b</sup>	1.41±0.06 <sup>b</sup>	20.3±1.4 <sup>bc</sup>	2.33±0.45 <sup>c</sup>	78.71±2.21 <sup>ab</sup>	44.44±12.36 <sup>ab</sup>
HP <sub>2-6</sub>	0.986±0.114 <sup>ab</sup>	0.56±0.13 <sup>b</sup>	1.43±0.07 <sup>b</sup>	20.4±1.4 <sup>bc</sup>	2.28±0.41 <sup>b</sup>	78.98±1.41 <sup>ab</sup>	45.56±15.90 <sup>ab</sup>
HP <sub>2-7</sub>	1.029±0.128 <sup>ab</sup>	0.53±0.09 <sup>b</sup>	1.43±0.04 <sup>b</sup>	21.0±1.7 <sup>b</sup>	2.24±0.42 <sup>b</sup>	79.18±0.68 <sup>ab</sup>	47.78±10.93 <sup>ab</sup>
HP <sub>2-8</sub>	1.099±0.129 <sup>a</sup>	0.52±0.10 <sup>a</sup>	1.48±0.07 <sup>a</sup>	22.5±2.2 <sup>a</sup>	2.22±0.41 <sup>a</sup>	79.48±1.06 <sup>a</sup>	58.89±10.54 <sup>a</sup>

**Determination of the optimal harvest period based on principal component analysis**

After standardization of the ripeness related indicator data of fresh *L. barbarum* fruit, correlation analysis was first performed on six ripeness related evaluation indicators, including fruit weight, fruit–pedicel detachment force, color parameters, soluble solids content, moisture content, and firmness, and the correlation matrix among these indicators was constructed, as shown in Fig. 3.



**Fig. 3 - Correlation analysis among evaluation indices across different harvesting cycles**  
(a) HP<sub>1</sub>; (b) HP<sub>2</sub>

On this basis, principal component analysis was performed separately for the two harvesting periods (HP<sub>1</sub> and HP<sub>2</sub>), and the extracted principal components are summarized in Table 5. The results showed that, for both harvesting periods, retaining only the first principal component was sufficient to capture the dominant information characterizing the ripening process, whereas the remaining components contributed little and mainly reflected minor fluctuations and random errors. Specifically, the eigenvalues of the first principal component for HP<sub>1</sub> and HP<sub>2</sub> were both greater than 1, with values of 5.465 and 5.730, respectively. The corresponding variance contribution rates were 91.089% and 95.500%, and the cumulative variance explained in both cases exceeded 90%. Therefore, the score of the first principal component was subsequently used as the comprehensive ripeness score of fresh *L. barbarum* fruit.

**Table 5**

**Principal component analysis of fresh-fruit ripeness across different harvesting periods**

Harvesting period	Principal component	Eigenvalue	Variance contribution rate [%]	Cumulative variance contribution rate [%]
HP <sub>1</sub>	1	5.465	91.089	91.089
HP <sub>1</sub>	2	0.306	5.102	96.191
HP <sub>1</sub>	3	0.144	2.399	98.590
HP <sub>2</sub>	1	5.730	95.500	95.500
HP <sub>2</sub>	2	0.151	2.512	98.012
HP <sub>2</sub>	3	0.090	1.504	99.516

Based on the principal component loading matrix, the scoring functions of the first principal component were further established for the two harvesting periods. These functions were used to calculate the daily comprehensive ripeness scores of fresh *L. barbarum* fruit, as given in Eqs. (1) and (2). In the scoring functions, the coefficients for fruit weight, color parameters, soluble solids content, and moisture content were positive, whereas those for fruit-pedicel detachment force and firmness were negative. This reflects the coupled changes occurring during ripening, namely quality accumulation accompanied by tissue softening and a reduction in detachment force.

$$Y_{HP_1} = 0.425x_1 - 0.392x_2 + 0.417x_3 + 0.376x_4 + 0.420x_5 - 0.418x_6 \tag{1}$$

$$Y_{HP_2} = 0.414x_1 - 0.399x_2 + 0.401x_3 + 0.412x_4 + 0.415x_5 - 0.409x_6 \tag{2}$$

where:  $x_1$  denotes fruit weight;  $x_2$  denotes fruit–pedicel detachment force;  $x_3$  denotes the color index ( $a^*/b^*$ );  $x_4$  denotes soluble solids content;  $x_5$  denotes moisture content; and  $x_6$  denotes firmness.

To facilitate intuitive comparison and ranking among different sampling dates, the comprehensive ripeness score  $Y$  was calculated for each harvesting period, and then normalized to obtain a dimensionless score  $Y'$ . Based on the normalized scores, the ripeness scores of all sampling dates were ranked, as shown in Tables 6 and 7.

**Table 6**

**Fresh-fruit maturity scores and rankings for the first harvesting period (HP<sub>1</sub>)**

No.	Fresh fruit ripeness score $Y$	Normalized score $Y'$	Rank
HP <sub>1-1</sub>	-3.46	0.00	8
HP <sub>1-2</sub>	-2.59	0.13	7
HP <sub>1-3</sub>	-1.59	0.28	6
HP <sub>1-4</sub>	0.24	0.55	5
HP <sub>1-5</sub>	0.91	0.65	4
HP <sub>1-6</sub>	1.23	0.70	3
HP <sub>1-7</sub>	1.99	0.81	2
HP <sub>1-8</sub>	3.28	1.00	1

**Table 7**

**Fresh-fruit maturity scores and rankings for the second harvesting period (HP<sub>2</sub>)**

No.	Fresh fruit ripeness score $Y$	Normalized score $Y'$	Rank
HP <sub>2-1</sub>	-4.46	0.00	8
HP <sub>2-2</sub>	-2.16	0.32	7
HP <sub>2-3</sub>	-0.87	0.50	6
HP <sub>2-4</sub>	0.36	0.66	5
HP <sub>2-5</sub>	0.87	0.74	4
HP <sub>2-6</sub>	1.51	0.82	3
HP <sub>2-7</sub>	1.95	0.88	2
HP <sub>2-8</sub>	2.79	1.00	1

After obtaining the ripeness scores of fresh *L. barbarum* fruit for each sampling date within the two harvesting periods, using ripeness alone as the criterion was insufficient to meet the quality requirements of mechanized harvesting. Fresh *L. barbarum* fruit has tender tissues and is prone to mechanical damage, such as compression and impact, during mechanized harvesting. Once damaged, juice leakage may occur, leading to fruit adhesion, and oily fruits may form after drying. This markedly deteriorates the quality of dried products and reduces their economic value. Therefore, fruit resistance to mechanical injury was incorporated into the evaluation system. An anti-damage score  $S$  was used to represent the ability of fruit to withstand mechanical damage, where  $S = 1 - \text{damage rate}$ . A larger  $S$  indicates stronger resistance to mechanical injury.

Considering both ripeness level and resistance to mechanical injury, a weighted comprehensive evaluation model was established, as shown in Eq. (3).

$$F = \omega_1 Y' + \omega_2 S \tag{3}$$

where:  $\omega_1$  and  $\omega_2$  denote the weights of the ripeness score and the resistance-to-damage indicator, respectively.

Considering that mechanical damage to fresh fruit can lead to the formation of oily fruits after drying and thus causes a greater deterioration in dried-product quality, a higher weight was assigned to resistance to mechanical injury in this study, namely  $\omega_1 = 0.4$  and  $\omega_2 = 0.6$ .

By assigning different weights to the two indicators, the comprehensive score  $F$  for each sampling date within the two harvesting periods was calculated and ranked.

The date corresponding to the maximum  $F$  was identified as the optimal harvest period. The statistical results are shown in Tables 8 and 9. The results indicate that the optimal harvest dates in both periods were separated by 7 days, enabling improved dried-product processing quality while balancing ripeness development and control of damage risk.

Table 8

Comprehensive score and ranking for the first harvesting period (HP<sub>1</sub>)

No.	Fresh fruit ripeness score $Y'$	Anti-damage capability score $S$	Comprehensive score $F$	Rank
HP <sub>1-1</sub>	0.00	0.900	0.540	8
HP <sub>1-2</sub>	0.13	0.844	0.558	7
HP <sub>1-3</sub>	0.28	0.778	0.578	6
HP <sub>1-4</sub>	0.55	0.700	0.640	4
HP <sub>1-5</sub>	0.65	0.633	0.640	3
HP <sub>1-6</sub>	0.70	0.611	0.645	2
HP <sub>1-7</sub>	0.81	0.544	0.650	1
HP <sub>1-8</sub>	1.00	0.389	0.633	5

Table 9

Comprehensive score and ranking for the second harvesting period (HP<sub>2</sub>)

No.	Fresh fruit ripeness score $Y'$	Anti-damage capability score $S$	Comprehensive score $F$	Rank
HP <sub>2-1</sub>	0.00	0.767	0.460	8
HP <sub>2-2</sub>	0.32	0.611	0.493	7
HP <sub>2-3</sub>	0.50	0.600	0.558	6
HP <sub>2-4</sub>	0.66	0.580	0.614	5
HP <sub>2-5</sub>	0.74	0.556	0.628	4
HP <sub>2-6</sub>	0.82	0.544	0.656	2
HP <sub>2-7</sub>	0.88	0.522	0.667	1
HP <sub>2-8</sub>	1.00	0.411	0.647	3

## CONCLUSIONS

To obtain improved dried-product processing quality of *L. barbarum*, this study used fruits from different harvesting rounds within the same harvesting season as experimental materials. A comprehensive evaluation was conducted by integrating fruit ripeness and resistance to mechanical injury, and an appropriate optimal harvest period for mechanized harvesting was determined using statistical analysis methods. The main conclusions are as follows.

(1) By classifying the ripeness distribution grades of fruits along fruit-bearing branches, significant correlations were confirmed between ripeness (position) and fruit weight, fruit-pedicle detachment force, firmness, and color parameters. Considering the quality requirements of dried-product processing, six indicators, namely fruit weight, fruit-pedicle detachment force, soluble solids content, firmness, color parameters, and moisture content, were ultimately selected as the indicators for ripeness determination and comprehensive evaluation of fresh *L. barbarum* fruit.

(2) Fruit weight, fruit–pedicel detachment force, color parameters, soluble solids content, firmness, moisture content, and damage rate were continuously measured across two adjacent harvesting periods (HP<sub>1</sub> and HP<sub>2</sub>). The results showed that, although the absolute levels of these indicators differed to some extent between the two harvesting periods, their overall temporal trends were essentially consistent. Fruit weight, color parameters, soluble solids content, and moisture content showed significant positive correlations with ripening, whereas fruit–pedicel detachment force and firmness showed significant negative correlations. These patterns reflect the coupled changes during ripening characterized by “quality accumulation, tissue softening, and reduced detachment force”.

(3) On this basis, principal component analysis was applied to the six ripeness-related indicators across different sampling dates within each harvesting period to obtain normalized ripeness scores. The resistance-to-damage score, defined as 1 - damage rate, was then introduced to establish a two-indicator weighted comprehensive evaluation model. Comprehensive scores were calculated and ranked for each date, and the date with the highest score was identified as the optimal harvest period. The results showed that the optimal harvesting period for both harvest batches was day 7, indicating that the appropriate harvesting interval was 7 days. At this stage, a better quality of dried *L. barbarum* products could be obtained while balancing fruit ripeness improvement and damage risk control.

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## REFERENCES

- [1] Cao, Y., Chen, Y., Li, Y., Li, C., Lin, S., Lee, B., Hsieh, C.-L., Hsiao, Y., Fan, Y.-F., Luo, Q., Zhao, J., Yin, Y., An, W., Shi, Z., Chow, C., Chang, W., Huang, C., Chang, W., Liu, Z., Tsai, W. (2024). Wolfberry genome database: Integrated genomic datasets for studying molecular biology. *Frontiers in Plant Science*, 15, 1310346. <https://doi.org/10.3389/fpls.2024.1310346>
- [2] Cañete, M. L., Hueso, J. J., Pinillos, V., & Cuevas, J. (2015). Ripening degree at harvest affects bruising susceptibility and fruit sensorial traits of loquat (*Eriobotrya japonica* Lindl.). *Scientia Horticulturae*, 187, 102-107. <https://doi.org/10.1016/j.scienta.2015.03.008>
- [3] Chen Z., Zhang S., Niu L., & Wei Y. (2010). Study on drying aids for processing *Lycium barbarum* powder by spray drying (喷雾干燥枸杞粉助干剂研究). *Science and Technology of Food Industry*, 31(2), 80-82. <https://doi.org/10.13386/j.issn1002-0306.2010.02.043>
- [4] Fan, X.-J., Zhang, B., Yan, H., Feng, J.-T., Ma, Z.-Q., & Zhang, X. (2019). Effect of lotus leaf extract incorporated composite coating on the postharvest quality of fresh goji (*Lycium barbarum* L.) fruit. *Postharvest Biology and Technology*, 148, 132-140. <https://doi.org/10.1016/j.postharvbio.2018.10.020>
- [5] Fatchurrahman, D., Amodio, M. L., Valeria De Chiara, M. L., Mastrandrea, L., & Colelli, G. (2022). Characterization and postharvest behavior of goji berry (*Lycium barbarum* L.) during ripening. *Postharvest Biology and Technology*, 191, 111975. <https://doi.org/10.1016/j.postharvbio.2022.111975>
- [6] Giongo, L., Ajelli, M., Pottorff, M., Perkins-Veazie, P., & Iorizzo, M. (2022). Comparative multi-parameters approach to dissect texture subcomponents of highbush blueberry cultivars at harvest and postharvest. *Postharvest Biology and Technology*, 183, 111696. <https://doi.org/10.1016/j.postharvbio.2021.111696>
- [7] Guevara-Terán, M., Padilla-Arias, K., Beltrán-Novoa, A., González-Paramás, A. M., Giampieri, F., Battino, M., Vásquez-Castillo, W., Fernandez-Soto, P., Tejera, E., & Alvarez-Suarez, J. M. (2022). Influence of Altitudes and Development Stages on the Chemical Composition, Antioxidant, and Antimicrobial Capacity of the Wild Andean Blueberry (*Vaccinium floribundum* Kunth). *Molecules*, 27(21), 7525. <https://doi.org/10.3390/molecules27217525>
- [8] Hu J., Mao J., Li Y., Ma W., & Ma Z. (2022). Determination of the optimal harvest time of Merlot and Marselan in Wuwei Region of Hexi Corridor (河西走廊武威产区美乐和马瑟兰葡萄果实最佳采收期的确定). *Journal of Gansu Agricultural University*, 57(5), 103-117. <https://doi.org/10.13432/j.cnki.jgsau.2022.05.013>
- [9] Kulczyński, B., & Gramza-Michałowska, A. (2016). Goji Berry (*Lycium barbarum*): Composition and Health Effects – a Review. *Polish Journal of Food and Nutrition Sciences*, 66(2), 67-75.

<https://doi.org/10.1515/pjfn-2015-0040>

- [10] Liang, X., An, W., Li, Y., Qin, X., Zhao, J., & Su, S. (2024). Effects of different nitrogen application rates and picking batches on the nutritional components of *Lycium barbarum* L. fruits. *Frontiers in Plant Science*, 15, 1355832. <https://doi.org/10.3389/fpls.2024.1355832>
- [11] Liu, D., Yuan, M., Wang, Y., Zhang, L., Yao, W., & Feng, M. (2024). Integrated metabolome and transcriptome analysis of differences in quality of ripe *Lycium barbarum* L. fruits harvested at different periods. *BMC Plant Biology*, 24(1), 82. <https://doi.org/10.1186/s12870-024-04751-z>
- [12] Liu, Y., Liu, J., Zhao, J., Wang, F., Zhang, H., Su, X., Sun, Y., Liu, J., & Zhao, D. (2025). Effects of Different Excitation Parameters on Mechanized Harvesting Performance and Postharvest Quality of First-Crop Organic Goji Berries in Saline–Alkali Land. *Agriculture*, 15(13), 1377. <https://doi.org/10.3390/agriculture15131377>
- [13] Ma, R., Zhang, X., Ni, Z., Thakur, K., Wang, W., Yan, Y., Cao, Y., Zhang, J., Rengasamy, K. R. R., & Wei, Z. (2022). *Lycium barbarum* (Goji) as functional food: A review of its nutrition, phytochemical structure, biological features, and food industry prospects. *Critical Reviews in Food Science and Nutrition*, 63(30), 10621-10635. <https://doi.org/10.1080/10408398.2022.2078788>
- [14] Mei, S., Wang, J., Song, Z., Tang, D., & Shen, C. (2024). Mechanism and experimental study on the fruit detachment of Chinese wolfberry through reciprocating vibration. *International Journal of Agricultural and Biological Engineering*, 17(2), 47-58. <https://doi.org/10.25165/j.ijabe.20241702.8482>
- [15] Mineață, I., Murariu, O. C., Sîrbu, S., Tallarita, A. V., Caruso, G., & Jităreanu, C. D. (2024). Effects of Ripening Phase and Cultivar under Sustainable Management on Fruit Quality and Antioxidants of Sweet Cherry. *Horticulturae*, 10(7), 720. <https://doi.org/10.3390/horticulturae10070720>
- [16] Mocan, A., Cairone, F., Locatelli, M., Cacciagrano, F., Carradori, S., Vodnar, D. C., Crișan, G., Simonetti, G., & Cesa, S. (2019). Polyphenols from *Lycium barbarum* (Goji) Fruit European Cultivars at Different Maturation Steps: Extraction, HPLC-DAD Analyses, and Biological Evaluation. *Antioxidants*, 8(11), 562. <https://doi.org/10.3390/antiox8110562>
- [17] Poggioni, L., Romi, M., Guarnieri, M., Cai, G., & Cantini, C. (2022). Nutraceutical profile of goji (*Lycium barbarum* L.) berries in relation to environmental conditions and harvesting period. *Food Bioscience*, 49, 101954. <https://doi.org/10.1016/j.fbio.2022.101954>
- [18] Rajkowska, K., Otlewska, A., Broncel, N., & Kunicka-Styczyńska, A. (2023). Microbial Diversity and Bioactive Compounds in Dried *Lycium barbarum* Fruits (Goji): A Comparative Study. *Molecules*, 28(10), 4058. <https://doi.org/10.3390/molecules28104058>
- [19] Sun M., Ju H., Jiang H., Yuan W., & Zhou H. (2023). Research progress of nondestructive detection technology in fruit maturity. *Food and Fermentation Industries*, 49(17), 354-362. <https://doi.org/10.13995/j.cnki.11-1802/ts.033166>
- [20] Wan F., Li W., Luo Y., Wei B., & Huang X. (2020). Effects of ultrasonic pretreatment on far infrared vacuum drying properties and quality of *Lycium barbarum* (超声预处理对枸杞远红外真空干燥特性及品质的影响). *Chinese Traditional and Herbal Drugs*, 51(18), 4654-4663. <https://doi.org/10.7501/j.issn.0253-2670.2020.18.008>
- [21] Yu, J., Yan, Y., Zhang, L., Mi, J., Yu, L., Zhang, F., Lu, L., Luo, Q., Li, X., Zhou, X., & Cao, Y. (2023). A comprehensive review of goji berry processing and utilization. *Food Science & Nutrition*, 11(12), 7445-7457. <https://doi.org/10.1002/fsn3.3677>
- [22] Zhang, Q., Zang, H., Guo, X., Li, S., Xin, X., & Li, Y. (2025). A systematic study on composition and antioxidant of 6 varieties of highbush blueberries by 3 soil matrixes in China. *Food Chemistry*, 472, 142974. <https://doi.org/10.1016/j.foodchem.2025.142974>
- [23] Zhao, Y., Zeng, Y., Li, X., Yuan, K., Li, Y., Tian, L., Sun, J., & Bai, W. (2023). Modeling and application of sensory evaluation of blueberry wine based on principal component analysis. *Current Research in Food Science*, 6, 100403. <https://doi.org/10.1016/j.crfs.2022.11.022>
- [24] Zhou, Y., Wang, D., Duan, H., Zhou, S., Guo, J., & Yan, W. (2023). Detection and analysis of volatile flavor compounds in different varieties and origins of goji berries using HS-GC-IMS. *LWT*, 187, 115322. <https://doi.org/10.1016/j.lwt.2023.115322>