

## Research Insight

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## Variation in Fruit Quality Traits of Peach (*Prunus persica*) Under Different Cultivation Conditions and Its Evaluation Methods

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Received: 5 Mar., 2026

Accepted: 31 Mar., 2026

Published: 20 Apr., 2026

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**Preferred citation for this article:**Chen Y., and Zhang J., 2026, Variation in fruit quality traits of peach (*Prunus persica*) under different cultivation conditions and its evaluation methods, Plant Gene and Trait, 17(2): 92-111 (doi: [10.5376/pgt.2026.17.0007](https://doi.org/10.5376/pgt.2026.17.0007))

**Abstract** This study summarizes the composition, variation patterns, and evaluation methods of fruit quality traits in peach (*Prunus persica*) under different cultivation conditions. Peach fruit quality is multidimensional, encompassing external, internal, and nutritional attributes, among which sugar-acid composition, texture, and aroma are key determinants of eating quality. Environmental factors (light, temperature, and water) and cultivation practices (fertilization, pruning, crop load regulation, etc.) significantly regulate fruit quality by influencing metabolic processes and interacting with genotype. In terms of evaluation methods, traditional physicochemical and sensory assessments remain fundamental, while modern chromatographic, spectroscopic, and non-destructive techniques (e.g., Vis/NIR and hyperspectral imaging) enable rapid and accurate quality evaluation. Meanwhile, multi-index comprehensive evaluation models (such as PCA and AHP) improve the scientific robustness and practical applicability of quality assessment. Future research should focus on integrating multi-omics and intelligent detection technologies, promoting standardized evaluation systems and precision regulation to achieve stable improvement of peach fruit quality.

**Keywords** *Prunus persica*; Fruit quality; Cultivation conditions; Non-destructive detection; Comprehensive evaluation

### 1 Introduction

Peach (*Prunus persica*) is one of the most widely cultivated temperate fruit trees worldwide, characterized by early ripening, desirable flavor, rich nutritional value, and high economic importance. It plays a significant role in both fresh consumption and processing markets. In China, the peach industry contributes substantially to agricultural structural optimization, regional brand development, and farmers' income growth. With rising living standards and shifts in consumption patterns, market demand has gradually transitioned from a focus on yield to a model emphasizing "high quality, safety, and distinctiveness." However, in some high-yield regions, per capita consumption has declined, mainly due to unstable eating quality and generally low fruit quality, such as insufficient sweetness, weak flavor, and suboptimal ripening characteristics. Therefore, improving and stabilizing peach fruit quality under diverse environments and production systems has become a key issue for industry development (Mosie et al., 2025).

Peach fruit quality is multidimensional and integrative, typically encompassing external, internal, and nutritional attributes. External quality mainly includes fruit shape, size, color, and uniformity, which directly influence consumer purchasing decisions. Internal quality involves flesh texture, firmness, soluble solids content (SSC), titratable acidity (TA), sugar-acid ratio, and volatile aroma compounds, which are the core determinants of taste and flavor; among these, SSC, TA, and their ratio are key indicators of sweetness-acidity balance. Nutritional quality is reflected by the content of functional components such as vitamin C, polyphenols, carotenoids, and mineral elements, which are associated with antioxidant capacity and overall health benefits (Mosie et al., 2025). In addition, with the advancement of evaluation systems, attributes such as storability, resistance to internal disorders, and transport tolerance have gradually been incorporated into quality assessment frameworks.

The formation of peach fruit quality is jointly regulated by genetic factors and environmental conditions, among which cultivation conditions represent important controllable factors. Environmental variables such as light, temperature, water availability, soil properties, and nutrient status influence photosynthesis and metabolic

processes, thereby regulating the accumulation of sugars, organic acids, and aroma compounds (Shin et al., 2023; Zhen et al., 2025). Meanwhile, management practices—including cultivar selection, pruning methods, crop load regulation, irrigation and fertilization, and protected cultivation—also significantly affect fruit quality. However, complex interactions among genotype, environment, and management (“G × E × M”) result in substantial variation in quality expression under different conditions, while existing studies largely focus on single factors, lacking systematic investigation. At the same time, quality evaluation methods are evolving from traditional physicochemical indices toward multi-index integration and non-destructive detection. Technologies such as visible–near infrared (Vis/NIR) spectroscopy and multivariate models provide new tools for rapid quality assessment (Mosie et al., 2025), supporting the development of standardized evaluation systems and high-quality production.

This study focuses on peach fruit quality traits under different cultivation conditions, aiming to elucidate their components and variation patterns, with particular emphasis on the mechanisms by which environmental factors and horticultural practices influence quality formation. Furthermore, it summarizes current methods for evaluating fruit quality and maturity, and explores the application potential of multi-index comprehensive evaluation and non-destructive detection technologies in peach quality research, production regulation, and postharvest grading. By integrating agronomic, physiological, and analytical perspectives, this study seeks to provide a theoretical basis and technical support for optimizing peach cultivation, improving quality stability, and promoting the high-quality development of the peach industry.

## 2 Types of Peach Fruit Quality Traits

### 2.1 External quality

External quality is the primary basis for consumers to evaluate the commercial value of peaches, directly influencing market acceptance, grading outcomes, and price. For fresh peaches, attributes such as fruit size, shape, color, surface integrity, and firmness at purchase are the first perceived quality cues and are therefore key indicators in commercial grading and distribution. Fruit shape is an important component of external quality, commonly including round, flat-round, oblong, and flat (donut) types. Significant differences in shape index (length/width ratio) are observed among cultivars and cultivation conditions (Figure 1). Studies have shown that different peach types, such as peaches, nectarines, and flat peaches, vary greatly in morphological traits including length, width, thickness, and geometric mean diameter. These differences affect not only visual uniformity and packaging suitability but also their suitability for fresh consumption or processing (Wang et al., 2023). Generally, fruits with regular shape, balanced development, and high uniformity are considered high-quality products, whereas irregular or inconsistent fruits reduce commercial grade and market value (Petruccelli et al., 2023).

Fruit color is another key external attribute affecting consumer preference. Peach skin and flesh colors typically range from white and yellow to varying degrees of red blush, mainly determined by the accumulation of anthocyanins, carotenoids, and other pigments. In recent years, CIELAB color parameters such as  $L^*$ ,  $a^*$ ,  $b^*$ , hue angle ( $h^\circ$ ), and chroma (C) have been widely used to quantify color characteristics (Masuda et al., 2023; Petruccelli et al., 2023). Anthocyanins are closely associated with red skin coverage, while carotenoids contribute to yellow flesh and background color. Light conditions play a critical role in color development, with sufficient light promoting anthocyanin synthesis and uniform coloration. Conversely, practices such as fruit bagging alter light exposure and significantly affect color expression. It is important to note that although a high proportion of red coloration enhances visual appeal, its correlation with eating quality or internal flavor is not always significant, indicating limitations in evaluating quality based solely on appearance (Masuda et al., 2023).

Fruit size is another important indicator of commercial value, typically expressed as fruit weight, diameter, or volume. It is influenced by both genetic traits and cultivation factors such as crop load, water and nutrient supply, and tree resource allocation. Studies have shown that reducing crop load can significantly increase fruit weight, size, and coloration, but may reduce firmness at harvest, reflecting a trade-off between improved appearance and texture retention (Wang et al., 2023). Therefore, production should not focus solely on large fruit size but instead balance shape uniformity, coloration, firmness, and internal quality. Although firmness is often classified as an

internal quality trait, it is also an important visual cue during purchase. Mechanical firmness measurements are now commonly included in external quality evaluation to distinguish fruit maturity stages such as “ready to buy” and “ready to eat” (Masuda et al., 2023).



Figure 1 External appearance and visual quality traits of peach fruit

## 2.2 Internal quality

Internal quality is the core determinant of peach eating quality and consumer satisfaction. Compared with external traits, it more directly determines whether the fruit is perceived as palatable and is a key factor influencing repeat purchases. Sugar-acid composition forms the chemical basis of peach flavor. Soluble sugars in peaches mainly include sucrose, glucose, fructose, and sorbitol, with sucrose typically accounting for 75%-88% of total sugars. Organic acids are dominated by malic acid, with contributions from other acids such as citric acid varying among cultivars (Wang et al., 2023). Soluble solids content (SSC) is commonly used as an indicator of sweetness, while titratable acidity (TA) reflects sourness; their ratio provides a more comprehensive measure of flavor balance (Petruccioli et al., 2023). Studies indicate that reducing crop load can increase SSC, total sugar, and sugar-acid ratio, thereby enhancing sweetness and overall flavor intensity (Zhang et al., 2020). Thus, the sugar-acid ratio is often a better predictor of consumer preference than sugar or acid alone.

Texture is another critical component of internal quality, including firmness, juiciness, crispness, mealiness, fibrousness, and melting/non-melting characteristics. Texture development is closely related to cell wall structure, pectin metabolism, and fruit softening during ripening. As fruit matures, cell walls degrade and pectin solubilization increases, leading to reduced firmness and changes in texture. Research indicates that firmness is not only a physical parameter but also closely associated with sensory perceptions such as sourness, green notes, and overripe flavors, making it an important indicator of maturity and overall quality (Masuda et al., 2023). Cultivation factors such as water supply, harvest timing, and crop load significantly influence texture; for example, moderate water stress helps maintain firmness, whereas excessive irrigation can lead to soft flesh and reduced storability.

Flavor quality results from the combined effects of sugar-acid balance, texture, and volatile aroma compounds. Peaches contain a wide range of volatile organic compounds (VOCs), including lactones, aldehydes, esters, and alcohols. Key compounds such as hexyl hexanoate and  $\gamma$ -decalactone contribute to characteristic fruity, floral, and sweet aromas. These aroma compounds, together with sugar and acid composition, shape the overall flavor profile. Sensory studies have shown that fruits with moderate size, higher SSC/TA ratio, strong aroma, and balanced texture are generally rated higher in eating quality than larger but bland fruits (Petruccioli et al., 2023). Therefore, evaluation of internal quality should integrate sugar-acid balance, texture, and aroma rather than relying on a single indicator.

### 2.3 Nutritional and functional quality

With increasing consumer awareness of health, the nutritional and functional quality of peaches has gained growing attention. In addition to carbohydrates, water, and minerals, peaches are rich in vitamins, polyphenols, carotenoids, flavonoids, and anthocyanins, which contribute to antioxidant, anti-inflammatory, and health-promoting properties (Wang et al., 2023; Qi et al., 2024). Vitamins are key components of nutritional quality, with vitamin C being particularly important due to its antioxidant activity. Other fat-soluble vitamins and pigment-related bioactive compounds also enhance the health value of peaches (Vuković et al., 2025). The accumulation of these nutrients is influenced by cultivar, maturity stage, and environmental conditions, leading to significant variation even within the same cultivar.

Polyphenols are among the most important functional compounds in peaches, including phenolic acids, flavonoids, flavonols, catechins, and anthocyanins. These compounds not only contribute to fruit coloration but also provide antioxidant, antimicrobial, and anti-inflammatory benefits (Qi et al., 2024). Studies have shown significant variation among cultivars in total phenolics ( $\approx$ 9-578 mg GAE/100 g), total flavonoids ( $\approx$ 1-95 mg CAE/100 g), and antioxidant capacity ( $\approx$ 136-462 mg TE/100 g), with higher concentrations typically found in the peel than in the flesh (Wang et al., 2023). Yellow-fleshed peaches generally contain higher levels of carotenoids and total polyphenols, whereas white-fleshed varieties may exhibit higher average antioxidant activity.

Antioxidant capacity is an important integrative indicator of functional quality, commonly assessed using methods such as DPPH, ABTS, and FRAP. It results from the synergistic effects of vitamin C, polyphenols, carotenoids, and other bioactive compounds (Qi et al., 2024). Significant variation in antioxidant capacity exists among cultivars and is strongly influenced by maturity and environmental conditions, indicating both genetic dependence and environmental sensitivity (Vuković et al., 2025). Increasingly, peaches are being considered as potential functional foods rather than merely fresh fruits. This suggests that breeding and cultivation strategies should not only focus on yield, appearance, and flavor, but also target enhanced levels of bioactive compounds and antioxidant capacity to improve overall nutritional and health value (Wang et al., 2023).

## 3 Effects of Cultivation Conditions on Peach Fruit Quality

### 3.1 Environmental factors

Environmental factors are fundamental external conditions influencing the formation of peach fruit quality, among which light, temperature, and water availability play central roles during fruit development. These factors determine photosynthetic production and metabolic activity, and regulate the accumulation of sugars, organic acids, pigments, and secondary metabolites, thereby shaping fruit appearance, flavor, and nutritional quality. Light is one of the most critical environmental factors affecting quality potential. Adequate and well-distributed light enhances photosynthesis, increases carbon supply, promotes fruit enlargement, and improves soluble solids content (SSC), dry matter content (DMC), and anthocyanin accumulation, leading to better red coloration. Studies have shown that training systems such as open-center and fruiting-wall structures, which improve light interception and canopy light distribution, generally result in higher fruit weight, a greater proportion of large fruits, and improved coloration (Figure 2) (Anthony and Minas, 2021). Within a single tree, fruits in the upper and outer canopy typically exhibit higher SSC, better color, and superior flavor compared to those in shaded inner or lower positions (Anthony and Minas, 2022).

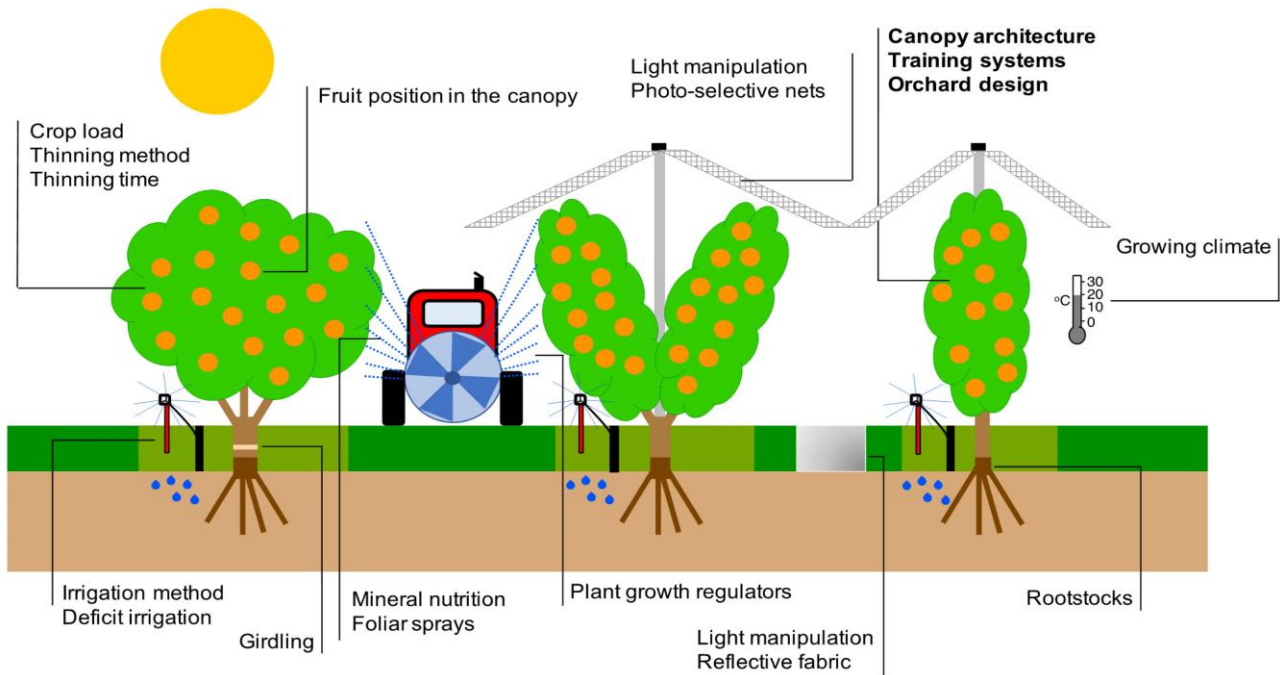


Figure 2 Overview of key orchard factors that influence preharvest peach tree and fruit physiology and affect harvest quality (Adapted from Anthony and Minas, 2021)

Temperature is another key factor regulating fruit growth and metabolic processes. Suitable temperatures and appropriate diurnal temperature variation favor sugar accumulation, acid balance, and aroma formation, thereby improving flavor quality. In general, a larger day-night temperature difference enhances the sugar-acid ratio and results in a more balanced taste. However, both extreme heat and insufficient heat accumulation can negatively affect quality (Shin et al., 2023). Controlled-environment studies indicate that high temperatures (e.g., 30 °C) accelerate early fruit growth and shorten the development period, advancing harvest by 2-3 weeks, but may reduce final fruit size and SSC, despite improving red skin coloration (Shin et al., 2023). In contrast, insufficient winter chilling can impair dormancy release, reduce fruit set and yield, and indirectly affect fruit quality (Babintseva, 2024).

Water conditions also have a profound impact on peach quality. Adequate water supply supports cell turgor, fruit expansion, and external quality, whereas excessive irrigation can dilute SSC, reduce firmness, weaken flavor, and increase the risk of cracking, diseases, and physiological disorders (Zhen et al., 2025). In contrast, moderate deficit irrigation strategies, such as deficit irrigation (DI) or partial root-zone drying (PRD), can increase DMC, firmness, SSC, glucose, and polyphenol content while reducing certain organic acids, thereby enhancing flavor intensity and antioxidant capacity. However, excessive water stress can limit fruit growth, reduce yield, and negatively affect the accumulation of some nutrients such as carotenoids. Therefore, irrigation management should be optimized according to developmental stages and regional conditions to balance yield and quality.

### 3.2 Cultivation practices

Cultivation practices serve as key regulatory tools linking environmental conditions to fruit quality formation. They influence tree nutritional status, canopy structure, light distribution, and source-sink relationships, thereby affecting external, internal, and nutritional quality traits (Figure 3). Fertilization management, particularly nitrogen (N), phosphorus (P), and potassium (K), plays a crucial role. Appropriate NPK application can improve yield, fruit size, SSC, total sugar, sugar-acid ratio, firmness, and vitamin C content while reducing titratable acidity (Babintseva, 2024). However, excessive nitrogen promotes vegetative growth, leading to poor coloration, lower SSC, and reduced flavor intensity. In contrast, potassium enhances sugar transport and coloration, whereas imbalanced phosphorus supply may negatively affect sugar accumulation. Since peach trees are perennial and

capable of recycling nitrogen, excessive fertilization does not consistently improve yield or quality, highlighting the importance of precision nutrient management.



Figure 3 Cultivation and management of peach trees

Pruning primarily affects fruit quality by regulating canopy structure and light conditions. Proper pruning improves light penetration and distribution, increases the proportion of well-exposed fruiting zones, and promotes uniform coloration and sugar accumulation. Conversely, dense canopies lead to shading, poor coloration, lower SSC, and uneven quality. Planting density also plays an important role. Appropriate density improves land use efficiency and yield per unit area while maintaining good light distribution when combined with proper pruning. However, excessive density and uncontrolled vigor increase competition and shading, resulting in poorer fruit quality. Modern high-density systems with small canopies, such as spindle or bush-type training, can achieve both high yield and good quality when light conditions are well managed.

Protected cultivation, including greenhouses and net systems, modifies environmental factors such as temperature, humidity, light, and wind, thereby influencing fruit development and quality formation. These systems often promote earlier maturity, extend the photosynthetic period, and improve external quality (Maatallah et al., 2024). However, insufficient light or excessive temperatures under protected conditions may reduce coloration, aroma, and overall flavor. Therefore, the effectiveness of protected cultivation depends on precise control of environmental and management factors to achieve optimal quality and yield.

### 3.3 Regulation techniques

In addition to environmental and conventional management practices, fine-tuning techniques such as thinning, plant growth regulator (PGR) application, and harvest timing are essential for improving fruit quality. These practices directly influence source–sink balance, fruit development, and maturation processes. Thinning is one of the most effective methods for regulating crop load and improving fruit quality. By reducing fruit number,

nutrient allocation per fruit increases, resulting in higher fruit weight, size, SSC, total sugar, sugar-acid ratio, and improved coloration (Wang et al., 2023). Studies show that retaining 25%-75% of initial fruit set can increase fruit weight by 20%-50% and SSC by up to 50% (Mazzoni et al., 2022). However, excessive thinning reduces total yield, so optimal thinning intensity must be determined based on cultivar characteristics, tree vigor, and market goals. Early thinning during bloom or early fruit development is generally more effective in improving quality and resource allocation.

Plant growth regulators (PGRs) are widely used to regulate fruit enlargement, maturity, and quality attributes such as firmness, coloration, and storability. Compounds such as gibberellins, cytokinins, calcium treatments, and biostimulants can improve fruit size, surface quality, and postharvest performance (Zhen et al., 2025). However, their effectiveness depends strongly on cultivar, dosage, timing, and environmental conditions. Improper use may lead to soft texture, poor sugar accumulation, or uneven ripening. Therefore, PGRs should be used as supplementary tools rather than substitutes for proper orchard management.

Harvest timing is a critical factor determining final fruit quality (Figure 4). Since postharvest handling can only maintain rather than improve quality, the maturity stage at harvest directly affects eating quality, storability, and consumer satisfaction. Early-harvested fruits are firmer and more suitable for storage and transport but often have lower SSC and weaker aroma. In contrast, delayed harvest improves sweetness and flavor but reduces shelf life and increases the risk of physiological disorders (Shin et al., 2023). In recent years, non-destructive indicators such as color indices, firmness, SSC, IAD, and DMC have been widely used to determine optimal harvest timing more accurately. This reflects a shift from experience-based decisions to data-driven, multi-index evaluation in harvest management.



Figure 4 Harvesting stage and maturity management of peach fruit

## 4 Mechanisms of Variation in Quality Traits

### 4.1 Physiological and biochemical mechanisms

The formation of peach fruit quality traits depends on a series of complex and coordinated physiological and biochemical processes. As a typical climacteric fruit, peach undergoes increased respiration and ethylene production during ripening, which further triggers a range of physiological changes, including carbohydrate and organic acid metabolism, cell wall remodeling, pigment reconfiguration, and volatile compound synthesis. These processes drive the transition of the fruit from a “growth stage” to a “ripening stage” quality state. Sugar and acid metabolism is the core basis determining peach flavor quality. During fruit development, photosynthetic products are transported to the fruit through the phloem and gradually converted into and accumulated as soluble sugars such as sucrose, glucose, fructose, and sugar alcohols, while organic acids such as malic acid and citric acid change dynamically at different developmental stages. In general, soluble sugars continue to accumulate and organic acids gradually decline during ripening, leading to an increase in the sugar-acid ratio and resulting in enhanced sweetness and reduced sourness. Metabolomic studies have shown that, in cultivars such as ‘Huangjin’, the color-change stage is a critical period characterized by significant accumulation of sugars and sugar alcohols and a marked decline in organic and phenolic acids, indicating that this stage is an important physiological turning point in peach flavor formation (Minas et al., 2018). Meanwhile, these primary metabolic changes also interact with cell wall degradation, causing fruit softening and texture changes, which in turn affect eating quality and postharvest storability.

Pigment synthesis and transformation are important physiological bases for external fruit quality. During peach ripening, chlorophyll gradually degrades, while anthocyanins and carotenoids accumulate, jointly driving the peel and flesh color from green to red, yellow, or mixed hues (Figure 5). Anthocyanin accumulation is usually closely related to red peel coloration, whereas carotenoids are more involved in the formation of yellow flesh and peel background color. Studies have shown that, during the color-change stage, key enzyme genes in the flavonoid pathway, such as CHS, F3'H, DFR, and A3GT, are upregulated, thereby promoting anthocyanin biosynthesis and intensifying red or mixed coloration in the fruit (Serrie et al., 2025). In addition to determining yellow coloration, carotenoids can also generate certain norisoprenoid volatiles through the carotenoid cleavage dioxygenase (CCD) pathway, thereby linking pigment metabolism with aroma formation.



Figure 5 Maturation process of peach fruit

Aroma formation further enriches peach flavor quality. The characteristic aroma of peach is composed of volatile organic compounds such as lactones, esters, aldehydes, alcohols, and terpenes. These compounds are mainly derived from the fatty acid  $\beta$ -oxidation pathway, the lipoxygenase (LOX) pathway, amino acid metabolism, and terpene and carotenoid cleavage pathways. For example, lactones usually contribute to the typical sweet and ripe-fruit aroma of peach, esters are associated with floral and fruity notes, while aldehydes and alcohols contribute to freshness (Li et al., 2023). Studies have shown that these volatile compounds change dynamically during fruit development and storage. Different cultivation conditions, such as light, temperature, and exogenous treatments, can alter the types and proportions of aroma compounds by regulating enzyme activities and the intensity of metabolic pathways, thereby leading to differences in fruit flavor among regions and years (Cao et al., 2024).

#### 4.2 Molecular genetic mechanisms

Differences in peach fruit quality traits are fundamentally controlled by genetic factors. In recent years, with the development of genomics, transcriptomics, and multi-omics integration, a large number of key genes and regulatory networks related to sugar and acid accumulation, fruit coloration, texture formation, and aroma biosynthesis have been gradually elucidated, providing important support for understanding the molecular basis of quality traits. In terms of sugar and acid metabolism, QTL mapping and genome-wide association studies (GWAS) have identified multiple genomic regions associated with soluble solids content (SSC), titratable acidity (TA), and sugar-acid balance. For example, major QTLs associated with SSC and TA have been identified on linkage group 5, and epistatic interactions among acidity-related loci can further regulate sugar-acid balance. At the candidate gene level, the malate transport-related gene *PpALMT1* and the sugar transporter gene *PpERDL16* have been confirmed to be closely associated with malate and fructose accumulation, thereby contributing to flavor differences among cultivars (Yao et al., 2025). This indicates that peach internal quality is not determined by a single metabolic enzyme but is coordinately controlled by transport, synthesis, degradation, and compartmentation processes.

In fruit coloration, structural genes and regulatory genes in the anthocyanin pathway together constitute a complex molecular regulatory network. Studies have shown that structural genes such as *CHS*, *DFR*, and *UFGT* control key steps in anthocyanin biosynthesis, while transcription factors such as MYB and bHLH act as upstream regulators that respond to environmental signals and coordinate downstream gene expression (García-Gómez et al., 2020; Da Silva Linge et al., 2021). In addition, some NAC family transcription factors are also involved in regulating flesh or peel coloration. For example, *PpBL* can affect red flesh pigmentation by regulating *PpNAC1*, and is also associated with the formation of certain aroma compounds such as linalool and (*Z*)-3-hexenyl acetate, reflecting a cross-link between color and aroma metabolism (Rawandoozi et al., 2020a). Aroma biosynthesis is likewise under the coordinated regulation of multiple genes. Studies have reported that terpene synthase genes, lipoxygenase-related genes, and carotenoid cleavage dioxygenase genes are all closely associated with the formation of volatile aroma compounds in peach (Li et al., 2023). *PpCCD4* and other CCD family members are closely related to the production of norisoprenoid aroma compounds, while GWAS has also identified terpene synthase genes associated with linalool synthesis. Meanwhile, different haplotypes of the *PpAAT* gene cluster can lead to variation in ester content, thereby influencing fruit aroma intensity and flavor style among cultivars. This suggests that peach aroma quality is essentially controlled by multiple gene modules and different metabolic branches (Feng et al., 2024).

In recent years, multi-omics technologies have further advanced the systematic dissection of peach quality regulatory networks. Transcriptomic studies have shown that hundreds to thousands of genes change expression during fruit ripening, involving sugar and acid metabolism, cell wall remodeling, ethylene signaling, stress response, and flavor compound formation (Veerappan et al., 2021). By integrating transcriptomic and metabolomic data, gene expression changes can be linked to the levels of sugars, organic acids, anthocyanins, and volatile compounds, thereby enabling the construction of “gene-metabolite-quality trait” regulatory network models. These studies indicate that peach quality traits are influenced not only by a few key structural genes, but also by complex transcription factor networks, coupled metabolic pathways, and polygenic control (Cao et al., 2024; Feng et al., 2024).

### 4.3 Genotype×environment interaction effects

The formation of peach fruit quality traits is not determined by genotype alone. Genotype × environment interaction (G×E) is an important cause of variation and stability differences in quality traits. In actual production, different cultivars may exhibit different quality under the same environment, while the same cultivar may show significantly different quality performance across regions, years, and management conditions. This phenomenon is a direct manifestation of G×E interaction. Multi-environment trials have shown that traits such as fruit weight, fruit size, coloration, and SSC usually display significant G×E effects. In contrast, traits such as titratable acidity and ripening date often have relatively high heritability and lower G×E effects, whereas fruit weight and shape are more environmentally sensitive and require region-specific selection and management (Rawandoozi et al., 2020b). This indicates that not all quality traits respond to the environment in the same way: some are relatively stable and suitable for wide adaptation, whereas others are highly environment-dependent and require precise matching between cultivar and region.

At the molecular level, multi-environment genomic prediction models show that the G×E effect on SSC mainly originates from the polygenic background, whereas some major QTLs and dominance effects remain relatively stable across environments. This means that peach quality traits are controlled both by stable major genes and by numerous minor-effect genes and environmental signals. Environmental factors such as light, temperature, water, canopy microclimate, and exogenous treatments interact with cultivar-specific regulatory networks by affecting sugar and acid metabolism, pigment accumulation, and volatile compound formation, ultimately leading to different quality outcomes (Cao et al., 2024). For example, in ‘Huangjin’ peach, the color-change stage is a key period of transcriptomic and metabolomic change, and the timing and intensity of this stage are strongly regulated by temperature and light. When exogenous treatments such as glutamic acid, sucrose, or brassinolide are applied, different cultivars show markedly different responses in fruit weight, firmness, SSC, anthocyanin accumulation, and the expression of key genes (e.g., *PpPAL*, *PpF3H*, *PpDFR*, *PpUFGT*, *PpGST1*, and *PpMYB10.1*), indicating that the effects of environmental or management signals are strongly genotype-dependent (Figure 6) (Kou et al., 2023). This suggests that the same management practice does not necessarily produce the same effect across cultivars, and quality regulation must be based on an understanding of cultivar-specific responses.

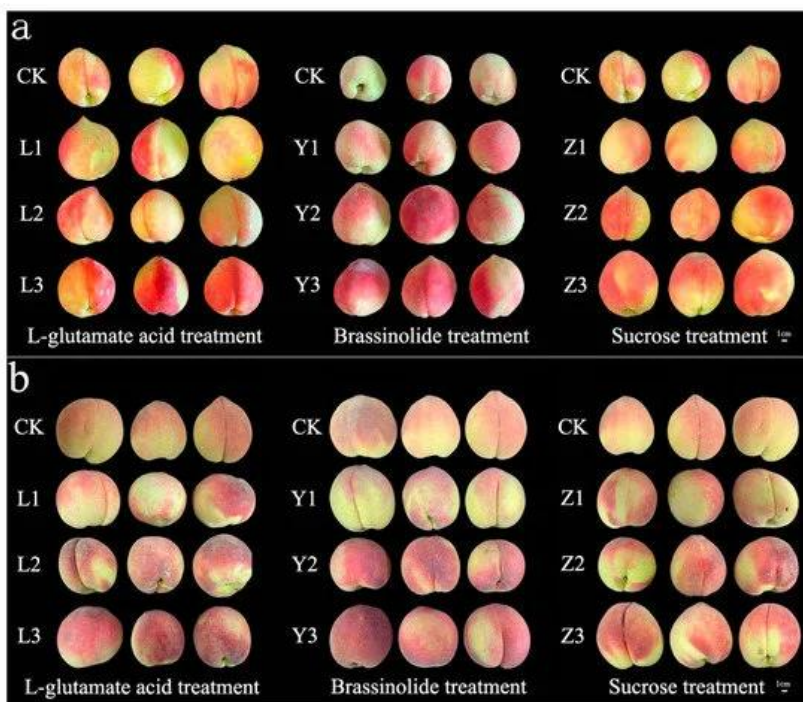


Figure 6 The ripening stage of the fruits of ‘Baifeng’ and ‘Weiduanmihong’ after treated with exogenous substances (Adopted from Kou et al., 2023)

Image caption: (a) is ‘Baifeng’; (b) is ‘Weiduanmihong’ (Adopted from Kou et al., 2023)

In addition, multi-environment GWAS studies in stone fruits have enabled researchers to distinguish between environment-shared QTLs and environment-specific QTLs, and have shown that some loci may have antagonistic effects across environments (Serrie et al., 2025). These results further demonstrate that G×E interactions are not only common but may profoundly influence quality breeding and the development of region-specific cultivation strategies. Incorporating G×E into QTL analysis, GWAS, and genomic prediction models can help identify stable trait loci and screen superior cultivars and management schemes suitable for different ecological regions. Therefore, a deeper understanding of G×E interaction mechanisms is of great importance for achieving precise matching between cultivars and environments, improving quality stability, and optimizing cultivation management. Future peach quality research needs to shift from “single-environment, single-trait” analysis toward a collaborative framework of “multi-environment, multi-omics, and multi-model” analysis in order to more comprehensively reveal the true sources of quality variation.

## 5 Methods for Evaluating Peach Fruit Quality

### 5.1 Physicochemical and sensory evaluation methods

Traditional methods for evaluating peach fruit quality mainly include physicochemical measurements and sensory evaluation. Physicochemical indicators are important for characterizing both internal and external quality and commonly include fruit size and weight, shape, density, peel and flesh color, firmness, soluble solids content (SSC, °Brix), titratable acidity (TA), pH, and sugar-acid ratio. These indicators are usually measured on harvested fruit. For example, calipers or image analysis are used to obtain fruit dimensions, shape index, and diameter; colorimeters are used to measure CIELAB color parameters; penetrometers or texture analyzers are used to determine firmness; refractometers are used to measure SSC; and titration is used to determine TA and pH. SSC is often regarded as an approximate indicator of sweetness, while TA and pH are used to characterize acidity. Firmness reflects not only texture status but is also closely related to harvest maturity and postharvest performance. Studies have shown that these physicochemical traits often vary significantly among cultivars or maturity stages. For example, late-ripening cultivars may have larger fruits and brighter coloration, but not necessarily the highest SSC or perceived sweetness (Farina et al., 2019).

To improve the interpretability of quality assessment, some studies have developed derived indices based on physicochemical measurements, such as sweetness index, total sweetness index, maturity index, and sugar-acid balance index, to integrate complex physicochemical composition into more interpretable quality scores (Popova et al., 2021). These approaches help move traditional physicochemical data from “single-trait measurement” toward “comprehensive quality characterization,” making them valuable for cultivar comparison and maturity evaluation. However, whether a fruit is ultimately accepted by consumers still depends on actual sensory experience. Therefore, sensory evaluation serves as an important bridge linking physicochemical indicators with eating quality. Sensory evaluation is usually performed by trained panels or consumer panels, which quantitatively score attributes such as aroma, sweetness, sourness, bitterness, astringency, juiciness, texture characteristics (e.g., firmness, crispness, fibrousness, mealiness), and overall acceptability, commonly using 9-point or 15-point scales (Table 1) (Felts et al., 2019; Sun et al., 2023). Studies have shown that SSC and TA are good predictors of sweetness and sourness perception, but more complex sensory attributes—such as fruity aroma, flavor intensity, and flavor harmony, still require direct sensory evaluation. For example, higher firmness is often associated with sourness and unripe flavor, while larger fruit tends to be perceived as juicier or more overripe (Felts et al., 2019).

In recent years, with the development of comprehensive quality evaluation concepts, researchers have increasingly tended to integrate physicochemical and sensory data. Through principal component analysis (PCA), cluster analysis, or comprehensive scoring methods, it is possible to identify cultivar types that exhibit “good appearance but average flavor” or “ordinary appearance but outstanding internal flavor,” thereby providing more refined criteria for breeding and cultivation management (Muto et al., 2022). Therefore, physicochemical measurements and sensory evaluation are not mutually substitutive but together form the basic framework for peach fruit quality assessment.

Table 1 Descriptive sensory exterior appearance attributes of fresh-market peach and nectarine genotypes evaluated on a 15-point scale (Adopted from Felts et al., 2019)

Genotype	Uniformity of color	Color-yellowness	Color-redness	Amount of bruises	Separation of pit	Pit size
A-827	10.1 cd2	9.8 bc	4.4 ab	2.1 abc	10.8 ab	8.7 bc
A-850	13.1 a	13.0 a	1.6 d	1.9 abcd	6.9 c	9.5 ab
A-865	10.8 bc	9.6 c	3.4 bc	1.1 bcde	11.9 ab	7.9 bc
Amoore Sweet	13.2 a	13.5 a	1.0 d	0.4 e	13.9 a	8.3 bc
Bowden	13.3 a	13.2 a	0.9 d	0.8 cde	13.1 a	8.1 bc
Effie	12.7 ab	12.2 ab	1.9 cd	0.6 de	13.6 a	9.4 ab
Loring	10.0 cd	10.1 bc	4.2 ab	2.5 a	8.6 bc	10.9 a
Souvenirs	9.9 cd	9.8 bc	4.4 ab	1.0 cde	11.8 ab	7.3 c
White River	8.5 d	7.9 c	5.9 a	2.3 ab	9.5 bc	11.0 a
<i>P</i> value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Table caption: 0= less of the attribute; 15 = more of the attribute in terms of intensity; Genotypes were evaluated in duplicate by trained panelists; Means with different letter(s) for each attribute are significantly different ( $P<0.05$ ) using Tukey's honestly significant difference test (Adopted from Felts et al., 2019)

## 5.2 Modern analytical techniques

With the advancement of analytical technology, modern instrumental methods have been increasingly applied in peach quality research and have gradually become important tools for analyzing fruit flavor, nutritional components, and functional compounds. Compared with traditional physicochemical methods, modern analytical techniques can reveal the chemical basis of peach quality at higher resolution and greater depth, especially in the analysis of volatile aroma compounds, trace metabolites, and complex compositional networks. Chromatographic techniques are among the most mature methods currently used in peach quality research. High-performance liquid chromatography (HPLC) is mainly used to analyze non-volatile compounds such as sugars, organic acids, polyphenols, and vitamins, allowing accurate quantification of glucose, fructose, sucrose, malic acid, citric acid, and related compounds (Sun et al., 2023). These data are important for understanding the formation of sweet-sour flavor, nutritional quality differences, and metabolic characteristics among cultivars. Meanwhile, gas chromatography-mass spectrometry (GC-MS) is widely used to identify and quantify volatile aroma compounds in peach. Gas chromatography-ion mobility spectrometry (GC-IMS), due to its rapid analysis and high sensitivity to volatile compounds, has increasingly been used for aroma fingerprinting of peach fruit. Studies have shown that the combined use of GC-IMS and GC-MS can identify key aroma compounds and thereby distinguish aroma styles among cultivars (Sun et al., 2022).

When combined with sensory evaluation, chromatographic techniques can further identify key flavor markers affecting consumer preference. For example, by integrating sugar-acid data obtained by HPLC, volatile compound data identified by GC-MS, and sensory evaluation results, researchers can more systematically elucidate the chemical basis of sensory attributes such as "sweetness," "fruity aroma," "ripe aroma," or "green notes" in peach fruit (Sun et al., 2023). Such studies are of great significance for germplasm screening, elite cultivar breeding, and flavor-oriented cultivation management. In addition to chromatography, spectroscopic techniques have rapidly expanded in peach quality evaluation because of their speed, high throughput, and potential for non-destructive analysis. Visible/near-infrared spectroscopy (Vis/NIR) estimates internal quality traits such as SSC, dry matter content (DMC), firmness, polyphenols, and pigments by measuring the interaction between light and fruit tissues. Studies have shown that high-accuracy prediction of SSC and DMC can be achieved using models such as partial least squares regression (PLS), multiple linear regression (MLR), and least-squares support vector machine (LS-SVM), often with coefficients of determination ( $R^2$ ) above 0.94 and RMSEP values around 0.3%-0.6% (Minas et al., 2020). Hyperspectral imaging further integrates spatial and spectral information, allowing not only estimation of SSC and firmness but also visualization of the spatial distribution of these quality parameters within the fruit, as well as prediction of fruit size and weight (Xuan et al., 2022).

In addition, fluorescence spectroscopy, electrical property detection, and electronic nose and tongue technologies have also expanded the methodological toolbox for peach quality detection (Qi et al., 2024). These methods show considerable potential for maturity recognition, internal defect detection, and flavor evaluation, and are especially suitable for breeding and grading scenarios requiring rapid, large-scale assessment. The introduction of modern analytical techniques has gradually shifted peach quality evaluation from traditional single-indicator measurement toward multidimensional, molecular-level, and high-throughput analysis.

### **5.3 Non-destructive detection and comprehensive evaluation models**

Non-destructive detection technology has become an important direction in peach quality evaluation in recent years. Its core objective is to achieve rapid, objective, and highly repeatable detection of internal quality without damaging fruit structure, thereby compensating for the limitations of destructive analysis and subjective sensory evaluation (Qi et al., 2024). Such technologies are particularly suitable for large-scale phenotyping, online grading of commercial fruit, and precision harvest decisions. At present, Vis/NIR and hyperspectral systems are the most widely used. With a single scan, they can rapidly predict SSC, DMC, firmness, and maturity indices (such as IAD), while maintaining high accuracy across different developmental stages, crop loads, and cultivars (Anthony et al., 2023). Studies have shown that by fully accounting for sources of variation such as genotype, canopy position, and management practices during model construction, the stability and generalization ability of predictive models can be significantly improved. This also helps reveal the influence of preharvest factors on fruit quality formation (Minas et al., 2023).

In addition to spectroscopic methods, a range of intelligent detection techniques has gradually been incorporated into non-destructive peach quality evaluation systems (Qi et al., 2024). Machine vision can be used to identify fruit shape, color distribution, and surface defects; hyperspectral imaging can simultaneously capture both external and internal quality information; acoustic vibration and electrical property detection show potential for firmness and internal defect recognition; and electronic noses and tongues enable rapid characterization of aroma and taste features. The integration of these technologies has promoted a shift in peach quality evaluation from traditional “static, destructive measurement” toward “dynamic, online, and intelligent monitoring.”

On this basis, the construction of comprehensive evaluation models has become increasingly important for transforming multi-source data into practical applications. Through principal component analysis (PCA), cluster analysis, and machine-learning approaches, multiple indicators such as shape, mass, firmness, color, SSC, TA, and electrical parameters can be integrated to achieve quality grading and to demonstrate that single appearance indicators cannot fully reflect overall fruit quality. In addition, the analytic hierarchy process (AHP) and fuzzy comprehensive evaluation methods can combine physicochemical indicators with sensory evaluation, weighting attributes such as sweetness, juiciness, and overall preference (Baviera-Puig et al., 2023; Sun et al., 2023). Overall, modern peach quality evaluation is shifting from reliance on single-indicator detection toward multi-source data integration, gradually establishing more comprehensive evaluation systems that better reflect actual consumer eating experience.

## **6 Construction of Quality Evaluation Systems**

### **6.1 Multi-index comprehensive evaluation methods**

Peach fruit quality is inherently multidimensional, and a single indicator cannot fully reflect its overall quality level. Therefore, multi-index comprehensive evaluation has become an important direction in current peach quality research and grading applications. Comprehensive evaluation systems usually integrate external quality (such as fruit shape, color, and size), physical quality (such as fruit weight, density, and firmness), internal quality (such as SSC, TA, sugar-acid ratio, texture, and flavor), and, when necessary, nutritional and functional quality (such as polyphenols and antioxidant capacity), as well as even electrical or spectral parameters, into a unified framework to achieve systematic evaluation of fruit quality (Farina et al., 2019). This approach effectively overcomes the limitations of single indicators and more objectively characterizes the comprehensive performance of fruit quality among different cultivars, maturity stages, and cultivation conditions.

Existing studies have shown that multi-index comprehensive evaluation is applicable not only to fresh peaches but also to processed products. For example, in fresh peach studies, an evaluation system based on 11 indicators—including shape index, volume, weight, density, firmness, color, impedance, phase angle, SSC, TA, and sugar-acid ratio—was able to classify fruits into different quality grades and revealed the important fact that the proportion of red peel color is only weakly correlated with internal eating quality (Zhang et al., 2020). This indicates that external traits intuitively preferred by consumers do not necessarily represent the true comprehensive quality of the fruit. Similarly, in freeze-dried peach powder studies, researchers integrated 14 indicators related to physicochemical properties, nutrition, and processing performance to evaluate samples of different cultivars and ripening stages, and found that a smaller number of core indicators could be selected without losing discriminatory power, suggesting that comprehensive evaluation systems also have potential for indicator compression and optimization (Liu et al., 2017).

From the perspective of evaluation logic, the advantages of a multi-index system are mainly reflected in three aspects. First, it can simultaneously take into account appearance, flavor, and nutritional value, thereby better meeting the actual needs of consumers and industry. Second, it helps compare materials for different purposes, such as distinguishing “high-quality fruit for fresh consumption” from “raw materials suitable for processing.” Third, it provides quantitative support for cultivar selection and optimization of cultivation practices, rather than relying solely on empirical judgment. In practice, multi-index comprehensive evaluation usually requires standardization of different indicators first to eliminate the influence of dimensional differences. Common methods include range standardization and Z-score normalization, which place all indicators on a comparable scale. Subsequently, weighted summation, comprehensive scoring functions, or multivariate models can be used to integrate multiple indicators into a single comprehensive quality score, enabling comparison among different treatments, cultivars, or regional materials (Zhang et al., 2020). At the same time, these methods are often combined with correlation and regression analyses to reveal internal relationships among different quality traits, such as sugar-acid ratio versus sensory sweetness, firmness versus maturity, and overall color parameters versus consumer preference, thereby providing a basis for selecting key indicators and improving evaluation efficiency.

## 6.2 Weight determination and model construction

After establishing a multi-index evaluation system, how to scientifically determine the weight of each indicator and construct a comprehensive evaluation model becomes the key step in achieving quantitative peach quality assessment. Because different quality indicators contribute unequally to overall quality, it is necessary to adopt reasonable weighting methods and model-construction strategies to transform raw data into interpretable comprehensive scores. Principal component analysis (PCA) is one of the most commonly used objective weighting and dimensionality-reduction methods in fruit quality evaluation studies (Farina et al., 2019; Zhang et al., 2020). Its core function is to deal with multicollinearity among multiple indicators, extract information components that explain the main variation from the original variables, and thus reduce redundancy while improving model simplicity. For example, in fresh peach studies, PCA based on 11 indicators extracted five principal components explaining about 85% of the total variation, and further combined with K-means clustering to classify fruits into five quality grades (Zhang et al., 2020). Similarly, in freeze-dried peach powder evaluation, PCA extracted five principal components from 14 variables, with a cumulative contribution rate of 84.46%, effectively distinguishing among cultivars and ripening stages. Thus, PCA not only increases the information density of evaluation models but also helps identify the dominant factors underlying comprehensive quality.

The analytic hierarchy process (AHP), by contrast, is a subjective weighting method that places greater emphasis on consumer preference or expert experience in evaluation systems. Its basic principle is to construct a judgment matrix and compare indicators pairwise to determine their relative importance. The advantage of AHP lies in its ability to reflect production goals and market demand. For example, in the evaluation of fresh peaches, consumers are often more concerned with sweetness, juiciness, and aroma than with firmness or external appearance alone. Studies have shown that, when AHP is combined with sensory analysis in peach and nectarine quality evaluation, the gustatory phase emerges as the most critical in overall quality judgment, with sweetness and juiciness usually

being the major positive contributors, whereas bitterness, sourness, and astringency have greater effects on negative evaluations (Baviera-Puig et al., 2023). Therefore, AHP has a unique advantage in building consumer-oriented evaluation systems.

However, AHP depends on expert experience and thus contains a certain degree of subjectivity, whereas PCA, although objective, lacks a direct reflection of consumer preference. For this reason, recent studies increasingly tend to adopt combined objective-subjective weighting methods, such as integrating PCA with AHP, or further combining entropy weighting, grey relational analysis, TOPSIS, and other multi-criteria decision-making methods (Tian et al., 2025; Zhou et al., 2025). These approaches can introduce preference information while preserving statistical objectivity, making weight allocation more consistent with real application needs. In other words, PCA mainly provides “importance from the data-structure perspective,” whereas AHP and related methods provide “importance from the decision-making perspective.” Their combination helps establish evaluation models that are both scientific and practical. On this basis, by constructing comprehensive quality functions, classification models, or predictive models, it becomes possible to quantitatively evaluate samples under different cultivation conditions, cultivars, or regions, and to provide support for cultivation decisions, cultivar recommendation, and commercial grading. Therefore, weight determination and model construction are not merely statistical issues, but crucial steps in transforming multidimensional quality information into actionable decision-making tools.

### **6.3 Regionalized and standardized evaluation systems**

The relative importance of peach quality traits varies with ecological conditions, production systems, major cultivars, and target markets across regions. Therefore, when constructing a quality evaluation system, both standardization and regional adaptability must be considered. In other words, an ideal system should combine a “standardized framework + regional calibration” rather than relying on a single uniform model. From the perspective of standardization, unified evaluation indicators, measurement methods, and reference systems are the basis for ensuring comparability of results across studies, regions, and experimental sites. For example, the large collaborative project represented by the EUFRIN Peach and Apricot Working Group proposed about 40 standardized indicators for new cultivar evaluation, covering phenological stages (such as flowering time and harvest date), yield, external quality, internal quality, and susceptibility to diseases, and achieved consistency in multi-environment trial results through unified measurement protocols and reference cultivars (Giovannini et al., 2021). This framework not only provides a common technical language for breeders, growers, and the industry chain, but also lays a methodological foundation for interregional quality comparison and cultivar promotion.

At the same time, peach fruit quality shows clear regional characteristics. Different ecological regions differ in light, temperature, water availability, soil conditions, and cultivation systems, so the importance of certain quality indicators also differs among regions. For example, in areas with large diurnal temperature differences and abundant light, sugar accumulation and coloration are usually more emphasized; whereas in humid regions or under protected cultivation, texture stability, flavor harmony, and disease resistance may be of greater evaluative value. This means that although the comprehensive evaluation system requires a unified basic framework, its indicator weights and application priorities should be recalibrated according to regional realities.

Studies have shown that comprehensive evaluation systems constructed using variance analysis, correlation analysis, PCA, cluster analysis, and AHP can recalculate principal components and weights by incorporating local cultivar resources, regional environmental data, and consumer preferences, thereby achieving regionalized evaluation (Mihaylova et al., 2021). On the one hand, such regional adjustments improve the suitability of the evaluation system to local production realities; on the other hand, they also provide a scientific basis for regional branding and the positioning of specialty cultivars. In addition, the recent development of non-destructive detection technologies has provided a new technical basis for integrating regionalized and standardized evaluation systems. Studies have shown that methods such as Vis/NIRS and hyperspectral imaging, after localized calibration under region-specific rootstocks, crop load levels, canopy positions, and light environments, can stably acquire

key indicators such as DMC, SSC, and maturity, and are expected to be embedded into standardized grading systems, thereby realizing an evaluation mode of “unified methods but adjustable models” across different regions (Minas et al., 2023).

## **7 Existing Problems and Development Trends**

### **7.1 Current limitations**

Although significant progress has been made in peach fruit quality research across multiple disciplines, the lack of unified evaluation systems remains a major bottleneck limiting result comparability and practical application. Differences in indicator selection, sampling stages, maturity criteria, and measurement methods are common among studies. Even when the same indicators (e.g., SSC, acidity, firmness) are used, inconsistencies in scales and standards reduce comparability and reproducibility. At the same time, research-oriented evaluation systems tend to be complex, whereas industry practices still rely mainly on appearance or a few simple indicators. This disconnect between research and industry affects quality stability and consumer experience (Mosie et al., 2025). In terms of mechanism studies, current research still focuses largely on phenotypic and physicochemical traits, with limited understanding of the molecular regulation underlying flavor harmony, aroma formation, and texture changes. Although GWAS and QTL studies have identified numerous loci associated with quality traits, many causal genes and regulatory pathways remain unresolved (Fan et al., 2025; Hayat et al., 2025). In addition, studies on multi-factor interactions are still insufficient. In practice, fruit quality is jointly influenced by genotype × environment × management, yet most existing research focuses on single-factor analysis, limiting systematic understanding of quality formation mechanisms and stability.

### **7.2 Application of emerging technologies**

The development of multi-omics technologies has greatly enhanced the ability to elucidate the mechanisms underlying peach fruit quality. At the genomic level, high-density SNP arrays, resequencing, and GWAS approaches have enabled the identification of key genomic regions associated with quality traits, providing a foundation for molecular breeding. Meanwhile, integrated metabolomic and transcriptomic analyses have revealed key pathways involved in the formation of sugars, acids, and aroma compounds, and have identified molecular markers related to flavor and antioxidant capacity (Feng et al., 2024). Research on aroma improvement is increasingly integrating metabolite profiles, gene regulatory networks, and consumer preferences, providing theoretical support for flavor-oriented breeding (Cao et al., 2024). On the phenotyping side, intelligent detection technologies are developing rapidly. Techniques such as Vis/NIR spectroscopy, hyperspectral imaging, electrical property sensing, and electronic noses have been applied for rapid assessment of fruit quality and maturity (Qi et al., 2024), while deep-learning-based machine vision enables simultaneous prediction of multiple traits and shows strong potential for automated sorting (Masuda et al., 2023). Compared with traditional methods, these technologies offer advantages in high throughput and objectivity, making them more suitable for modern fruit production systems. Moreover, a convergence trend is emerging between multi-omics and intelligent detection technologies: the former provides molecular-level explanations, while the latter enables rapid field-level assessment. Their integration is expected to establish predictive systems linking “molecular mechanisms-field phenotypes-market quality,” thereby promoting a more systematic and dynamic approach to quality research (Fan et al., 2025; Hayat et al., 2025).

### **7.3 Climate change and precision cultivation strategies**

Climate change has profound impacts on peach fruit quality. Rising temperatures, altered precipitation patterns, and more frequent extreme weather events influence phenology, metabolism, and pigment formation, thereby affecting fruit flavor and quality. For example, high temperatures may inhibit anthocyanin accumulation and accelerate ripening, while abnormal rainfall can dilute SSC and increase disease risk. These effects vary by region and cultivar, making it difficult for traditional cultivation systems to maintain stable quality (Deori et al., 2024). Therefore, precision cultivation has become an important strategy to address climate change. By regulating canopy structure, crop load, rootstock-scion combinations, and planting density, it is possible to optimize light utilization and carbon allocation, thereby improving quality stability. Studies indicate that favorable environmental conditions support optimal metabolic regulation and high-quality fruit formation, whereas adverse

conditions often lead to reduced flavor quality, suggesting that quality management should be shifted upstream to orchard-level control (Bacelar et al., 2024). Future development should integrate environmental monitoring, non-destructive detection, and decision-support models to enable real-time regulation of fruit quality and risk (Masuda et al., 2023; Qi et al., 2024). At the breeding level, combining multi-omics approaches with genomic selection will facilitate the development of new cultivars that possess both stress resistance and high quality (Fan et al., 2025; Hayat et al., 2025).

## 8 Concluding Remarks

Cultivation conditions are key determinants of peach fruit quality, mainly acting through their effects on canopy microclimate, tree carbon allocation, and fruit development. Preharvest factors such as cultivar-rootstock combinations, crop load, training systems, irrigation regimes, nitrogen supply, and temperature during fruit development can individually or interactively regulate key quality traits, including dry matter content, soluble solids concentration (SSC), acidity, firmness, color, and nutritional-functional components. The light environment within the canopy, regulated by tree architecture and pruning, significantly influences fruit size, coloration, and sugar-acid balance. Open canopies and upper canopy positions typically exhibit higher light interception, resulting in increased SSC, dry matter content, and improved color. In addition, moderate deficit irrigation and optimized fertilization can enhance SSC, firmness, polyphenol, and mineral content, whereas excessive vegetative growth or high temperatures often reduce fruit sweetness and size, despite accelerating ripening. These findings indicate that fruit quality is not a fixed varietal attribute but a highly plastic phenotype jointly shaped by environmental conditions and cultivation practices. Achieving stable, high-quality production therefore requires regionally adapted and integrated cultivation strategies.

Under varying cultivation conditions, the complexity and plasticity of peach fruit quality traits make multidimensional evaluation systems indispensable. Reliance on single external indicators, such as peel color or fruit size, is insufficient to ensure consumer satisfaction and has contributed to declining peach consumption in some markets. Modern research suggests that robust evaluation systems should integrate physical, chemical, functional, and sensory dimensions, including dry matter, SSC, titratable acidity, sugar-acid ratio, firmness, color metrics, bioactive compounds, and, where appropriate, microbial stability and storage characteristics. Multi-index evaluation frameworks, combined with multivariate statistical analysis, sensory evaluation, and advanced non-destructive technologies such as Vis/NIR and hyperspectral imaging, enable consistent characterization of fruit quality across different cultivation systems, climatic conditions, and postharvest treatments. At both breeding and production levels, such integrated systems facilitate the identification of superior genotype-management combinations, support marker-assisted and genomic selection, and provide a unified technical standard for producers, processors, and regulators. Establishing standardized, multidimensional quality evaluation systems is therefore essential for enhancing industry credibility and meeting consumer expectations.

Future progress in regulating peach fruit quality under diverse cultivation conditions will depend on deeper mechanistic understanding and the integration of emerging technologies. Multi-omics approaches—including genomics, transcriptomics, metabolomics, volatilomics, and phenomics—are increasingly revealing how sugars, acids, pigments, and secondary metabolites respond to crop load, light, water status, temperature, and postharvest stresses. Integrating these molecular insights with high-throughput, non-destructive phenotyping platforms (such as NIRS, Vis/NIR, imaging technologies, and electronic noses), along with environmental and management data, will enable predictive models of quality formation, more precise genomic selection, and improved decision support for harvest and storage. At the same time, climate change and the demand for sustainable production require that quality-focused research be embedded within adaptive training systems, deficit irrigation strategies, nutrient management, and disease control frameworks, ensuring both yield and eating quality under complex conditions. The development of integrated databases combining multi-environment trials, multi-omics data, sensor information, and sensory evaluation, along with intelligent decision-support tools for breeders and growers, will be crucial for advancing high-quality, consumer-oriented peach production systems.

## Acknowledgments

We extend sincere thanks to Mrs. Luo for her feedback on the manuscript.

## Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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