

# Variation in Quality Traits Among Different Tea Cultivars Used for Longjing Tea

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**Abstract** This study investigates different tea plant cultivars used for Longjing tea processing, focusing on their quality trait differences and underlying formation mechanisms. First, the typical quality characteristics of Longjing tea are summarized from aspects such as appearance, aroma, taste, liquor color, and infused leaves, and the synergistic effects of cultivar, environment, and processing techniques on quality formation are clarified. Furthermore, differences among cultivars in key chemical components, including amino acids, tea polyphenols, caffeine, and volatile aroma compounds, are compared to reveal their contributions to freshness, bitterness-astringency balance, and aroma profiles. The results indicate that cultivars determine the flavor type and quality level of Longjing tea by regulating metabolite composition and processing response pathways. In addition, this study discusses differences in processing suitability and quality stability among cultivars, and highlights recent advances in molecular biology and multi-omics technologies for elucidating quality traits and breeding new cultivars. In response to current limitations such as incomplete evaluation systems and insufficient multi-factor studies, it proposes strengthening multidimensional evaluation and integrated research on cultivar-environment-processing interactions, providing references for the selection of high-quality cultivars and the development of the Longjing tea industry.

**Keywords** Longjing tea; Tea plant cultivars; Quality traits; Chemical composition; Processing suitability

## 1 Introduction

Longjing tea, one of the most representative pan-fired flat green teas in China, is produced in Hangzhou, Zhejiang Province. It is renowned both domestically and internationally for its typical quality characteristics of “green color, rich aroma, mellow taste, and beautiful shape,” and has been granted geographical indication protection (Shen et al., 2024). Its distinctive sensory quality and profound cultural heritage place it at the core of China’s premium green tea system, while its limited early-spring yield and well-established grading system confer significant economic value (Yu et al., 2023; Zhao et al., 2024). In recent years, with the shift toward premium and health-oriented consumption, demand for high-quality green tea—particularly Longjing tea with strong geographical identity—has continued to increase, promoting industrial expansion and making it a key pillar of the tea industry in Zhejiang and across China (Huang et al., 2024; Teng et al., 2024).

Against this background, the formation mechanism and stability of Longjing tea quality have become important research focuses. Previous studies have shown that Longjing tea quality depends not only on processing techniques but also on the combined effects of cultivar, growing environment, and harvesting period (Yu et al., 2023). With the advancement of metabolomics, sensory science, and genomics, researchers are now able to systematically elucidate, at the molecular level, the dynamic changes of amino acids, catechins, phenolic acids, and volatile compounds during processing, as well as their contributions to key quality attributes such as freshness, bitterness-astringency balance, and chestnut-like aroma (Huang et al., 2024; Teng et al., 2024; Zeng et al., 2024). Meanwhile, techniques such as stable isotope analysis, near-infrared spectroscopy, and chemometric modeling have been applied to authenticity identification and quality grading, reflecting increasing industry demands for quality stability and traceability (Zhao et al., 2024; Wu et al., 2025).

Among the various influencing factors, tea plant cultivars are considered one of the core determinants of quality differences in Longjing tea. Significant variations exist among cultivars in genetic background, physiological

traits, and metabolic profiles, leading to distinct accumulation patterns of flavonoids, amino acids, alkaloids, and aroma precursors even under similar cultivation and processing conditions (Yu et al., 2023; Bassiony et al., 2024). These differences directly affect the freshness, bitterness, and overall flavor balance of the tea infusion. For example, “Longjing 43” and local population varieties differ markedly in chlorophyll composition, amino acid content, and responses to environmental factors, thereby influencing the color and taste of the final product (Teng et al., 2024), while variations in volatile compounds determine characteristic aroma types such as bean-like and chestnut-like notes (Yan et al., 2025). With advances in breeding and molecular biology, several improved cultivars suitable for Longjing tea processing (e.g., Longjing 43, Wuniuzao, and Zhenong series) have been developed and widely adopted. However, differences in processing suitability and quality stability among cultivars remain evident (Teng et al., 2024). Meanwhile, genomic tools such as QTL mapping and molecular markers have provided new insights into the genetic basis of quality traits (Gao et al., 2023a; Ao et al., 2025), yet systematic comparisons among specialized Longjing cultivars are still lacking, highlighting the need for comprehensive multi-dimensional studies (Huang et al., 2024).

This study focuses on different tea plant cultivars used for Longjing tea processing, aiming to analyze their differences in appearance, sensory characteristics, and chemical composition. Special attention is given to the roles of non-volatile and volatile metabolites in quality formation, as well as processing suitability and its molecular regulation mechanisms. Furthermore, by integrating advances in metabolomics and genetics, this study evaluates the potential applications of cultivar differences in quality grading, authenticity identification, and the breeding of high-quality specialized cultivars. The findings are expected to provide a theoretical basis for cultivar selection and precise matching between cultivars and processing techniques, thereby promoting the high-quality development of the Longjing tea industry.

## **2 Basis of Longjing Tea Quality Formation**

### **2.1 Typical quality characteristics of Longjing tea**

Longjing tea, as a typical representative of flat green tea in China, exhibits its quality characteristics mainly in appearance, aroma, taste, liquor color, and infused leaves, forming a stable and highly recognizable style. High-quality Longjing tea is characterized by flat, smooth, straight, and uniform dry leaves, with a tender green or bright green color; the brewed liquor appears bright yellow-green and clear, while the infused leaves are tender, uniform, soft, and well-expanded (Bassiony et al., 2024; Zeng et al., 2024). This distinctive “flat, smooth, straight” appearance results not only from the tenderness and uniformity of fresh leaves but also from key processing steps such as flattening and shaping, serving as an important feature distinguishing it from other green teas. Generally, fresh leaves consisting of one bud with one or two young leaves are more suitable for producing high-quality appearance. Some studies have shown that the appearance quality of Longjing tea can be quantitatively evaluated using colorimetric parameters, where L, a, b values and chlorophyll content are significantly correlated with sensory evaluation. Moderate brightness and yellow-green coloration are favorable for high-quality appearance, whereas excessive chlorophyll may lead to darker color and reduced visual quality (Shan et al., 2023a; Bassiony et al., 2024; Zhang et al., 2024). In addition, higher-grade samples often exhibit lighter and brighter liquor, reflecting more tender raw materials and more precise processing control (Shan et al., 2025).

Aroma and taste are the core dimensions in evaluating Longjing tea quality. Longjing tea is typically characterized by a fresh aroma, with high-quality samples exhibiting prominent bean-like and chestnut-like notes, often accompanied by floral or sweet nuances, resulting in a delicate, persistent, and layered aroma profile (Teng et al., 2024). Its aroma is mainly derived from volatile compounds such as linalool, geraniol, hexanal, and various aldehydes, ketones, and pyrazines, whose combinations can effectively reproduce the characteristic Longjing aroma (Bassiony et al., 2024). Aroma formation depends on both precursor compounds in fresh leaves and transformations during processing, with the initial pan-firing stage playing a critical role, while subsequent steps modulate aroma composition (Zeng et al., 2024). In terms of taste, Longjing tea is characterized by freshness, mellow sweetness, moderate bitterness and astringency, and a lasting aftertaste (Zhang et al., 2024). Its flavor is

determined by the balance among amino acids, catechins, caffeine, and other compounds, where amino acids contribute to freshness, while polyphenols and caffeine form the structural basis of taste. Bitterness and astringency are mainly associated with catechins (e.g., EGCG) and related flavonoids and are strongly influenced by processing conditions (Shan et al., 2023a; Shan et al., 2025). Therefore, the taste of Longjing tea is essentially the result of the synergistic interaction of multiple compounds.

## 2.2 Main factors affecting quality formation

### 2.2.1 Cultivar factors

Tea plant cultivars determine the genetic background and metabolic characteristics of fresh leaves and are the fundamental source of quality differences in Longjing tea. Significant variations exist among cultivars in the composition of amino acids, catechins, flavonoids, alkaloids, and aroma precursors, leading to distinct sensory profiles even under identical cultivation and processing conditions (Shan et al., 2023; Zeng et al., 2024; Ao et al., 2025). For example, commonly used materials such as “Longjing 43,” “Baie No.1,” and local population varieties differ markedly in metabolic profiles and quality expression. Longjing 43 generally contains higher levels of flavonoids and chlorophyll b, contributing to its typical color and style, whereas Baie No.1 often exhibits higher glutamic acid and glutamine levels along with different caffeine/theobromine ratios, influencing freshness enhancement and bitterness expression (Teng et al., 2024; Zhang et al., 2024). Thus, differences in freshness, chestnut-like aroma intensity, body, and briskness among cultivars fundamentally reflect variations in metabolic composition and processing responses.

### 2.2.2 Environmental factors

Environmental conditions constitute an important external basis for Longjing tea quality formation. Suitable temperature, light, precipitation, soil properties, and ecological conditions promote tea plant growth and metabolite accumulation, thereby improving raw material quality. Recent studies have shown that altitude, habitat, and cultivation environment can significantly regulate key metabolites such as amino acids, flavonoids, sugars, and aroma precursors (Bassiony et al., 2024). For instance, higher altitudes generally favor the accumulation of flavonoids, amino acids, and soluble sugars, enhancing sweetness and freshness, while regional climatic conditions further shape the characteristic flavor profiles of Longjing tea. Therefore, the quality potential of Longjing tea is not determined solely by cultivar but arises from genotype  $\times$  environment interactions, which establish the metabolic basis later expressed through processing (Ao et al., 2025).

### 2.2.3 Processing factors

Processing is the key external factor determining Longjing tea quality and the core step in transforming raw material potential into final product quality. The typical process includes withering, fixation (kill-green), shaping/pan-firing, further frying, and drying or aroma enhancement, each contributing differently to the formation of appearance, aroma, and taste (Zeng et al., 2024; Zhang et al., 2024). Withering significantly influences non-volatile compounds such as amino acids, catechin dimers, organic acids, and phenolic acids, thereby affecting taste and liquor color. Studies indicate that optimal sensory quality is achieved when leaf moisture content is about 70% at the end of withering (Shan et al., 2023). Fixation temperature affects enzyme inactivation and thermal reactions; for example, around 215 °C can reduce bitterness while preserving beneficial amino acids and phenolic acids, leading to improved taste balance (Figure 1) (Shan et al., 2025).

Processing is also crucial for aroma development. Metabolomic studies show that flavonoids, amino acids, alkaloids, lipids, and carbohydrates undergo significant changes during processing. While different cultivars exhibit similar trends, the magnitude of change varies. The initial frying stage is critical for the rapid formation of volatile compounds, whereas subsequent steps adjust the balance among fresh, chestnut-like, sweet, and floral aromas (Zeng et al., 2024; Zhang et al., 2024). Brewing conditions also affect quality expression; for instance, lower temperatures (70°C - 80°C) favor amino acid extraction while slowing the release of bitter compounds, enhancing freshness and reducing astringency (Teng et al., 2024; Deng et al., 2025).

## 2.3 Quality evaluation indicators and methods

### 2.3.1 Sensory evaluation

Sensory evaluation is the core basis for assessing Longjing tea quality. According to national and industry standards, a 100-point scoring system is typically used, evaluating appearance, liquor color, aroma, taste, and infused leaves, with aroma and taste often assigned higher weights (Shan et al., 2023; Bassiony et al., 2024; Zeng et al., 2024; Zhang et al., 2024). Trained panelists assess tea samples through visual inspection, aroma perception, tasting, and leaf observation. This method effectively captures key sensory attributes such as freshness, chestnut-like aroma, tenderness, mellowness, and sweetness.



Figure 1 Different stages in the production process of Longjing tea

To improve interpretability, quantitative descriptive analysis (QDA) is increasingly used to break down flavor attributes into subcategories such as umami, sweetness, bitterness, astringency, freshness, chestnut aroma, floral aroma, and grassy notes (Shan et al., 2025; Zeng et al., 2024). The CATA method has also been applied to link descriptive terms with consumer preferences. Studies show that enhanced umami, sweetness, and pleasant aromas increase consumer acceptance, whereas excessive bitterness and grassy notes reduce it (Deng et al., 2025).

### 2.3.2 Physicochemical indicators and instrumental analysis

To overcome subjectivity in sensory evaluation, physicochemical measurements are widely applied. Common indicators include amino acids, tea polyphenols, caffeine, water extractives, catechins, phenolic acids, organic acids, and flavonol glycosides, which are closely related to taste attributes (Shan et al., 2025). Non-volatile compounds mainly determine taste, while volatile compounds govern aroma. Techniques such as GC-MS, GC-IMS, and LC-MS are widely used to analyze these components (Shan et al., 2023; Zhang et al., 2024).

Comprehensive chemical analysis has advanced quality evaluation from simple composition measurement to biomarker identification. By correlating key volatile compounds (e.g., linalool, geraniol, aldehydes, pyrazines) and non-volatile compounds (e.g., theanine, EGCG, flavonol glycosides) with sensory scores, quantitative relationships can be established (Shan et al., 2023; Bassiony et al., 2024; Zhang et al., 2024; Shan et al., 2025).

### 2.3.3 Chemometrics, intelligent sensing, and rapid detection

In recent years, multivariate analysis, machine learning, and intelligent sensing technologies have been increasingly applied in Longjing tea evaluation. Methods such as PCA, logistic regression, PLS-DA, and neural networks are used to identify key quality markers and predict taste, aroma, and overall quality (Bassiony et al., 2024). Indicators such as total amino acids, theanine, EGCG, and specific flavonol glycosides show strong discriminative ability (Shan et al., 2025).

Meanwhile, technologies such as electronic noses, electronic tongues, and near-infrared spectroscopy enable rapid and non-destructive quality assessment. For example, electronic noses can differentiate tea grades and brands (Moreira et al., 2024), while NIR combined with machine learning can predict sensory scores and chemical composition. Integrated multi-scale analytical frameworks combining metabolomics, colorimetry, intelligent sensing, and sensory evaluation are increasingly used to systematically reveal how processing and brewing influence final tea quality (Shan et al., 2023; Teng et al., 2024; Zhang et al., 2024; Deng et al., 2025).

## 3 Major Types of Tea Cultivars Used for Processing

### 3.1 Traditional and main cultivars

Traditional Longjing tea processing has long relied on local population-type tea germplasm, among which the Longjing population variety is the most representative. Population varieties are genetically heterogeneous groups that gradually formed through long-term farmer selection, natural adaptation, and local cultivation practices, and are characterized by broad genetic backgrounds, strong ecological adaptability, and diverse flavor types. These materials show considerable individual variation in bud and leaf size, sprouting time, leaf structure, and metabolite composition. However, it is precisely this within-population variation that provides an important material basis for the formation of the classic Longjing tea style in the core West Lake production area (Yu et al., 2023). From a quality perspective, fresh leaves of population varieties are generally rich in internal compounds, especially with advantages in aroma performance. The teas produced from them often exhibit more complex volatile profiles and stronger aroma layering, forming typical bean-like and chestnut-like notes, and sometimes even certain floral and fruity characteristics (Figure 2) (Ao et al., 2025; Yan et al., 2025). Therefore, population varieties have long been regarded as important raw materials for producing high-quality Longjing tea with a traditional style.

However, the advantages of population varieties coexist with limitations. Due to their large genetic variation within the population, different individual plants vary significantly in sprouting uniformity, bud plumpness, yield potential, and metabolite accumulation. As a result, under modern standardized and large-scale production systems, they often face problems such as uneven sprouting, inconsistent harvesting periods, and large batch-to-batch quality fluctuations (Figure 3) (Ao et al., 2025). Comparative metabolomic studies under uniform cultivation and processing conditions have shown that, between Longjing population varieties and Longjing 43, flavonoid metabolites often contribute the most to quality differences, and this cultivar effect may even exceed some effects of production area and storage time (Yu et al., 2023). This indicates that although population varieties possess advantages in traditional flavor, their insufficient stability in quality expression limits their application in large-scale mechanized production systems.

Compared with population varieties, Longjing 43 (LJ43) is currently one of the most widely used elite clonal cultivars in Longjing tea production and is also the dominant cultivar in the modern standardized production system. Longjing 43 was selected from superior local germplasm and has advantages such as early sprouting, uniform bud emergence, relatively strong cold resistance, wide adaptability, and stable yield, making it suitable for premium green tea processing as well as mechanized harvesting and standardized processing (Gao et al., 2023a). In terms of quality, Longjing 43 generally has relatively high amino acid levels, a well-balanced taste

foundation, and a stable chestnut-like aroma style. At the same time, its relatively high contents of flavonoids, flavonols, and free fatty acids provide a metabolic basis for aroma formation and mouthfeel expression (Zeng et al., 2024). Therefore, teas made from Longjing 43 usually exhibit fresh, balanced, and stable overall quality characteristics. Although in some cases its aroma complexity is slightly simpler than that of traditional population varieties, its industrial adaptability and commercial consistency are stronger. Notably, Longjing 43 is not only a major production cultivar but has also become an important model material in tea plant basic research. Its high-quality chromosome-level genome assembly has shown that gene loci related to flavor formation, metabolic regulation, and disease resistance underwent strong selection during tea domestication (Gao et al., 2023a). The establishment of this genomic resource has not only enhanced the understanding of the mechanisms underlying the superior traits of Longjing 43, but has also provided a theoretical basis for subsequent marker-assisted breeding, target metabolite-oriented improvement, and the breeding of specialized cultivars for Longjing-type tea processing.

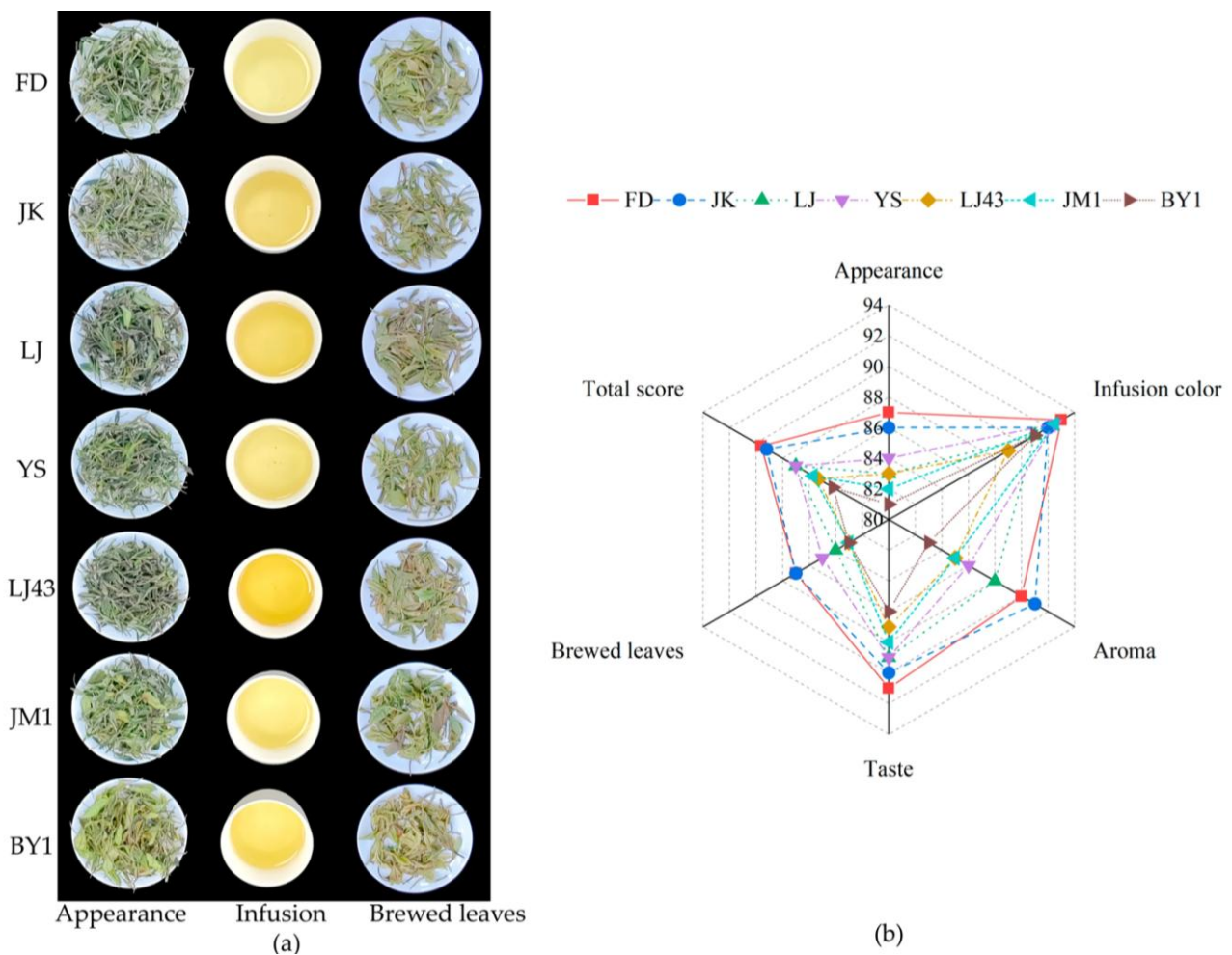


Figure 2 The sensory qualities of HGW (Adopted from Ao et al., 2025)

Image caption: (a) The photos of tea samples, infusions, and brewed tea leaves. (b) Evaluation of each quality factor and calculation of the total score (Adopted from Ao et al., 2025)

### 3.2 Promoted cultivars

With the expansion of the Longjing tea industry and increasing market demand for early harvesting, high yield, strong processing suitability, and cross-regional adaptability, a group of promoted cultivars has gradually been applied in Longjing tea production. Among them, Wuniuzao is a typical extremely early-sprouting cultivar. Because of its early spring bud break and significantly advanced market entry, it has high economic value, especially for capturing the early-spring premium tea market. The fresh leaves of Wuniuzao are relatively tender and show good potential for appearance formation, producing fairly uniform flat green tea under proper harvesting

and processing conditions. At the same time, its strong sprouting capacity also helps increase the supply of fresh leaves in early spring. However, in terms of flavor expression for high-end Longjing tea, some studies have shown that Wuniuzao is slightly inferior to traditional population varieties or Longjing 43 in aroma layering and taste body, especially when developing products with a high-end traditional style, where a trade-off often needs to be made between “earlier market entry” and “depth of quality.”



Figure 3 Morphological characteristics of Longjing 43 under different conditions

In addition to Wuniuzao, cultivars in the Zhenong series (such as Zhenong 117) have also become important clonal materials gradually promoted in some Longjing-producing areas in recent years. These cultivars usually possess strong adaptability, high yield potential, and good bud uniformity, and they show relatively stable growth vigor and processing suitability under multiple ecological conditions. In non-traditional Longjing-producing regions such as western Sichuan, materials such as Wuniuzao, Changye Longjing, and Zhenong 117 have all performed well in bud-leaf traits, biochemical composition, and suitability for premium green tea processing. Among them, Wuniuzao and Changye Longjing have relatively high total catechin and amino acid contents and moderate tea polyphenol levels, giving them better overall quality, while Zhenong 117 maintains similar quality but yields more than local control cultivars, making it suitable for medium-scale promotion. These results indicate that, under proper cultivation and processing conditions, promoted cultivars can reproduce the key quality characteristics of the Longjing style to a certain extent.

From the perspective of aroma metabolite profiles, there are obvious differences among promoted cultivars. Comparative studies have found that after being processed into Longjing tea, Wuniuzao differs from Longjing 43 and population varieties in the relative contents of esters, aldehydes, heterocyclic compounds, alcohols, and acids, suggesting some specificity in its aroma expression pathway. However, core aroma compounds such as linalool, D-limonene,  $\beta$ -ionone, jasmone, and (Z)-hexenyl esters still dominate across different materials, indicating that the basic aroma framework of Longjing tea can still be maintained (Ao et al., 2025). In general, teas made from Longjing 43 and population varieties tend to have relatively higher ester and aldehyde contents, whereas some introduced materials may accumulate more heterocyclic compounds or organic acids, thereby altering the balance among chestnut-like, fresh, and sweet aromas to some extent (Ao et al., 2025). In terms of non-volatile components, these promoted cultivars usually combine relatively high amino acid contents with moderate catechin levels, which is favorable for forming a good freshness foundation while maintaining a balance between

astringency and body. Therefore, such cultivars are particularly suitable as important supplementary raw materials outside the core traditional production areas, meeting the needs for early harvesting and yield, while also providing more options for developing Longjing-type products with different market positions.

### **3.3 Newly bred cultivars and their biological characteristics**

In recent years, as tea breeding objectives have shifted from simply pursuing high yield toward high quality, functional flavor, and precise processing suitability, a number of newly bred cultivars and special germplasm suitable for Longjing tea processing have gradually attracted attention. During the breeding process, these new materials place greater emphasis on targeted improvement, such as high amino acid content, high aroma potential, low bitterness and astringency, and strong environmental responsiveness, thereby providing a new resource base for the premiumization and diversification of Longjing tea. Among them, albino or color-variant materials are currently one of the most actively studied groups. Represented by cultivars such as “Baie No.1,” their spring tender shoots are jade white or pale yellow and are characterized by high amino acid content and relatively low catechin levels, making them more likely to produce tea with fresh, sweet, and mild taste and lower bitterness and astringency (Li et al., 2025; Yan et al., 2025). Metabolomic studies have shown that these materials are rich in various amino acids and sugars, whereas bitterness-related components are significantly reduced, resulting in a fresher and sweeter flavor profile in the final tea (Bassiony et al., 2024).

From the perspective of genetics and metabolic mechanisms, newly bred cultivars not only exhibit significant sensory differences but also have analyzable molecular bases. In population studies constructed using Longjing 43 and albino materials, key QTL regions controlling the accumulation of theanine and multiple free amino acids have been identified, providing clear targets for breeding high-umami cultivars (Yan et al., 2025). In terms of processing response, the metabolic pathways also differ among cultivars. For example, Baie No.1 shows obvious dynamic changes in volatile compounds during processing, with floral and fresh aroma compounds dominating in the early stage and chestnut-like aroma-related compounds gradually accumulating in the later stage, showing a distinct aroma formation trajectory compared with traditional cultivars (Li et al., 2025). At the same time, under the same processing conditions, different cultivars show significant differences in non-volatile metabolite composition, reflecting different quality formation patterns.

In addition, newly bred cultivars also show important potential in environmental adaptability. For example, Longjing 43 exhibits specific flavonoid synthesis and light-response regulation characteristics under shading conditions, providing a basis for screening cultivars with stable quality under different ecological conditions (Li et al., 2025; Cui et al., 2026). However, these new varieties still face challenges in their promotion and application, including insufficient regional adaptability verification and limited evidence for long-term quality stability. Some special cultivars may show outstanding freshness or aroma, but whether they conform to the traditional Longjing style and market perception still requires further evaluation. Therefore, future studies should combine multi-location and multi-year trials, metabolomic analysis, and sensory evaluation to systematically verify the processing suitability and quality stability of new cultivars, so as to support their scientific promotion and application.

## **4 Differences in Quality Traits Among Cultivars**

### **4.1 Differences in appearance quality**

The inherent differences in bud–leaf morphology among tea cultivars are an important basis affecting the appearance quality of Longjing tea. Longjing tea has high requirements for raw material morphology, and fresh leaves with tender buds and leaves, moderate length, soft texture, and balanced thickness are generally more conducive to forming the typical “flat, smooth, straight, and even” appearance. Studies have shown significant differences among germplasm resources in bud length, leaf size, leaf thickness, and hundred-bud weight, which gives some cultivars greater shaping potential, whereas cultivars with thicker leaves or coarser buds are more likely to show insufficient flatness or reduced uniformity during processing (Li et al., 2025). For example, Longjing 43 has relatively short buds and high uniformity, making it easier to form a smooth and straight appearance, whereas population varieties, due to their strong genetic heterogeneity, exhibit greater variation in

bud and leaf traits and thus relatively lower appearance consistency in the finished tea (Yu et al., 2023; Yan et al., 2025). In addition, technologies such as hyperspectral imaging can quantitatively identify differences in fresh leaf morphology and texture among cultivars, further indicating that appearance quality has a clear genetic basis (Figure 4) (Zhao et al., 2024).

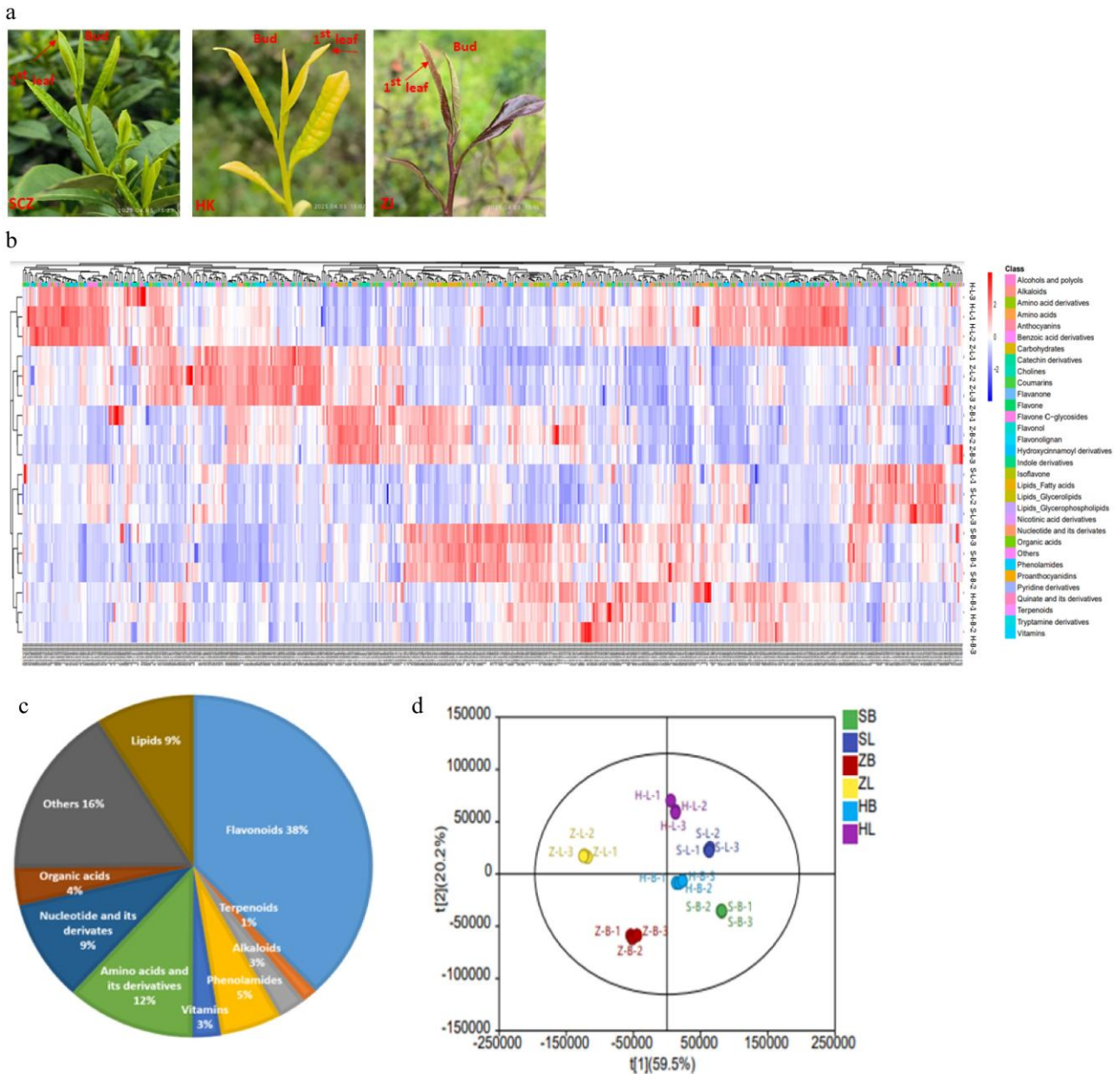


Figure 4 Detection and identification of specialized metabolites (Adopted from Zhao et al., 2024)

Image caption: (a) The phenotypes of two tissues of the three cultivars. 'Shuchazao' (SCZ), 'Huangkui' (HK) and 'Zijuan' (ZJ). (b) Clustering heatmap tree of total metabolites of two tissues of the three cultivars. Z-scores normalize the value. Red indicates a high abundance, and blue indicates a low relative abundance of metabolites. (c) Composition and proportion of different metabolites in different tea cultivars. (d) PCA of the metabolites in different tissues of tea plants. SB: SCZ-bud; ZB: ZJ-bud; HB: HK-bud; SL: SCZ-leaf; ZL: ZJ-leaf; HL: HK-leaf (Adopted from Zhao et al., 2024)

Color is another key indicator of the appearance quality of Longjing tea. Differences among cultivars in chlorophyll, carotenoids, and anthocyanin contents lead to variations in the overall color of dry tea, liquor, and infused leaves. High-quality Longjing tea usually appears tender green or bright green with luster, while different cultivars may show light green, yellow-green, or composite hues. Studies have shown that the relatively high chlorophyll b content in Longjing 43 contributes to the formation of a typical overall color (Teng et al., 2024). In

contrast, albino or color-variant cultivars such as “Baie No.1”, “Huangjinya”, and “Zijuan” often display lighter, bright yellow, or darker tones due to differences in pigment composition (Shan et al., 2023; Zeng et al., 2024). Among them, albino cultivars show lighter and brighter color because of reduced chlorophyll, whereas purple cultivars may exhibit darker overall color and some degree of bitterness and astringency due to anthocyanin accumulation (Zeng et al., 2024).

Uniformity reflects sprouting consistency and processing adaptability and is an important component of appearance quality. Clonal elite cultivars such as Longjing 43 and some promoted cultivars, due to their high genetic consistency and uniform sprouting, are conducive to standardized harvesting and raw material grading, thereby improving the uniformity of the finished tea. By contrast, population varieties and some highly heterogeneous materials tend to produce greater raw material variation because of inconsistent sprouting, which affects the final visual quality (Yu et al., 2023). Therefore, cultivar selection plays a fundamental role in the formation of Longjing tea appearance quality, influencing the entire process from fresh leaf development to harvest grading and final processing.

#### 4.2 Differences in sensory quality

Aroma and taste are the most critical sensory dimensions for distinguishing different Longjing tea cultivars. Because cultivars differ in volatile precursors, non-volatile taste compounds, and processing response patterns, the finished teas show different aroma types, freshness, bitterness–astringency intensity, and aftertaste characteristics (Yu et al., 2023; Teng et al., 2024). In general, traditional population varieties, with their more complex metabolic background, tend to produce richer bean-like and chestnut-like aromas with some floral nuances, resulting in more variable and regionally distinctive aroma styles. In contrast, Longjing 43 is mainly characterized by a more balanced fresh–chestnut aroma, a more elegant aroma profile, and better stability, giving it a strong advantage in standardized processing (Yan et al., 2025). Studies on different aroma styles of Longjing tea have shown that when classified into tender-aroma, fresh-aroma, or high-aroma types, their volatile profiles differ markedly, with systematic changes in the types and contents of alcohols, aldehydes, terpenes, and heterocyclic compounds. For example, in bean-aroma and fresh-aroma Longjing teas, geraniol and (E,E)-2,4-heptadienal are important contributors to bean-like aroma, whereas hexanal-d and heptanal-d are more associated with fresh green notes (Ao et al., 2025). This indicates that aroma differences among cultivars are reflected not merely in intensity but more importantly in characteristic aroma combinations and relative proportions.

Among special cultivars, the albino cultivar “Baie No.1” exhibits a different aroma formation pathway from ordinary green-leaf cultivars. Studies have shown that during the early stages of processing, it tends to accumulate more fresh and floral volatile compounds, while during the later frying and aroma-enhancing stages, it gradually develops an aroma framework dominated by pyrazines associated with chestnut-like notes (Teng et al., 2024; Yan et al., 2025). Therefore, even when processed into Longjing tea, different cultivars may express different aroma styles, such as “floral-dominant,” “bean-aroma prominent,” or “chestnut-aroma pronounced,” which directly affects product style classification and market positioning. Taste differences are likewise clearly cultivar-dependent. Variations among cultivars in amino acids, flavonoids, alkaloids, lipids, and peptides systematically influence freshness, bitterness–astringency, mellowness, and aftertaste potential of the tea liquor (Yu et al., 2023; Yan et al., 2025). Cultivars with higher amino acid content usually exhibit stronger freshness and lower stimulation, making them suitable for producing a fresh and balanced taste profile, whereas cultivars with higher levels of tea polyphenols, complex catechins, and flavonol glycosides often show stronger taste, more obvious astringency, but also a more defined body and longer aftertaste (Yu et al., 2023; Li et al., 2025).

Taking Longjing 43 as an example, it usually contains higher levels of theanine and glutamine, along with greater flavonoid accumulation, and therefore often produces tea with better freshness and balance. By contrast, albino or special cultivars such as Baie No.1 generally accumulate more glutamic acid and glutamine but relatively lower levels of bitterness-related alkaloids such as caffeine and theobromine, resulting in a sweeter, fresher, milder, and less stimulating taste (Teng et al., 2024). In addition, Longjing 43 and population varieties differ not only in small-molecule metabolites but also in peptide composition. Studies have shown that population varieties contain

more water-soluble peptides, whereas Longjing 43 has higher theanine and glutamine contents, and these jointly affect umami, kokumi, and mellowness formation (Yan et al., 2025). Research on differently colored cultivars also indicates that green and purple cultivars generally exhibit stronger bitterness and astringency because of higher flavan-3-ol and anthocyanin levels, while yellow or albino cultivars usually have a milder flavor due to higher free amino acid contents (Zeng et al., 2024). Therefore, cultivar differences do not simply determine a single flavor attribute, but rather shape distinct sensory styles by altering the balance among freshness, sweetness, astringency, body, and aftertaste. For this reason, aroma and taste are regarded as the core indicators for distinguishing different Longjing tea cultivars and their product types (Yu et al., 2023; Ao et al., 2025).

#### 4.3 Differences in liquor color and infused leaf performance

Liquor color and infused leaves are important components of the visual quality of Longjing tea and are also the result of the combined effects of cultivar traits and processing suitability. High-quality Longjing tea usually has a tender bright green or yellow-green, clear liquor with high transparency, while the infused leaves are soft, uniform, and consistent in color. Due to differences in soluble substances, tea polyphenol and catechin composition, pigment background, and leaf structure, cultivars vary in liquor brightness, overall hue, and the unfolding state of infused leaves (Teng et al., 2024). Studies have shown that cultivars with higher water extract and tea polyphenol contents tend to have deeper-colored liquor with a stronger sense of concentration, whereas cultivars with lower internal compounds produce lighter and brighter liquor with a thinner mouthfeel (Zhang et al., 2024), indicating that liquor color not only reflects processing outcomes but also the chemical basis of the cultivar.

Further studies have found that the overall color of tea liquor is closely related to various metabolites, such as catechin dimers, phenolic acids, organic acids, and galloyl glucose, which play important roles in liquor brightness and yellow-green balance (Teng et al., 2024). Because the accumulation of these compounds varies among cultivars, even under the same processing and brewing conditions, significant differences may still be observed in liquor brightness and overall tone. For example, albino and low-chlorophyll cultivars tend to produce brighter, more yellow-green or pale-yellow liquor, whereas purple cultivars rich in anthocyanins may present darker or mixed hues (Shan et al., 2023; Zeng et al., 2024).

The performance of infused leaves reflects leaf structural characteristics and processing response. Differences among cultivars in bud-leaf tenderness, leaf thickness, and cell structure affect the unfolding, softness, and integrity of leaves after brewing. High-quality cultivars usually have tender leaves with relatively uniform structure, resulting in soft, bright, and even infused leaves. In contrast, cultivars with thicker leaves or higher maturity are more likely to show rough, broken, or unevenly colored infused leaves (Li et al., 2025). In addition, clonal cultivars such as Longjing 43 generally show better consistency in infused leaves because of their uniform buds and leaves, whereas population varieties often show greater variation (Yan et al., 2025). Overall, liquor color and infused leaf performance are important comprehensive manifestations of cultivar differences and the degree of match between cultivar and processing method (Zeng et al., 2024; Zhang et al., 2024).

### 5 Differences in Chemical Components and Their Roles

#### 5.1 Differences in major quality components

Amino acids, tea polyphenols, and caffeine are the core chemical bases determining the taste characteristics of Longjing tea. Significant differences in their contents and proportions among cultivars directly affect freshness, bitterness–astringency, and overall taste balance (Zeng et al., 2024). Among these, amino acid differences are particularly prominent. Studies have shown that “Baie No.1” is rich in L-glutamic acid and L-glutamine, whereas “Longjing 43” contains higher levels of flavonoids (Shan et al., 2023). Comparative analyses between Longjing 43 and population varieties indicate that the former has higher theanine and glutamine contents, while total catechin levels are similar, suggesting that differences in freshness mainly arise from amino acids and related peptides (Huang et al., 2024). Therefore, high amino acid accumulation is a key basis for the formation of a fresh and mellow taste.

Tea polyphenols, especially catechins, are the main contributors to bitterness, astringency, and the structural backbone of taste. Cultivars with higher polyphenol content generally exhibit stronger body and aftertaste

potential, although imbalanced proportions may lead to excessive bitterness (Shan et al., 2025). Studies indicate that flavan-3-ols are the most abundant compounds in Longjing tea and constitute the main chemical basis of bitterness and intensity. Differences among cultivars in polyphenols and their derivatives further result in the differentiation of “fresh-type” and “mellow-type” flavor styles (Huang et al., 2024). Caffeine also plays a regulatory role in bitterness perception and taste balance; for example, the lower caffeine content in “Baie No.1” is consistent with its milder bitterness (Shan et al., 2023).

In addition, processing and environmental conditions further regulate the dynamic changes of these components. Studies have shown that with increasing withering degree, amino acids and certain catechin dimers increase, while organic acids and phenolic acids decrease, thereby affecting taste and liquor color (Shan et al., 2025). Multi-cultivar studies also demonstrate that tea polyphenols, catechins, and amino acids exhibit significant cultivar-dependent differences (Zeng et al., 2024). Overall, the proportional relationships among these three major components are more explanatory than individual component levels: a high amino acid/low polyphenol combination favors a fresh style, whereas higher polyphenols enhance body and aftertaste.

### 5.2 Differences in volatile aroma composition

Volatile aroma compounds are fundamental determinants of the aroma type and complexity of Longjing tea, and their composition varies significantly among cultivars. The aroma of Longjing tea mainly consists of alcohols, aldehydes, esters, ketones, and heterocyclic compounds, which originate from precursor substances in fresh leaves and are gradually formed through enzymatic and thermal reactions during processing (Gao et al., 2023b; Zhang et al., 2024). Therefore, cultivar differences are first reflected in the composition of aroma precursors.

The aroma profiles of different cultivars exhibit clear specificity. Studies have identified 97 key aroma-active compounds across multiple cultivars, among which aldehydes, ketones, and heterocyclic compounds play important roles in aroma formation (Zeng et al., 2024). Core aroma compounds such as linalool, geraniol, hexanal, and  $\beta$ -ionone are commonly present in Longjing tea, but their relative contents differ significantly and are closely related to quality evaluation (Zhang et al., 2024). This indicates that aroma differences are mainly derived from variations in the proportions of multiple compounds rather than the presence or absence of a single compound.

Differences among aroma types further highlight the role of cultivars. For example, in bean-aroma Longjing tea, geraniol and (E,E)-2,4-heptadienal contribute significantly, whereas fresh-aroma types are more associated with hexanal and heptanal (Bassiony et al., 2024). During processing of Baie No.1, volatile compounds change dynamically, with floral and fresh aromas dominating in the early stage and chestnut-like aromas forming in the later stage (Gao et al., 2023b). Thus, cultivars determine aroma style by influencing precursor metabolism and transformation pathways during processing (Li et al., 2024).

### 5.3 Correlation between chemical components and quality traits

There is a clear correlation between tea chemical composition and sensory quality, which provides an important basis for explaining quality differences among cultivars. In general, amino acids are positively correlated with freshness, tea polyphenols and caffeine with bitterness, astringency, and intensity, while volatile compounds determine aroma types (Huang et al., 2024). Studies on different withering degrees show that compounds such as theaflavins, thearubigins, organic acids, and amino acid derivatives are significantly correlated with taste and liquor color, indicating that quality formation depends on the synergistic effects of multiple components (Shan et al., 2025).

Large-scale sample analyses have identified EGCG, caffeine, theanine, and organic acids as key quality markers, which can be used to achieve high-accuracy predictions through statistical models. For example, specific flavonoid derivatives and amino acids can effectively distinguish different taste types, with model accuracy reaching 97.6%. This demonstrates that quantitative relationships between chemical composition and quality traits can be established.

Further cultivar-focused studies show that different combinations of amino acids and catechins correspond to distinct taste characteristics. Certain amino acids are associated with a mellow taste, whereas gallic acid and theobromine tend to enhance astringency (Guo et al., 2023). At the same time, variations in volatile compound proportions directly influence aroma style (Zhang et al., 2024). Environmental factors also regulate quality expression by altering metabolite accumulation; for instance, high-altitude conditions are conducive to enhancing sweet and mellow flavors (Bassiony et al., 2024). Overall, quality traits are the result of multi-component interactions dominated by cultivar and modulated by the environment.

## **6 Processing Suitability and Cultivar Response**

### **6.1 Adaptability of different cultivars to processing techniques**

The processing suitability of tea cultivars in Longjing tea production is mainly reflected in the responses of their biochemical composition and physical structure to various processing steps. Longjing tea processing involves key stages such as withering, fixation, shaping, and pan-firing. Due to differences in bud–leaf structure, moisture content, and internal composition, cultivars exhibit distinct behaviors during heat treatment and moisture loss, thereby affecting appearance, aroma, and taste (Li et al., 2023a; Shan et al., 2023; Teng et al., 2024). Overall, cultivar differences determine the range of processing adaptability and the potential for quality expression.

From a general processing perspective, some cultivars exhibit strong adaptability. For example, Longjing 43 can produce markedly different metabolic profiles under various tea processing methods and thermal treatments, indicating its broad adaptability across multiple processing conditions (Chen et al., 2024). In addition, its relatively high chlorophyll b content contributes to the formation of the typical dry tea color, further demonstrating its suitability for the Longjing processing pathway (Zeng et al., 2024). In contrast, different cultivars show significant variation in both volatile and non-volatile components during thermal processing, reflecting differences in flavor formation pathways.

At specific processing stages, bud–leaf structure and moisture status are critical for shaping. Leaves that are soft and of moderate thickness are more likely to form a flat and smooth appearance, whereas thicker or unevenly tender leaves tend to break or fail to achieve sufficient flatness (Yu et al., 2023). Studies indicate that when leaf moisture content is within 30%-50%, plasticity is optimal, facilitating stable shaping and reducing breakage (Li et al., 2023a). Furthermore, cultivars differ in their responses to fixation and withering; for example, cultivars with high amino acid content require careful temperature control to preserve freshness, whereas those with high polyphenol content are more prone to increased bitterness and astringency if improperly processed (Shan et al., 2023).

### **6.2 Stability and consistency of finished tea quality**

The stability and consistency of finished tea quality are key indicators for evaluating cultivar suitability. Stability refers not only to the reproducibility of quality under the same processing conditions but also to the ability to maintain consistent quality across different years or environmental fluctuations. Generally, clonal cultivars with uniform genetic backgrounds exhibit more stable fresh leaf traits and metabolic profiles, making them more likely to produce consistent finished tea quality.

Studies have shown that under identical processing conditions, cultivar effects on flavonoid and other metabolites are greater than those of production region or storage factors, indicating that cultivars play a dominant and stable role in quality formation. This means that major cultivars can maintain their characteristic flavor profiles within a certain range of environmental variation, thereby supporting standardized production. Further research indicates that although different cultivars follow similar metabolic trends during processing, differences in concentration levels lead to distinct and stable quality expressions (Zeng et al., 2024).

However, environmental conditions and processing parameters still influence quality consistency. For instance, Longjing 43 can maintain relatively high catechin levels under shading conditions, demonstrating strong metabolic stability (Li et al., 2023b). In processing, controlling key parameters—such as maintaining leaf moisture at around 70% after withering—can significantly improve taste and liquor color (Shan et al., 2023).

Additionally, leaf mechanical properties vary with moisture content, with the 30%-50% range being optimal for stable shaping, indicating that quality consistency results from the combined effects of cultivar, environment, and process control.

### **6.3 Evaluation indicators and methods for processing suitability**

The evaluation of processing suitability of tea cultivars requires a comprehensive approach integrating sensory, physicochemical, and physical performance indicators. Traditional sensory evaluation, based on scoring appearance, aroma, and taste, provides a direct reflection of cultivar performance under different processing conditions. For example, in studies on Baie No.1, subdividing aroma and taste attributes has been effective in identifying optimal processing schemes (Teng et al., 2024). When combined with electronic tongue analysis, sensory results can be linked to changes in chemical composition (Shan et al., 2023).

Physicochemical indicators provide an objective basis for evaluating suitability, including amino acids, tea polyphenols, caffeine, and volatile compounds (Chen et al., 2024; Zeng et al., 2024). At the same time, physical parameters such as leaf thickness, moisture content, and mechanical properties reflect shaping ability and resistance to damage during processing (Li et al., 2023b). Together, these indicators form the foundation of suitability evaluation.

In recent years, multidimensional evaluation methods have been increasingly developed. Near-infrared spectroscopy combined with models such as PLSR and SVR enables rapid prediction of quality indicators (Chen et al., 2024), while technologies such as electronic noses and machine vision provide objective assessments of aroma and appearance. In addition, texture analysis and mechanical modeling can quantify leaf processing behavior and provide parameter support for process optimization (Li et al., 2023b). These approaches are promoting a shift in suitability evaluation from experience-based judgment to data-driven analysis.

## **7 Molecular Mechanisms and Advances in Breeding Research**

### **7.1 Genes and regulatory mechanisms related to quality traits**

The formation of quality traits in Longjing tea—such as freshness, bitterness – astringency, aroma type, and leaf color—is essentially driven by complex genetic regulatory networks involving the coordinated regulation of multiple metabolic pathways, including those of amino acids, tea polyphenols, alkaloids, and volatile compounds. In recent years, studies based on the reference genome of Longjing 43 (LJ43) and population resequencing have shown that, during the domestication of *Camellia sinensis* var. *sinensis*, genes related to flavor formation and stress resistance have undergone strong selection pressure, indicating that quality-related metabolic pathways have long been key targets of artificial selection (Gao et al., 2023b). For non-volatile components, amino acid and polyphenol metabolic pathways are central to taste formation. Genes involved in theanine biosynthesis (e.g., CsTS, CsGS) regulate amino acid accumulation and directly affect freshness, while key structural genes in flavonoid/catechin biosynthesis (e.g., CHS, F3H, DFR) control polyphenol production, thereby influencing bitterness and aftertaste. In addition, caffeine biosynthesis is regulated by N-methyltransferase genes, and differences in their expression among cultivars form an important molecular basis for taste variation.

In terms of pigment formation and bitterness regulation, multi-omics studies have revealed that chlorophyll and carotenoid biosynthesis/degradation pathways, anthocyanin biosynthesis, and transport systems jointly determine leaf color and associated quality traits. For example, in albino materials, chlorophyll synthesis is inhibited while degradation is enhanced, whereas in purple-leaf materials, anthocyanin biosynthesis and transport genes are upregulated. These changes not only affect appearance but also influence amino acid and polyphenol accumulation through altered carbon allocation (Li et al., 2023b). Under environmental regulation, key genes such as CsANS and CsANR respond to changes in light and temperature, modulating catechin and flavonoid levels and leading to differences in quality stability among cultivars under shading or elevated temperature conditions (Wu et al., 2025).

Regarding aroma formation, lipid oxidation (LOX pathway), amino acid degradation, and terpenoid biosynthesis pathways jointly contribute to the production of volatile compounds. LOX and downstream enzymes are involved

in the formation of green-leaf volatiles, while terpene synthases (TPS) regulate the accumulation of floral and fruity compounds such as linalool and geraniol. Transcription factors, including MYB, bHLH, ERF, and MYC, play central regulatory roles in these pathways. For example, CsMYB1, CsERF2, and bHLH13 form regulatory networks that influence bitterness and temperature adaptability by modulating flavonoid synthesis and carbon allocation (Shen et al., 2024). In addition, pan-genome studies have shown that LTR transposon expansion can lead to gene copy number variation, resulting in functional diversity affecting leaf color, sprouting time, and flavor metabolism. This indicates that quality differences in Longjing tea arise not only from gene expression regulation but also from structural genetic variation.

## **7.2 Application of multi-omics technologies in quality research**

Multi-omics technologies—including genomics, transcriptomics, metabolomics, and proteomics—have become essential tools for elucidating the mechanisms of Longjing tea quality formation, enabling systematic analysis from genes to metabolites to phenotypes. At the genomic level, the LJ43 reference genome and population resequencing have revealed the evolutionary history of tea plants and selection signals in quality-related genes. Pan-genome studies further integrate structural variation information across multiple cultivars, allowing the detection of presence/absence variation (PAV) and copy number variation (CNV), which can then be associated with flavor and leaf color traits (Chen et al., 2023).

In integrated transcriptomic and metabolomic analyses, thousands of differentially expressed genes have been identified among cultivars, mainly enriched in pathways such as amino acid metabolism, flavonoid biosynthesis, lipid metabolism, and carbon metabolism. The expression patterns of these genes can directly explain differences in catechin, theanine, and caffeine contents (Wen et al., 2023). Through weighted gene co-expression network analysis (WGCNA), key hub gene modules regulating flavonoid and aroma biosynthesis can be identified, enabling the pinpointing of core regulatory nodes of quality traits (Yu et al., 2025). At the metabolomic level, analytical techniques such as LC-MS, GC-MS, and NMR are widely used to compare metabolic differences among cultivars, production regions, and processing methods, and to identify quality markers. For example, the dynamic changes of polyphenols and amino acids during processing can be tracked to elucidate the regulatory pathways of quality formation.

Notably, multi-omics research has evolved from single-layer analysis to multi-scale integration, including genome×transcriptome×metabolome integration, as well as epigenetics × environmental factors × quality phenotypes. These integrative analyses reveal that environmental factors such as shading and temperature influence quality formation in a cultivar-dependent manner by regulating gene expression and metabolic networks (Shen et al., 2024; Wu et al., 2025). Therefore, multi-omics approaches not only deepen the understanding of quality formation mechanisms but also provide molecular targets for precision breeding.

## **7.3 Marker-assisted breeding and development of new cultivars**

With the advancement of molecular technologies, the breeding of cultivars suitable for Longjing tea processing is shifting from traditional empirical selection to molecular design breeding. Molecular marker-assisted selection (MAS), QTL mapping, and genome-wide association studies (GWAS) have provided powerful tools for the precise improvement of quality traits. For example, in QTL mapping studies based on a genetic population derived from Longjing 43 and albino cultivars, high-density SNP maps (average spacing of 0.69 cM) have successfully identified multiple QTLs controlling free amino acids such as theanine and glutamic acid, explaining approximately 11.8%-23.7% of phenotypic variation (Chen et al., 2023). These findings provide clear genetic targets for breeding high-umami Longjing tea cultivars. At the genome-wide level, GWAS has identified multiple loci associated with catechins, caffeine, leaf color, and stress resistance (Gao et al., 2023a). Meanwhile, SNP resources based on the LJ43 reference genome facilitate the development of molecular markers, enabling early-stage prediction and selection of quality traits.

In terms of marker types, ILP (intron length polymorphism) markers, due to their high polymorphism and cross-species applicability, are widely used in cultivar identification and genetic analysis (Liu, 2024). In addition, graph-based pan-genome technologies allow structural variations to be incorporated into breeding systems,

providing new approaches for improving complex traits. Future trends in molecular breeding are expected to include multi-trait improvement (quality, stress resistance, and processing suitability), multi-omics-driven precision breeding, and the integration of high-throughput phenotyping with artificial intelligence models. Nevertheless, as tea plants are perennial crops with long breeding cycles, new cultivars still require long-term multi-regional trials to verify quality stability and processing adaptability. Therefore, the deep integration of molecular technologies with traditional breeding methods will remain the key pathway for improving Longjing tea cultivars.

## 8 Existing Issues and Future Perspectives

The current evaluation system for tea cultivars used in Longjing tea processing remains inadequate, mainly manifested in limited indicators, inconsistent standards, and a lack of systematic approaches. Existing studies often focus on sensory quality or partial physicochemical parameters, lacking a unified multi-dimensional evaluation system that integrates appearance, aroma, taste, and chemical composition, resulting in poor comparability among studies. In addition, differences in cultivar selection and quality evaluation standards across production regions have hindered the establishment of a standardized system specifically for Longjing tea cultivars. The strong subjectivity in evaluation, coupled with insufficient objective and quantitative indicators, further limits the scientific basis for cultivar selection and promotion. Therefore, it is necessary to develop a comprehensive evaluation system integrating sensory assessment and physicochemical analysis, while promoting the standardization and unification of evaluation criteria.

The formation of Longjing tea quality is the result of interactions among cultivar, environment, and processing techniques; however, systematic research on these interactions remains insufficient. Most studies focus on single factors, such as cultivar differences or process optimization, while comprehensive analyses of cultivar performance under varying ecological conditions and their responses to processing are relatively scarce. In practice, the same cultivar may exhibit significant differences in chemical composition and quality traits under different climates, soils, and altitudes, and the optimal processing parameters may also vary accordingly. The lack of integrated multi-factor studies limits a deeper understanding of the mechanisms underlying quality formation. Future research should emphasize multi-location and multi-year experiments and establish integrated “cultivar-environment-processing” interaction models to support precision production.

With the transformation of the Longjing tea industry toward high-quality development, the integration of specialized cultivar breeding and intelligent processing technologies will become a key direction. On the one hand, breeding efforts should target high aroma intensity, strong freshness, and low bitterness–astringency, while also considering yield and stress resistance to achieve a balance between quality and productivity. On the other hand, with the advancement of intelligent manufacturing technologies, automated and digital processing equipment is increasingly being applied in tea production, enabling precise control of processing conditions through temperature regulation, time management, and real-time monitoring. However, given that different cultivars respond differently to processing parameters, future research should focus on optimizing the compatibility between cultivars and intelligent processing systems. Promoting the coordinated development of “improved cultivars + optimized techniques + intelligent equipment” will be essential for enhancing quality stability and industrial competitiveness of Longjing tea.

## Conflict of Interest Disclosure

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

## References

- Ao C., Niu X., Huang H., Yu J., and Cheng Z., 2025, Metabolite analysis of Hangzhou Gongmei white tea of different varieties, *Foods*, 14(9): 1622.  
<https://doi.org/10.3390/foods14091622>
- Bassiony A., Peng Q.H., Baldermann S., Feng S., Yang K., Zhang Y.C., Fu J., Lü H., Lin Z., and Shi J., 2024, Differential accumulation patterns of flavor compounds in Longjing 43 and Qunti fresh leaves and during processing responding to altitude changes, *Food Research International*, 187: 114392.  
<https://doi.org/10.1016/j.foodres.2024.114392>

- Chen S., Wang P.J., Kong W.L., Chai K., Zhang S.C., Yu J., Wang Y., Jiang M., Lei W., Chen X., Wang W., Gao Y., Qu S., Wang F., Wang Y.B., Zhang Q., Gu M., Fang K., Ma C., Sun W., Ye N., Wu H., and Zhang X., 2023, Gene mining and genomics-assisted breeding empowered by the pangenome of tea plant *Camellia sinensis*, *Nature Plants*, 9(12): 1986-1999.  
<https://doi.org/10.1038/s41477-023-01565-z>
- Chen Y., Guo M.Q., Chen K., Jiang X.F., Ding Z.Z., Zhang H.W., Lu M., Qi D.D., and Dong C.W., 2024, Predictive models for sensory score and physicochemical composition of Yuezhou Longjing tea using near-infrared spectroscopy and data fusion, *Talanta*, 273: 125892.  
<https://doi.org/10.1016/j.talanta.2024.125892>
- Cui H.C., Cheng Z.Q., Shi D., Yin J., Feng Z., Zhao Y., and Zhang J., 2026, Non-volatile metabolomics analysis of heating withering method for processing white tea from Longjing 43 tea variety by UHPLC-Q-TOF/MS, *Frontiers in Nutrition*, 12: 1735183.  
<https://doi.org/10.3389/fnut.2025.1735183>
- Deng S., Cao Q.Q., Gao Y., Wu W.W., Chen J.X., Wang F., Zou Q., Xu F., Cao X., Sun W., Yin J., and Xu Y., 2025, Elucidating the effect of brewing temperature on the sensory quality of Longjing tea based on multi-scale molecular sensory science, *Food Chemistry: X*, 28: 102635.  
<https://doi.org/10.1016/j.fochx.2025.102635>
- Gao T., Hou B., Shao S., Xu M., Zheng Y., Jin S., Wang P., and Ye N., 2023a, Differential metabolites and transcriptional regulation of seven major tea cultivars (*Camellia sinensis*) in China, *Journal of Integrative Agriculture*, 22: 9.  
<https://doi.org/10.1016/j.jia.2023.02.009>
- Gao T., Shao S.X., Hou B.H., Hong Y.P., Ren W.W., Jin S., Gao S., Wang P., and Ye N., 2023b, Characteristic volatile components and transcriptional regulation of seven major tea cultivars (*Camellia sinensis*) in China, *Beverage Plant Research*, 3(1): 1-5.  
<https://doi.org/10.48130/bpr-2023-0017>
- Guo Y.T., Shen Y.L., Hu B.Y., Ye H.C., Guo H.W., Chu Q., and Chen P., 2023, Decoding the chemical signatures and sensory profiles of Enshi Yulu: insights from diverse tea cultivars, *Plants*, 12(21): 3707.  
<https://doi.org/10.3390/plants12213707>
- Huang D.J., Chen X., Tan R.R., Wang H.J., Jiao L., Tang H.Y., Zong Q.B., and Mao Y.X., 2024, A comprehensive metabolomics analysis of volatile and non-volatile compounds in matcha processed from different tea varieties, *Food Chemistry: X*, 21: 101234.  
<https://doi.org/10.1016/j.fochx.2024.101234>
- Li C., Wang X.Y., Zhang D., Chen Y.Q., Jiang X.F., and Ni D.J., 2023a, Study on the variation law of the main mechanical properties in the processing of Longjing tea., *Foods*, 12(13): 2587.  
<https://doi.org/10.3390/foods12132587>
- Li H.Z., Song K.K., Zhang X.H., Wang D., Dong S.L., Liu Y., and Yang L., 2023b, Application of multi-perspectives in tea breeding and the main directions, *International Journal of Molecular Sciences*, 24(16): 12643.  
<https://doi.org/10.3390/ijms241612643>
- Li W.X., Fang Q.T., Han Q.O., Huang H.H., Zheng X.Q., Lu J.L., Liang Y.R., and Ye J.H., 2025, Different performance of tea plants to shade based on key metabolites and transcriptome profiles: case study of cultivars Longjing 43 and Yabukita, *Physiologia Plantarum*, 177(1): e70103.  
<https://doi.org/10.1111/ppl.70103>
- Li Y.C., Zhou J.T., Xu W.L., He C., Zhu J.Y., Zhang D., Chen Y., Yu Z., Wan X., and Ni D., 2024, Key aroma components in Lu'an guapian green tea with different aroma types from five tea tree varieties decoded by sensomics, *Food Bioscience*, 61: 104551.  
<https://doi.org/10.1016/j.fbio.2024.104551>
- Liu F., 2024, The influence of plant genomics on plant evolution, *MedScien.*, 9(1): 8mne6e71.  
<https://doi.org/10.61173/8mne6e71>
- Moreira J., Aryal J., Guidry L., Adhikari A., Chen Y., Sriwattana S., and Prinyawiwatkul W., 2024, Tea quality: an overview of the analytical methods and sensory analyses used in the most recent studies, *Foods*, 13(22): 3580.  
<https://doi.org/10.3390/foods13223580>
- Shan X., Deng Y., Niu L., Chen L., Zhang S., Jiang Y., Yuan H., Wang Y., and Li J., 2023a, The influence of fixation temperature on Longjing tea taste profile and the underlying non-volatile metabolites changes unraveled by combined analyses of metabolomics and E-tongue, *LWT*, 191: 115560.  
<https://doi.org/10.1016/j.lwt.2023.115560>
- Shan X.J., Niu L.C., Zhang Q.T., Fang Z.Z., Feng Y.N., Liang R., Xu Z.X., Zhang S., Chen L., Dai W., Zhou Q., Jiang Y., Yuan H., and Li J., 2025, Quantitative non-volatile sensometabolome of Longjing tea and discrimination of taste quality by sensory analysis large-scale quantitative metabolomics and machine learning, *Food Chemistry*, 485: 144496.  
<https://doi.org/10.1016/j.foodchem.2025.144496>
- Shan X.J., Yu Q.Y., Chen L., Zhang S., Zhu J.Y., Jiang Y.W., Yuan H.B., Zhou Q., Li J., Wang Y., Deng Y., and Li J., 2023b, Analyzing the influence of withering degree on the dynamic changes in non-volatile metabolites and sensory quality of Longjing green tea by non-targeted metabolomics, *Frontiers in Nutrition*, 10: 1104926.  
<https://doi.org/10.3389/fnut.2023.1104926>
- Shen Y., He X., Zu F., Huang X., Yin S., Wang L., Geng F., and Cheng X., 2024, Development of genome-wide intron length polymorphism (ILP) markers in Tea Plant (*Camellia sinensis*) and related applications for genetics research, *International Journal of Molecular Sciences*, 25(6): 3241.  
<https://doi.org/10.3390/ijms25063241>

- Teng R.M., Ao C., Huang H.T., Shi D.L., Mao Y.X., Zheng X.X., and Zhao Y., 2024, Research of processing technology of Longjing tea with 'Baiye 1' based on non-targeted aroma metabolomics, *Foods*, 13(9): 1338.  
<https://doi.org/10.3390/foods13091338>
- Wen M., Zhu M., Han Z., Ho C., Granato D., and Zhang L., 2023, Comprehensive applications of metabolomics on tea science and technology: opportunities hurdles and perspectives, *Comprehensive Reviews in Food Science and Food Safety*, 22(6): 4890-924.  
<https://doi.org/10.1111/1541-4337.13246>
- Wu T.Y., He J.J., Deng X.J., Wang X.H., Yuan W.X., Wang Q.M., Chen X.Y., Zou M., An H., Wang B., and Che R., 2025, Influencing factors and regulatory mechanisms of fresh tea leaf quality: a review, *Foods*, 14(18): 3268.  
<https://doi.org/10.3390/foods14183268>
- Yan K.N., Wang J.T., Zhou M.X., Peng Q.H., Mahmoud A.B., Bai X., Baldermann S., Jiang X., Feng S., Wu Y., Fu J., Lin Z., Lü H., and Shi J., 2025, Insights into potential flavor-active peptides and taste-related compounds in Longjing teas: a comparative study of 'Longjing 43' and 'Qunti' cultivars, *Food Chemistry*, 471: 142790.  
<https://doi.org/10.1016/j.foodchem.2025.142790>
- Yu J., Wang W., Shen K., Bai P., Mao Y., Mohamed A.S., Ma R., Ge S., Yin R., and Li X., 2025, Multi-omics profiling of *Camellia sinensis* reveals mechanisms of bitter metabolism and temperature adaptation during spring warming, *Industrial Crops and Products*, 236: 121857.  
<https://doi.org/10.1016/j.indcrop.2025.121857>
- Yu X., Li J., Yang Y., Zhu J., Yuan H., and Jiang Y., 2023, Comprehensive investigation on flavonoids metabolites of Longjing tea in different cultivars geographical origins and storage time, *Heliyon*, 9(6): e17305.  
<https://doi.org/10.1016/j.heliyon.2023.e17305>
- Zeng L., Fu Y.Q., Gao Y., Wang F., Liang S., Yin J.F., Fauconnier M.L., Ke L., and Xu Y., 2024, Dynamic changes of key metabolites in Longjing green tea during processing revealed by widely targeted metabolomic profiling and sensory experiments, *Food Chemistry*, 450: 139373.  
<https://doi.org/10.1016/j.foodchem.2024.139373>
- Zhang H., Zhang J., Liu S., Li T., Wei Y., Gu Z., Su Z., Ning J., Wang Y., and Hou Z., 2024, Characterization of the key volatile compounds in Longjing tea (*Camellia sinensis*) with different aroma types at different steeping temperatures by GC-MS and GC-IMS, *LWT*, 200: 116183.  
<https://doi.org/10.1016/j.lwt.2024.116183>
- Zhao X., Chi N., Xu X., Lai J., Chen J., and Chen L., 2024, Metabolome profiling unveil the composition differences of quality of different tea cultivars, *Beverage Plant Research*, 4: e023.  
<https://doi.org/10.48130/bpr-0024-0012>



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