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Seasonal Variation in Tea Quality: Evidence from Spring, Summer, and Autumn Harvests

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Abstract Harvest season is one of the most direct factors affecting tea quality, but it is also one of the most oversimplified. In tea production and trade, spring tea is usually regarded as the quality benchmark, whereas summer and autumn teas are often considered lower-grade raw materials. However, seasonal changes alter temperature, light intensity, rainfall, shoot growth rate, and leaf maturity in different tea types and production regions. These environmental changes regulate the balance of amino acids, catechins, caffeine, soluble sugars, and aroma precursors, ultimately affecting sensory quality and processing suitability. Studies from Zhejiang Province and other major tea-growing regions indicate that seasonal differences should not simply be interpreted as a distinction between "high-quality" and "low-quality" tea. Instead, each harvest season has its own biochemical characteristics and end-use value. This review discusses the main production factors responsible for seasonal variation in tea quality and examines practical strategies for increasing the value of summer and autumn teas through appropriate processing, diversified product development, and well-planned harvesting schedules. Sustainable development of the tea industry depends not only on producing premium spring tea but also on building a year-round production system that matches fresh leaves from different seasons with suitable processing methods and target markets.
Keywords Harvest season; Spring tea; Summer tea; Autumn tea; Longjing tea; Anji White Tea; Amino acids; Catechins; Tea processing

1 Introduction

Tea quality begins in the tea garden. Although cultivar and processing technology are the key factors determining final quality, the harvest season largely determines what kind of finished tea can be produced from fresh leaves. Secondary metabolites that contribute to taste, aroma, and health benefits are highly sensitive to harvest time because seasonal changes reflect the combined effects of temperature, light intensity, humidity, rainfall patterns, and shoot growth dynamics (Moreira et al., 2024). In black tea research, harvest season has been recognized as an important factor affecting quality alongside plucking standard, withering, rolling, oxidation, and drying. Therefore, season is not simply a background condition but an important management factor that directly influences tea quality.

Early spring tea usually commands the highest market price because young shoots are limited in quantity and have tender leaves with a fresh and desirable chemical composition. Even within spring green tea, clear metabolic differences exist among different harvesting periods. This is one of the main reasons why consumers are willing to pay a much higher premium for the earliest spring tea rather than for ordinary spring tea in general (Cui et al., 2023). The harvest season has a systematic effect on the accumulation of chemical components. This pattern is not limited to high-quality spring green tea but has also been widely reported in white tea, oolong tea, black tea, dark tea, and other tea categories (Fu et al., 2024).

This review analyzes the major cultivation factors responsible for seasonal variation in tea quality and uses Zhejiang Province as a representative case. Zhejiang has a long history of green tea production, distinctive tea cultivars, and a rapidly developing modern tea industry, making it an ideal region for discussion. At present, the major challenge facing the tea industry is not simply how to produce high-quality spring tea but how to convert summer and autumn teas into value-added products that can generate stable income throughout the year. Recent studies on microbial fermentation, aroma improvement in black tea, light-assisted withering, and diversified tea processing have provided practical approaches for increasing the utilization value of summer and autumn teas. These findings offer useful references for improving the year-round utilization of fresh tea leaves harvested in different seasons.

2 Seasonal Variation in Tea Quality Formation

2.1 Quality characteristics of spring tea

Spring tea is generally regarded as the highest-quality tea of the year. It is characterized by a fresh taste, natural sweetness, clean aroma, and well-balanced flavor. Whether for green tea, white tea, or black tea, spring-harvested leaves usually produce better sensory quality than summer or autumn teas. Ye et al. (2022) compared black teas produced from the large-leaf cultivars Yinghong 9 and Huangyu and found that spring tea achieved the highest scores for aroma, taste, liquor color, and overall sensory quality. Studies on white tea and Xinyang Maojian also showed that spring tea had a fresher aroma, stronger umami taste, and higher consumer acceptance than teas harvested in later seasons (Yin et al., 2022). Even within the spring season, early spring tea is often superior to late spring tea, indicating that the quality advantage of spring tea gradually changes as temperatures rise and new shoots develop.

The high quality of spring tea is mainly associated with the accumulation of umami-related compounds. Cool spring temperatures slow the growth of young shoots, allowing more theanine, free amino acids, and other flavor-enhancing metabolites to accumulate. Chen et al. (2024) used metabolomic analysis of different tea cultivars and found that spring tea contained higher levels of theanine, theogallin, and gallotannins than summer tea. Zaman et al. (2023) analyzed 87 tea cultivars over four consecutive harvest rounds and reported that the first spring flush had the highest average free amino acid content, reaching about 4.0%. Research on Changqing tea also showed that umami-related amino acids declined significantly in summer and autumn teas, while several bitter amino acids increased. These compositional changes give spring tea its characteristic fresh, sweet, smooth taste with relatively low bitterness and astringency.

Spring tea also has clear advantages in aroma. White tea and green tea harvested in spring contain relatively high levels of floral and fresh aroma compounds such as geraniol (Zhang et al., 2022). A study of black tea made from the cultivar Baiye No.1 further showed that its sweet and honey-like aroma was closely associated with the accumulation of β-ocimene, geraniol, and citral during the spring season (Chen et al., 2025). Spring tea produced from Rucheng Baimao tea also exhibited stronger floral, fruity, and fresh aromas than summer and autumn teas, resulting in better overall aroma quality (Zhu et al., 2025). However, not every chemical component reaches its highest concentration in spring. Total polyphenols and some catechins can sometimes be higher in summer tea. This indicates that the superior quality of spring tea results from a balanced composition of multiple quality-related compounds rather than from the highest concentration of any single component.

Overall, the major strengths of spring tea are its rich umami compounds, pure aroma, and balanced taste. These characteristics make it the preferred raw material for premium green tea, white tea, and high-grade black tea, and it remains the most important source of fresh leaves for famous and high-quality teas.

2.2 Quality characteristics of summer tea

Summer tea is generally characterized by stronger bitterness and astringency and lower freshness than spring tea. However, this does not mean that summer tea is of poor quality. Instead, it has its own chemical characteristics and processing advantages. Higher temperatures and stronger sunlight during summer accelerate shoot growth and promote the accumulation of tea polyphenols, catechins, and flavonoids, while reducing the levels of umami-related compounds. As a result, summer tea has a stronger taste but also more pronounced bitterness and astringency.

Liu et al. (2023) analyzed a large number of commercial samples of Yinghong 9 black tea and found that total polyphenol content reached 10.24% in summer tea, compared with 9.22% in spring tea. Total catechin content also increased from 30.01 mg/g in spring to 38.28 mg/g in summer. Among these compounds, EC and ECG, which are closely associated with bitterness and astringency, showed the greatest increases. Using an electronic tongue system, Li et al. (2025a) found that summer Lu'an Guapian tea had significantly higher bitterness and astringency but lower umami than spring tea (Figure 1). Ma et al. (2022) further demonstrated that flavonoid biosynthesis was enhanced during summer, whereas umami-related amino acids decreased, providing a metabolic explanation for the stronger bitterness of summer tea.

Although summer tea is less fresh than spring tea, its high concentrations of polyphenols and catechins provide considerable processing potential. Liang et al. (2024) suggested that summer tea is well suited for producing black tea, functional teas, and food ingredients through fermentation. During processing, polyphenols are converted into quality-related compounds such as theaflavins and thearubigins, which reduce bitterness and improve aroma. Cultivation practices can also improve summer tea quality. For example, appropriate nitrogen fertilization can increase total polyphenols, catechins, and caffeine while improving the chemical composition of fresh leaves, making them more suitable for different processing purposes.

The value of summer tea does not lie in competing with spring tea. Instead, its high polyphenol content and rich bioactive compounds make it an excellent raw material for black tea, fermented tea, tea beverages, and functional foods through targeted processing and product diversification.

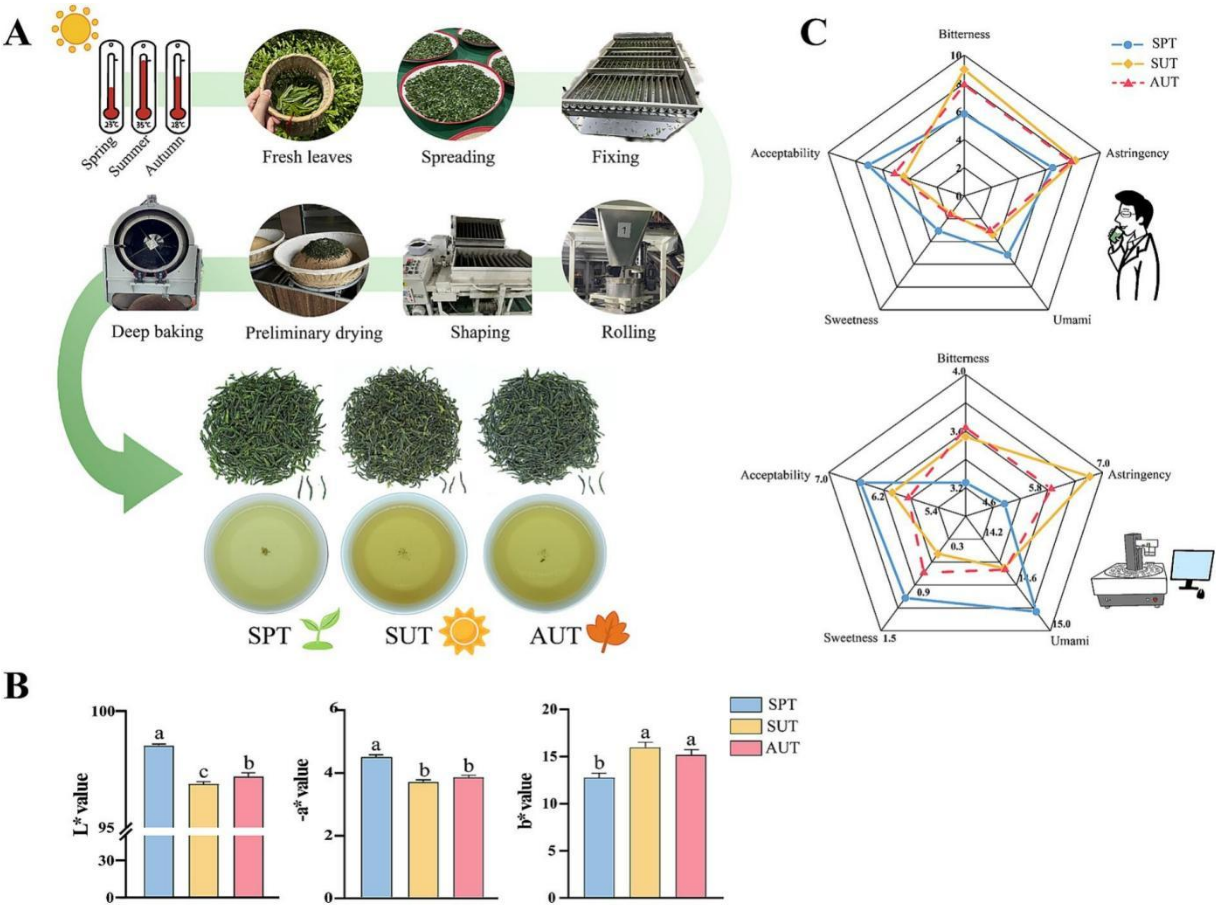

Figure 1 Processing flow and sensory quality of Lu'an Guapian tea in different seasons. (A) Processing flow charts of Lu'an Guapian tea. Spring tea (SPT), Summer tea (SUT), Autumn tea (AUT). (B) The colorimetric values of SPT, SUT, and AUT tea infusions. Errors bars represent mean ± SD. Different letters indicate a significant difference at the 0.05 level, as determined by one-way ANOVA and Tukey's post-hoc test. (C) Radar chart for quantitative descriptive analysis of taste and E-tongue analysis (Adopted from Li et al., 2025a)

2.3 Quality characteristics of autumn tea

The quality of autumn tea generally falls between that of spring and summer tea, although considerable variation exists among tea types and growing environments. Autumn tea usually contains fewer umami compounds than spring tea, while its bitterness and astringency are weaker than or similar to those of summer tea. Therefore, autumn tea has a relatively balanced quality profile.

Research on white tea showed that autumn tea generally contained higher levels of caffeine, total polyphenols, and catechins than spring tea, with ECG showing the greatest increase. This increase was closely associated with the stronger astringency of autumn tea (Huang et al., 2025). Likewise, a study on Lu'an Guapian reported that autumn tea had higher bitterness and astringency but lower umami than spring tea, while its sweetness was intermediate between spring and summer teas (Li et al., 2025a). Although autumn tea loses some of the freshness found in spring tea, its taste is generally less harsh than that of summer tea.

Compared with summer tea, autumn tea often has an advantage in aroma. Sensory evaluation of Rucheng Baimao black tea showed that the aroma quality of autumn tea ranked second only to spring tea and was clearly better than that of summer tea, with a cleaner and more balanced aroma profile (Zhu et al., 2025). Pulimamidi et al. (2024) monitored Assam tea throughout the production season and found that EGCG and ECG levels declined from summer to autumn and winter, indicating that some bitter and astringent compounds decreased, although the freshness did not fully recover to spring levels. These seasonal changes produce a relatively balanced combination of aroma and taste in autumn tea.

Moderate polyphenol levels, balanced aroma, and relatively stable raw material quality make autumn tea suitable for fermentation and further processing. It can be used to produce dark tea, specialty fermented teas, and other value-added functional products, improving the utilization of autumn-harvested tea leaves.

Although autumn tea is less fresh than spring tea, its balanced aroma, stable quality, and good processing potential make it an important component of a year-round tea production system.

3 Main Drivers of Seasonal Variation in Tea Quality

3.1 Effects of temperature on tea quality formation

Temperature is one of the most important environmental factors affecting seasonal differences in tea quality. Studies simulating high-altitude conditions have shown that the combination of lower temperature and weaker light suppresses catechin biosynthesis while increasing the accumulation of free amino acids. As a result, the polyphenol-to-amino acid ratio decreases, leading to improved taste and aroma. The optimum temperature for tea plant growth is generally between 20 ℃ and 25 ℃. Higher temperatures regulate the metabolism of catechins, anthocyanins, and theanine through changes in transcription factors, hormones, and structural genes. When the temperature reaches 38°C, the expression of NADH-GOGAT is downregulated, reducing the synthesis of theanine while enhancing the formation of phenylethanol-related volatile compounds (Wu et al., 2025).

Short-term low-temperature conditions can increase the accumulation of amino acids, soluble sugars, ascorbic acid, and some flavonoids. They also enhance aroma formation by activating LOX-related genes. Low winter temperatures have likewise been associated with improved tea aroma. The difference between day and night temperatures is another important factor. A diurnal temperature difference of about 10 ℃ is considered favorable for amino acid accumulation, whereas larger temperature differences have inconsistent effects on caffeine, flavonoids, and catechins, suggesting the existence of threshold effects and cultivar-dependent responses. In black tea produced from the large-leaf cultivars Yinghong 9 and Huangyu, tea polyphenols reached their highest level in summer. From spring to summer, soluble sugars and caffeine increased, while free amino acids decreased, and spring-harvested Huangyu tea showed the best overall physicochemical quality (Ye et al., 2022). Temperature effects are also evident within the spring season itself. Yu et al. (2020) reported that Congou black tea made from early spring leaves had better quality than tea produced later in spring. As spring progressed, total polyphenols, total catechins, and EGCG increased, whereas total amino acids declined.

Temperature also affects quality during tea processing. Ye et al. (2018) withered fresh green tea leaves at 15, 20, and 25 ℃ for 0~21 h and found that most free amino acids gradually increased during the first 18 h of withering before declining, whereas most catechins decreased as withering time and temperature increased. Based on the changes in major taste-related compounds, the authors suggested maintaining the withering temperature below 25 °C and limiting the withering period to 15~18 h to promote amino acid accumulation while avoiding excessive quality loss caused by over-withering.

3.2 Light conditions and changes in tea quality

Light intensity and day length are major factors regulating seasonal differences in tea quality. Stronger light and longer sunshine duration generally promote the accumulation of flavonoids and catechins, whereas shaded conditions favor the retention of amino acids and compounds associated with fresh taste. Seasonal metabolic studies have shown that theanine reaches its highest level in spring, while catechins peak during summer. This pattern of "fresh spring tea and bitter summer tea" is mainly explained by light-induced changes in photosynthesis, which regulate the expression of transcription factors and structural genes involved in secondary metabolism. When spring and autumn have similar temperatures, the compositional differences observed in white tea are more closely related to differences in light intensity than to temperature itself.

Ultraviolet radiation, especially UV-B, plays an important role in regulating flavonoid metabolism in tea plants. Removing ambient UV-B reduces the accumulation of bitter flavonol glycosides such as kaempferol, myricetin, and quercetin derivatives, while increasing some non-esterified catechins. In contrast, supplemental UV-B promotes flavonol accumulation but decreases catechin content. This regulatory pathway is mainly controlled by CsHY5, which activates the expression of CsMYB12 and regulates flavonoid biosynthesis genes including CsFLS, CsLARa, and CsDFRa, thereby altering the metabolic balance between flavonols and catechins (Lin et al., 2021).

Flavonol glycosides are more sensitive to changes in light intensity than catechins. Under different shading levels and light spectrum treatments, total flavonol glycosides decreased by as much as 79.6%, whereas total catechins declined by a maximum of 38.7%. At the same time, the expression of flavonoid biosynthesis genes such as PAL, CHS, and F3H was significantly reduced (Ye et al., 2021). These findings indicate that changes in light conditions are an important reason for the seasonal differences in tea chemical composition and sensory quality.

3.3 Rainfall and water supply

Appropriate soil moisture is essential for bud growth and photosynthesis. However, prolonged rainfall, high air humidity, or excessive water availability can alter shoot growth rate, leaf development, and the accumulation of secondary metabolites, thereby affecting tea flavor and quality. Hazra et al. (2021) compared 22 tea cultivars across the spring, rainy, and autumn seasons. Tea harvested during the rainy season generally contained higher levels of total phenolics, flavonoids, proanthocyanidins, and antioxidant activity. However, individual catechin components showed substantial differences among cultivars, and no consistent seasonal trend was observed. Photosynthetic rate, transpiration rate, leaf temperature, and intercellular CO_2 concentration were all significantly correlated with phenolic compounds and antioxidant capacity, indicating that rainfall influences tea quality not only by changing soil water availability but also by modifying leaf physiological activity and secondary metabolism.

Benti et al. (2023) monitored the yield, harvesting cycle, and fresh leaf quality of five tea clones over four seasons in southwestern Ethiopia. They found that monthly rainfall and temperature significantly affected shoot composition and the proportion of marketable leaves. Fresh leaf quality was highest in June, when premium shoots accounted for 78.21% of the harvest. After July, increased rainfall and lower temperatures resulted in a 5%~10% increase in soft-stem leaves, while the proportion of premium shoots declined to 68.83%. Long-term observations further showed that tea yield and harvesting frequency were highest when the daily maximum temperature remained between 23.03 ℃ and 26.35 ℃. When the maximum temperature exceeded 28.34 ℃ or the minimum temperature fell below 10.38 ℃, both fresh leaf quality and yield declined.

3.4 Tea growth stage and leaf maturity

Seasonal differences are also reflected in the developmental stage of fresh tea leaves. Tea harvested in spring, summer, and autumn usually enters the processing chain at different levels of maturity. In addition to marked differences in chemical composition, morphological traits such as bud length, bud density, mature leaf biomass, and the weight of 100 buds also vary greatly among harvest seasons. Therefore, seasonal effects are closely associated with changes in the structure and maturity of harvested raw materials. Studies on commercial CTC black tea have shown that as leaves develop from one bud with two leaves to one bud with three or four leaves, total polyphenols, total catechins, caffeine, theaflavins, water extract, and antioxidant activity all decrease, whereas crude fiber increases. Tea made from one bud with two leaves consistently achieves the best sensory quality.

The interaction between leaf maturity and harvest season also explains why spring tea is preferred for producing premium teas. The quality of black tea and dark tea largely depends on phenolic substrates present in young shoots. Longer harvesting intervals increase the proportion of coarse and mature leaves beyond the one-bud-two-leaf stage, reducing both yield and quality (Aaqil et al., 2023). After winter dormancy, spring shoots enter the harvesting period with relatively high levels of amino acids and theanine but lower levels of polyphenols, making them more suitable for non-fermented or lightly fermented teas. In contrast, summer and autumn leaves accumulate more polyphenols and are therefore better suited for black tea and other products requiring stronger oxidation during processing. Even within the same cultivar, total polyphenols, free amino acids, theanine, and caffeine vary considerably among spring, summer, and autumn harvests, indicating that the effects of leaf maturity interact with cultivar characteristics and growing environment to determine seasonal tea quality.

4 Field Evidence from Zhejiang Tea-Producing Regions

4.1 Longjing tea-why is spring tea the best

Longjing tea is the most representative premium green tea in Zhejiang Province and one of the best-known green teas in China. For many years, tea growers in Zhejiang have followed the traditional belief that “pre-Qingming tea is as valuable as gold” and that spring tea produces the highest quality. Even when the same tea garden is managed with identical cultivation practices and processing methods, Longjing tea made from spring leaves usually has a fresher taste, a stronger tender aroma, and a higher market value. In contrast, tea harvested in summer becomes noticeably more bitter and astringent, resulting in lower quality and reduced market prices. This raises an important question: why does spring produce the best Longjing tea?

Jiang et al. (2021) addressed this question using materials from the National Tea Germplasm Repository in Hangzhou, maintained by the Tea Research Institute of the Chinese Academy of Agricultural Sciences. The study compared 90 samples from 10 tea germplasm accessions, including Longjing Changye (01), Longjing Yuanye (02), Tengcha (03), Shuigucha (04), Houyezhong (05), Enbiao (06), Lantian (07), Lanshan Kucha (08), Jianghongzhong (09), and Jiangku No. 2 (10). All materials were grown under the same cultivation management and harvested at the one-bud-two-leaf stage during spring (April 3), summer (July 8), and autumn (September 30). This experimental design minimized the effects of cultivar and field management, allowing seasonal environmental conditions to become the major source of quality variation.

Most tea accessions showed the same seasonal pattern. Tea quality was highest in spring, declined in summer, and changed further in autumn. The Catechin Quality Index (CQI), which integrates catechin composition, was highest in spring for most materials and decreased in both summer and autumn, indicating that spring provides the most favorable conditions for producing premium green tea. Lower temperatures and milder sunlight during spring slow the growth of young shoots and promote the accumulation of theanine and other umami-related compounds while limiting the formation of bitter and astringent substances. As a result, spring tea has a fresh, mellow taste and a pleasant aftertaste that match the quality requirements of Longjing tea. During summer, higher temperatures and stronger sunlight accelerate vegetative growth, leading to increased catechin and flavonoid accumulation and a lower proportion of free amino acids. Consequently, summer-harvested leaves produce green tea with stronger bitterness, lower freshness, and reduced smoothness (Figure 2).

4.2 Anji white tea-why is the albino stage the best

Although its name contains the term "white tea," Anji White Tea is actually processed as a green tea. Its unique characteristic is that the leaves temporarily become white under low spring temperatures, giving the tea distinctive quality characteristics that differ from other green teas. In the Anji tea-growing region of Zhejiang, growers often say, "One day earlier is treasure, one day later is grass." Although this saying is somewhat exaggerated, it reflects an important fact: the quality of Anji White Tea depends heavily on harvesting during the optimal spring period rather than throughout the entire spring season.

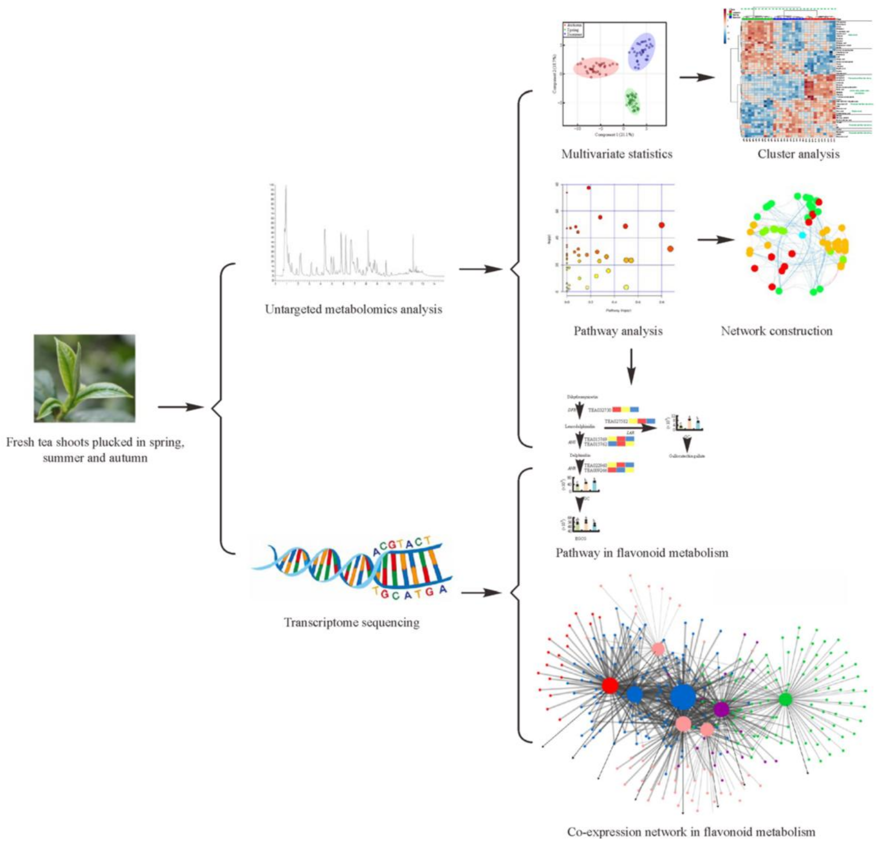

Figure 2 Workflow of integrated transcriptomic and untargeted metabolomic analyses for seasonal variation in tea shoots (Adapted from Jiang et al., 2023)

The albino stage is the key period for quality formation. Zeng et al. (2020) compared the chemical composition of fresh leaves collected during the albino stage and the subsequent re-greening stage. Even within the spring season, clear differences in quality were observed between these harvest periods. Leaves collected during the albino stage contained higher concentrations of amino acids and several aroma precursors, while bitter and astringent compounds remained relatively low. As a result, the processed green tea showed a fresher taste, cleaner aroma, and smoother mouthfeel. As temperatures continued to rise during spring, the leaves gradually turned green, the concentration of freshness-related compounds declined, and bitter compounds increased. Even under identical processing conditions, the resulting tea showed lower freshness and a weaker tender aroma.

These quality changes are closely associated with the leaf albinism process. Low spring temperatures temporarily inhibit normal chloroplast development, causing the leaves to appear pale green or creamy white while promoting the accumulation of amino acids. This physiological response gives Anji White Tea its characteristic fresh and delicate taste. As temperatures increase, chloroplast development resumes, the leaves regain their green color, and the tea plants return to normal growth. At the same time, the chemical composition of the fresh leaves changes accordingly. Therefore, for Anji White Tea, the highest quality depends not simply on harvesting in spring but on harvesting during the peak albino stage.

4.3 Wuniuzao-why is early harvest so important

Wuniuzao is one of the earliest-sprouting green tea cultivars in Zhejiang Province. It originated in Wuniu Town, Yongjia County, Wenzhou, and is one of the first tea cultivars to enter the spring market each year. Compared with conventional green tea cultivars such as Longjing 43, the main advantage of Wuniuzao is not a stronger flavor but its exceptionally early bud break. Harvesting usually begins from late February to early March, approximately one to two weeks earlier than most other green tea cultivars. For this reason, Wuniuzao is widely known as the earliest spring tea in Zhejiang. For the tea industry, early harvesting is valuable not only because it advances the harvest date but also because it allows producers to enter the premium spring tea market ahead of competitors. In recent years, Yongjia County has continuously expanded Wuniuzao cultivation and developed an integrated industry combining tea production, processing, branding, and tea tourism. Today, Wuniuzao has become an important specialty crop that contributes to local agricultural development and farmers' income.

The early sprouting habit of Wuniuzao is mainly determined by its genetic characteristics. In comparative trials of early-maturing, high-quality green tea cultivars conducted by the Tea Research Institute of the Chinese Academy of Agricultural Sciences, Wuniuzao was evaluated together with cultivars such as Zhongcha 108 and Longjing 43. The results showed that Wuniuzao consistently initiated bud growth earlier than the other cultivars, allowing it to reach the harvesting stage first during the spring production season in Zhejiang. As a result, it has become one of the most important sources of fresh leaves for premium early spring green tea (Yang et al., 2003).

The high quality of Wuniuzao is also closely related to the environmental conditions during early spring. Because bud break occurs very early, young shoots develop under relatively low temperatures and weak light conditions. These conditions slow shoot growth, favor the accumulation of umami-related compounds, and reduce the formation of bitter and astringent substances. Consequently, processed green tea has a distinct tender aroma, a fresh taste, and a clear liquor. As temperatures continue to increase later in the season, tea plants enter a period of rapid growth, and bitter compounds gradually accumulate in the leaves. This explains why Wuniuzao can be harvested throughout the growing season but why its highest-value products are almost always produced from the earliest spring harvest.

5 Practical Recommendations for Tea Growers and Agricultural Extension Workers

5.1 Optimal harvesting time

Tea quality first depends on whether the leaves are harvested within the proper harvesting window, rather than simply pursuing the earliest possible harvest or delaying harvest to obtain a higher yield. In spring, low temperatures slow shoot growth and keep the leaves tender, making this the best period for producing premium green tea. As temperatures rise, buds and leaves grow rapidly and gradually mature. Compounds related to freshness begin to decline, while bitter and astringent substances increase. Therefore, even when the leaves are still classified as spring tea, harvesting too late can reduce the final product quality. For premium green teas in Zhejiang, such as Longjing tea and Anji White Tea, harvesting should be arranged according to the actual development of buds and leaves. One bud with one leaf or one bud with two leaves should be used as the main harvesting standard. Growers should avoid delaying harvest simply to increase yield, as this may result in missing the best quality period.

A reasonable harvesting frequency is also important. Aaqil et al. (2023) found that shortening the harvesting interval appropriately not only increased fresh leaf yield but also maintained a higher proportion of tender buds and one-bud-two-leaf shoots. In contrast, excessively long harvesting intervals increased the proportion of coarse and mature leaves and reduced processing quality (Figure 3). Benti et al. (2023) pointed out that tea bud growth is jointly affected by temperature and rainfall. Harvesting plans should therefore be adjusted according to local phenological changes rather than being organized according to fixed calendar dates. At the farm level, harvesting dates should be adjusted promptly according to changes in spring temperature. Labor, transportation, and processing capacity should also be arranged in advance to ensure that fresh leaves are harvested and processed on the same day, thereby maintaining their quality as much as possible.

5.2 How to improve spring tea quality

The key to improving spring tea quality is not simply to harvest as early as possible, but to maintain leaf tenderness during the proper harvesting period and make full use of the quality advantages created by low spring temperatures. Spring tea usually contains relatively high levels of amino acids and has a good aroma foundation. Therefore, tender shoots should be harvested at the correct time, and overly long harvesting intervals should be avoided. Once the leaves become mature, the freshness and tender aroma of the tea liquor decline noticeably, even when the same processing method is used. Timely harvesting therefore remains the most effective measure for maintaining spring tea quality.

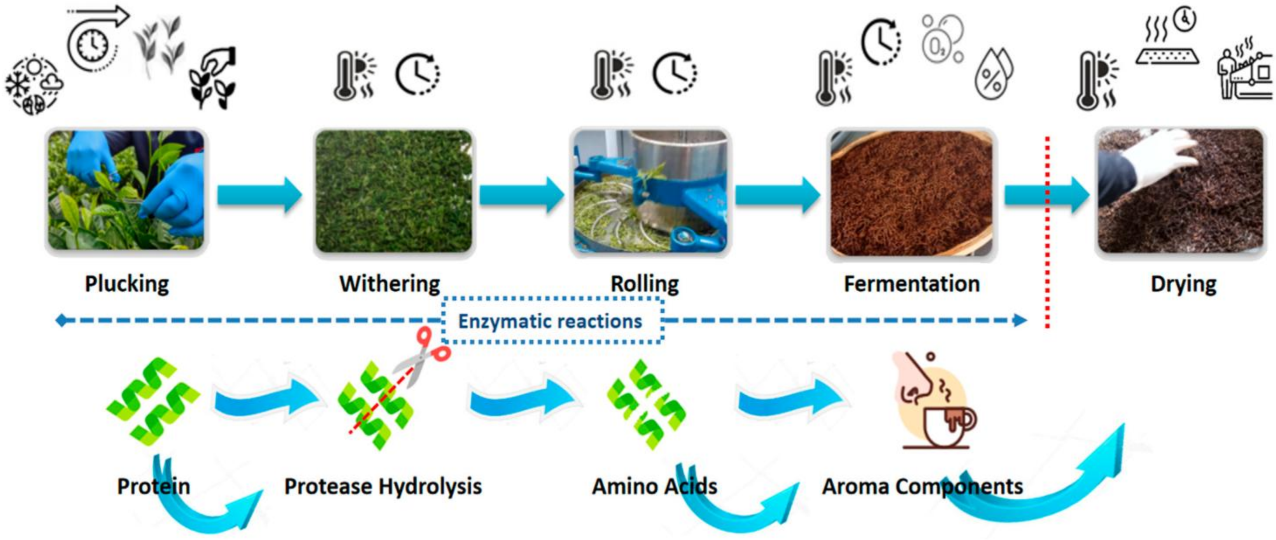

Figure 3 Factors affecting black tea quality and changes that occur in chemical composition during processing (Adopted from Aaqil et al., 2023)

Cultivation management can further improve spring tea quality. Zhu et al. (2023) found that moderate shading during spring increased compounds related to freshness and improved the quality of premium green tea. However, the effects of shading differed among seasons, so the same shading treatment should not be used throughout the year. Regarding fertilization, Raza et al. (2024) suggested that organic fertilizer or a combination of organic and inorganic fertilizers can improve fresh leaf quality, promote the accumulation of freshness-related compounds, and reduce bitterness and astringency. Long-term application of chemical fertilizer alone may promote plant growth, but it can also increase the polyphenol-to-amino acid ratio, which is unfavorable for premium green tea production. Tea gardens should therefore establish a fertilization system based mainly on organic fertilizer, supplemented with an appropriate amount of chemical fertilizer. Moderate spring shading, reasonable pruning, and environmentally friendly pest and disease control should also be combined to improve spring tea quality.

5.3 How to increase the utilization value of summer and autumn tea

Summer and autumn fresh leaves usually account for a large proportion of annual tea yield. However, high temperatures promote the rapid accumulation of tea polyphenols while reducing amino acid contents. As a result, processing summer and autumn leaves into green tea using the same standards as spring tea often produces strong bitterness and astringency and results in a low market price. The key to increasing the value of summer and autumn tea is not to make them resemble spring tea, but to adjust the processing direction according to their own chemical characteristics and achieve differentiated utilization.

Fermentation processing can effectively improve the quality of summer and autumn tea. Wu et al. (2025) found that optimizing processing conditions reduced some bitter and astringent compounds and increased substances related to umami and sweetness, resulting in a more balanced taste in summer tea products (Figure 4). Chiang et al. (2022) showed that appropriate enzymatic transformation or fermentation promoted the formation of quality-related compounds such as theaflavins and thearubigins, thereby improving flavor and overall product quality. For small tea enterprises and family farms, part of the summer and autumn harvest can be used to produce black tea, white tea, dark tea, or specialty fermented tea instead of being processed entirely into traditional green tea. Producers may also develop tea bags, flavored tea, instant tea, and raw materials for tea beverages. These products can improve the use efficiency of summer and autumn tea resources, reduce unharvested leaves, and increase annual operating income.

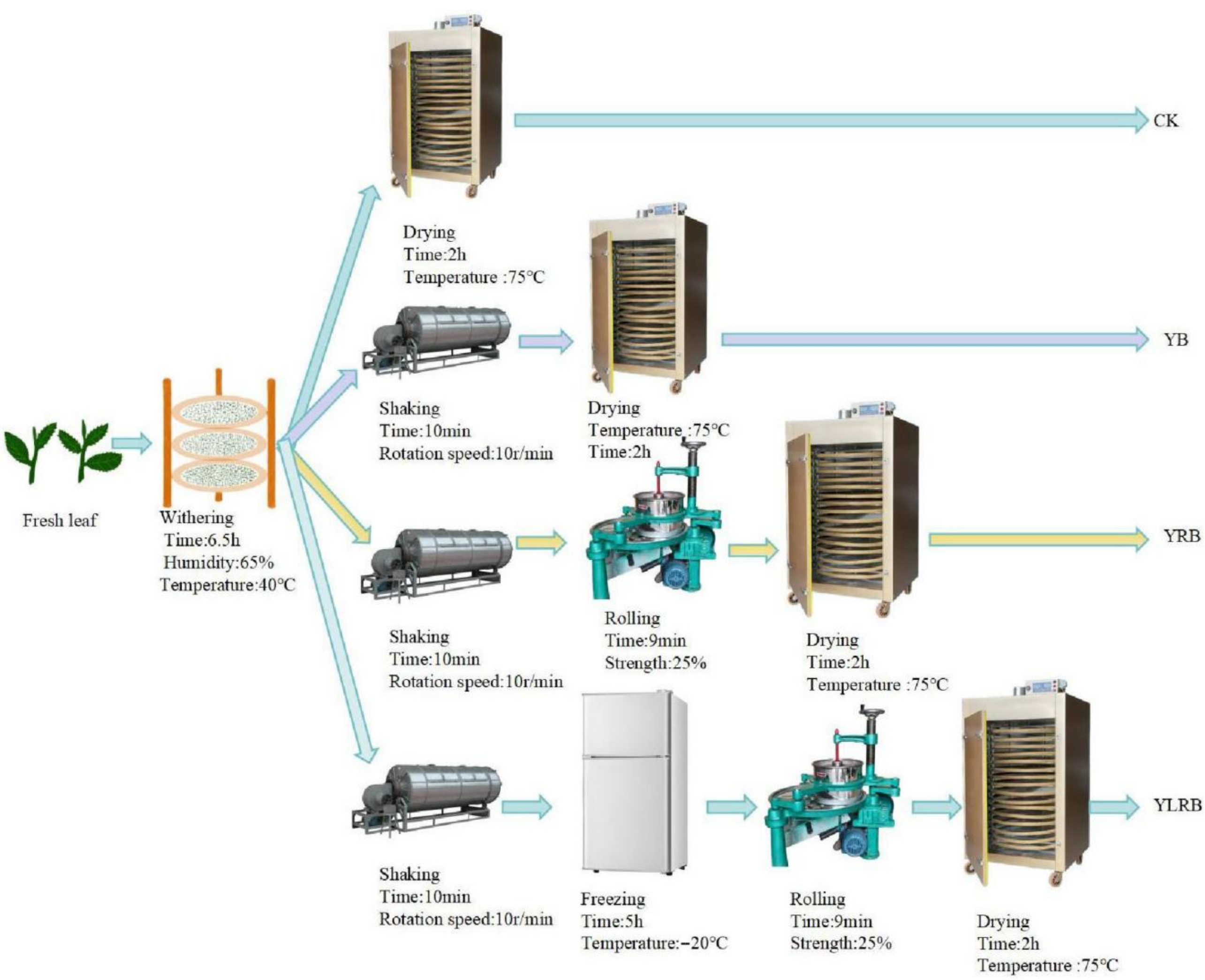

Figure 4 Process flow diagrams for four tea samples. CK: samples made with traditional white tea processing techniques; YB: sample made by adding shaking to the traditional white tea process; YRB: sample made by adding shaking and rolling in the traditional white tea processing; YLRB: sample made by adding shaking, rolling, and freezing to the traditional white tea process (Adopted from Wu et al., 2025)

6 Future Directions for Season-Based Tea Production

6.1 Precision seasonal harvest management

Future tea production will place greater emphasis on the precise use of fresh leaves from different seasons rather than only improving harvesting efficiency. For a long time, tea garden harvesting has mainly depended on growers' experience in judging bud emergence and harvest dates. However, with climate change and rising labor costs, experience-based management alone can no longer fully meet the needs of high-quality tea production. Tea garden management will gradually become more digital and precise. Bud emergence, fresh leaf yield, and optimal harvesting windows will be predicted according to the growth characteristics of tea plants in spring, summer, and autumn, thereby improving the annual utilization efficiency of fresh leaves.

Technologies such as unmanned aerial vehicle remote sensing, satellite imagery, machine vision, and artificial intelligence are gradually being applied in tea production. UAV remote sensing combined with machine-learning models can predict spring, summer, autumn, and annual fresh leaf yields with relatively high accuracy. This provides useful information for harvesting plans, processing capacity allocation, and labor arrangements (Liu et al., 2025). Machine-vision systems can also identify the positions of tea buds automatically, allowing pre-harvest yield estimation and post-harvest quality evaluation. These systems provide technical support for precision harvesting. Junagade et al. (2024) showed that UAVs combined with deep-learning technology could identify different seasonal flushes of new shoots, providing a new method for batch harvesting and harvest scheduling.

The future development of precision harvesting should not be limited to improving recognition accuracy. Instead, an integrated management system should be established to cover tea plant growth monitoring, bud emergence prediction, fresh leaf grading, harvesting organization, transportation scheduling, and processing capacity allocation. Through the close integration of digital agriculture and production management, spring tea can be harvested more precisely, summer and autumn leaves can be more fully utilized, and continuous year-round production can be achieved. This will improve tea garden resource-use efficiency and the stability of tea quality.

6.2 A quality-centered seasonal production system

Future tea production will gradually shift from a yield-oriented approach to a quality-oriented approach. Spring, summer, and autumn teas differ clearly in chemical composition, processing suitability, and market position. Therefore, using the same cultivation and processing methods throughout the year can no longer meet the needs of the modern tea industry. Establishing differentiated production systems according to the quality characteristics of fresh leaves from different seasons will become an important direction for future development.

During processing, the specific advantages of fresh leaves from each season should be fully used. Spring leaves contain relatively high levels of amino acids and have a fresh taste, making them more suitable for premium green tea production. Summer leaves contain higher levels of tea polyphenols and are more suitable for black tea and other fermented teas, in which fermentation can reduce bitterness and improve aroma. Autumn leaves can be processed into dark tea and specialty products through pile fermentation and other methods, allowing more reasonable allocation of fresh leaf resources throughout the year. A seasonal production model based on "premium products from spring tea, specialty products from summer tea, and further processing of autumn tea" can improve the value of fresh leaves harvested in different seasons and strengthen the market competitiveness of the tea industry.

Future quality management should also cover the entire tea production process, including cultivar selection, fertilization, pruning, shading, fresh leaf grading, and processing. Cai et al. (2024) reported that season-specific nitrogen application not only increased fresh leaf yield but also improved leaf quality in different seasons. Summer fertilization was more effective in promoting tea polyphenol accumulation, whereas autumn fertilization helped increase amino acid and theanine contents. Dong et al. (2026) found that optimizing canopy structure, pruning systems, and fertilization management could balance mechanical harvesting efficiency with the quality of summer and autumn tea, providing technical support for high-quality mechanized production.

Future tea garden management should place greater emphasis on season-specific practices. Cultivation measures, harvesting standards, and processing routes should be developed according to the characteristics of spring, summer, and autumn leaves. In this way, quality management can be applied throughout the production process and support stable, high-quality tea production throughout the year.

6.3 Development of high-value seasonal tea products

The future development of the tea industry should focus not only on further improving spring tea quality but also on making full use of summer and autumn tea resources. Increasing annual fresh leaf utilization is essential for the sustainable development of the tea industry. For many years, summer and autumn teas have had relatively low market prices because of their stronger bitterness and astringency. In some areas, these leaves are not harvested, resulting in resource waste. With continued improvements in processing technology and changing consumer demand, summer and autumn teas are gradually being transformed from traditional tea-drinking materials into raw materials for functional foods, health products, and specialty processed products.

Summer and autumn teas are rich in tea polyphenols, catechins, and other bioactive compounds and therefore have considerable development potential. Yang et al. (2023) pointed out that future functional tea products may include γ-aminobutyric acid (GABA)-rich tea, low-caffeine tea, selenium-enriched tea, and tea products with high levels of bioactive compounds. Fresh leaves from different seasons can be used to develop different products according to their quality characteristics. A meta-analysis by Li et al. (2025b) showed that selenium enrichment significantly increased selenium concentrations in tea and improved the composition of amino acids, soluble sugars, and catechins. Autumn tea showed a relatively strong capacity for selenium accumulation, providing a new option for the development of specialty functional tea products.

Advances in processing technology have further expanded the possible uses of summer and autumn tea. Fermentation, enzymatic transformation, and raw material grading can improve flavor, increase the concentrations of quality-related compounds such as theaflavins and thearubigins, and enhance overall product quality. Summer and autumn leaves may also serve as important raw materials for steamed Tencha, matcha, and tea powder. These materials can then be used to develop tea beverages, tea bags, cakes, noodles, ice cream, and other food products, thereby improving the annual utilization rate of fresh leaves.

Future high-value product development will also place greater emphasis on green processing and intelligent manufacturing. Green technologies such as microwave-assisted extraction, ultrasonic extraction, and supercritical fluid extraction can improve the extraction efficiency of bioactive compounds, reduce energy consumption, and increase product stability. At the same time, future tea processing will increasingly focus on balancing functional compounds with flavor quality. Precision processing can be used to develop specialty products with strong aroma, high amino acid or catechin levels, and low caffeine contents (Wei et al., 2024). The future seasonal tea industry should no longer focus only on raising the price of spring tea. Instead, it should establish a diversified product system based on the characteristics of leaves harvested in different seasons. Spring tea should focus on premium quality, summer tea on processing, and autumn tea on product development. This approach can create a complete industrial chain covering year-round production, processing, and marketing.

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

Aaqil M., Peng C., Kamal A., Nawaz T., Zhang F., and Gong J., 2023, Tea harvesting and processing techniques and its effect on phytochemical profile and final quality of black tea: A review, Foods, 12: 4467.
https://doi.org/10.3390/foods12244467

Benti T., Debela A., Bekele Y., and Suleman S., 2023, Effect of seasonal variation on yield and leaf quality of tea clone (*Camellia sinensis* (L.) O. Kuntze) in South West Ethiopia, Heliyon, 9: e14051.
https://doi.org/10.1016/j.heliyon.2023.e14051

Cai J., Qiu Z., Liao J., Li A., Chen J., Wu Z., Khan W., Sun B., Liu S., and Zheng P., 2024, Comprehensive analysis of the yield and leaf quality of fresh tea (*Camellia sinensis* cv. Jin Xuan) under different nitrogen fertilization levels, Foods, 13: 2091.
https://doi.org/10.3390/foods13132091

Chen L., Shi Y., Sun J., Wang H., Wang Y.-F., Shu Z., He W., Dong C., and Xu P., 2025, Deciphering the flavor profile and seasonal variation of black tea processed from cultivar 'Baiye 1', Food Research International, 208: 116181.
https://doi.org/10.1016/j.foodres.2025.116181

Chen L., Zhang S., Feng Y., Jiang Y., Yuan H., Shan X., Zhang Q., Niu L., Wang S., Zhou Q., and Li J., 2024, Seasonal variation in non-volatile flavor substances of fresh tea leaves (*Camellia sinensis*) by integrated lipidomics and metabolomics using UHPLC-Q-Exactive mass spectrometry, Food Chemistry, 462: 140986.
https://doi.org/10.1016/j.foodchem.2024.140986

Chiang S.H., Yang K.M., Wang S.Y., and Chen C.W., 2022, Enzymatic treatment in black tea manufacturing processing: Impact on bioactive compounds, quality, and bioactivities of black tea, LWT, 163: 113560.
https://doi.org/10.1016/j.lwt.2022.113560

Cui H.N., Gu H.W., Li Z.Q., Sun W., Ding B., Li Z., Chen Y., Long W., Yin X.L., and Fu H., 2023, Integration of lipidomics and metabolomics approaches for the discrimination of harvest time of green tea in spring season by using UPLC-Triple-TOF/MS coupled with chemometrics, Frontiers in Sustainable Food Systems, 7: 1119314.
https://doi.org/10.3389/fsufs.2023.1119314

Fu Z., Chen L., Zhou S., Hong Y., Zhang X., and Chen H., 2024, Analysis of differences in the accumulation of tea compounds under various processing techniques, geographical origins, and harvesting seasons, Food Chemistry, 430: 137000.
https://doi.org/10.1016/j.foodchem.2023.137000

Hazra A., Saha S., Dasgupta N., Kumar R., Sengupta C., and Das S., 2021, Ecophysiological traits differentially modulate secondary metabolite accumulation and antioxidant properties of tea plant (*Camellia sinensis* (L.) O. Kuntze), Scientific Reports, 11: 2795.
https://doi.org/10.1038/s41598-021-82454-3

Huang F., Wu H., Luo F., Wang Y., Ye Y., Gong Y., and Ye X., 2025, Effect of harvest seasons on biochemical components and volatile compounds in white teas from two cultivars, Foods, 14: 1795.
https://doi.org/10.3390/foods14101795

Jiang C. K., Ni D. J., Yao M. Z., and Chen L., 2021, Metabolic and transcriptome analysis reveals metabolite variation and flavonoid regulatory networks in fresh shoots of tea (*Camellia sinensis*) over three seasons, Frontiers of Agricultural Science and Engineering, 8: 215-230.

Junagade S., Sarangi S., Choudhury S. B., Patil R., Singh D., and Pappula S., 2024, Robust estimation of plucking points across seasonal flushes in tea with UAV imaging, Proceedings of the 2024 IEEE Global Humanitarian Technology Conference (GHTC): 262-269.
https://doi.org/10.1109/GHTC62424.2024.10771579

Li J., Song Y., Huang D., Yu J., Zhai X., Liu L., Wang Y., Wan X., and Wang X., 2025a, Exploring seasonal differences in taste and nonvolatiles of Lu'an Guapian tea and perceptual interactions between odorants and EGCG via multi-sensory analysis and metabolomics, Food Chemistry: X, 27: 102497.
https://doi.org/10.1016/j.fochx.2025.102497

Li L., Liu Q., Luo L., Wu S., Chen C., and Yin C., 2025b, Optimizing selenium biofortification in *Camellia sinensis*: A meta-analysis of fertilization strategies, cultivar selection, and harvest timing on tea Se accumulation and quality, Food Research International: 117400.
https://doi.org/10.1016/j.foodres.2025.117400

Liang S., Gao Y., Granato D., Ye J. H., Zhou W., Yin J. F., and Xu Y. Q., 2024, Pruned tea biomass plays a significant role in functional food production: A review on characterization and comprehensive utilization of abandon-plucked fresh tea leaves, Comprehensive Reviews in Food Science and Food Safety, 23: e13406.
https://doi.org/10.1111/1541-4337.13406

Lin N., Liu X., Zhu W., Cheng X., Wang X., Wan X., and Liu L., 2021, Ambient ultraviolet B signal modulates tea flavor characteristics via shifting a metabolic flux in flavonoid biosynthesis, Journal of Agricultural and Food Chemistry, 69: 3401-3414.
https://doi.org/10.1021/acs.jafc.0c07009

Liu C., Li J., Li H., Xue J., Wang M., Jian G., Zhu C., and Zeng L., 2023, Differences in the quality of black tea (*Camellia sinensis* var. Yinghong No. 9) in different seasons and the underlying factors, Food Chemistry: X, 20: 100998.
https://doi.org/10.1016/j.fochx.2023.100998

Liu H., Liu Y., Xu W., Wu M., Wang L., Lu N., and Ou G., 2025, A seasonal fresh tea yield estimation method with machine learning algorithms at field scale integrating UAV RGB and Sentinel-2 imagery, Plants, 14: 373.
https://doi.org/10.3390/plants14030373

Ma Q., Qin M., Song L., Sun H., Zhang H., Wu H., Ren Z., Liu H., Duan G., Wang Y., and Ding Z., 2022, Molecular link in flavonoid and amino acid biosynthesis contributes to the flavor of Changqing tea in different seasons, Foods, 11: 2289.
https://doi.org/10.3390/foods11152289

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: 3580.
https://doi.org/10.3390/foods13223580

Pulimamidi S. S., Naik D. D., Yadav M., Suryawanshi K. G., Marathe S., Jorvekar S. B., Ponneganti S., Ahmed S., Hazarika A., and Borkar R. M., 2024, Seasonal dynamics of phytometabolites content in Assam tea, *Camellia sinensis* var. assamica, by LC-MS/MS: Implications for quality, Journal of Food Composition and Analysis, 134: 106546.
https://doi.org/10.1016/j.jfca.2024.106546

Raza A., Chaoqun C., Luo L., Asghar M. A., Li L., Shoaib N., and Yin C., 2024, Combined application of organic and chemical fertilizers improved the catechins and flavonoids biosynthesis involved in tea quality, Scientia Horticulturae, 337: 113518.
https://doi.org/10.1016/j.scienta.2024.113518

Wei Y., Pang Y. P., Miao S., Xu J., Wei K., Wang Y., and Wei X., 2024, Green preparation, safety control and intelligent processing of high-quality tea extract, Critical Reviews in Food Science and Nutrition, 64: 11468-11492.
https://doi.org/10.1080/10408398.2023.2239348

Wu C., Li H., Lin Q., Wang Z., Zhou C., Zhang C., and Guo Y., 2025, Enhancing summer tea quality through integrated shaking, freezing, and rolling processing, Foods, 14: 3159.
https://doi.org/10.3390/foods14183159

Yang G., Meng Q., Shi J., Zhou M., Zhu Y., You Q., Xu P., Wu W., Lin Z., and Lv H., 2023, Special tea products featuring functional components: Health benefits and processing strategies, Comprehensive Reviews in Food Science and Food Safety, 22: 1686-1721.
https://doi.org/10.1111/1541-4337.13127

Yang Y. J., Yang S. J., Wang Y. S., and Zeng J. M., 2003, Selection of early budding and high quality green-tea cultivar, Journal of Tea Science, 23: 9-15.

Ye F., Guo X., Li B., Chen H., and Qiao X., 2022, Characterization of effects of different tea harvesting seasons on quality components, color and sensory quality of "Yinghong 9" and "Huangyu" large-leaf-variety black tea, Molecules, 27: 8720.
https://doi.org/10.3390/molecules27248720

Ye J. H., Lv Y. Q., Liu S. R., Jin J., Wang Y. F., Wei C. L., and Zhao S. Q., 2021, Effects of light intensity and spectral composition on the transcriptome profiles of leaves in shade grown tea plants (*Camellia sinensis* L.) and regulatory network of flavonoid biosynthesis, Molecules, 26: 5836.
https://doi.org/10.3390/molecules26195836

Ye Y., Yan J., Cui J., Mao S., Li M., Liao X., and Tong H., 2018, Dynamic changes in amino acids, catechins, caffeine and gallic acid in green tea during withering, Journal of Food Composition and Analysis, 66: 98-108.
https://doi.org/10.1016/j.jfca.2017.12.008

Yin P., Kong Y. S., Liu P. P., Jiang C. L., Sun M. F., Guo G. Y., and Liu Z. H., 2022, Temporal variation of the non-volatile compounds and key odorants in Xinyang Maojian green teas during the spring and autumn seasons, Agronomy, 12: 1085.
https://doi.org/10.3390/agronomy12051085

Yu P., Huang H., Zhao X., Zhong N., Zheng H., and Gong Y., 2020, Distinct variation in taste quality of Congou black tea during a single spring season, Food Science & Nutrition, 8: 1848-1856.
https://doi.org/10.1002/fsn3.1467

Zaman F., Zhang E., Xia L., Deng X., Ilyas M., Ali A., Guo F., Wang P., Wang M., Wang Y., Ni D., and Zhao H., 2023, Natural variation of main biochemical components, morphological and yield traits among a panel of 87 tea (*Camellia sinensis* (L.) O. Kuntze) cultivars, Horticultural Plant Journal, 9: 563-576.
https://doi.org/10.1016/j.hpj.2022.08.007

Zeng C., Lin H., Liu Z., and Liu Z., 2020, Metabolomics analysis of *Camellia sinensis* with respect to harvesting time, Food Research International, 128: 108814.
https://doi.org/10.1016/j.foodres.2019.108814

Zhang C., Zhou C., Xu K., Tian C., Zhang M., Lu L., Zhu C., Lai Z., and Guo Y., 2022, A comprehensive investigation of macro-composition and volatile compounds in spring-picked and autumn-picked white tea, Foods, 11: 3628.
https://doi.org/10.3390/foods11223628

Zhu J., Zhou Y., and Wen H., 2025, Analysis of differences in volatile components of Rucheng Baimao (*Camellia pubescens*) black tea in different seasons, Foods, 14: 763.
https://doi.org/10.3390/foods14050763

Zhu W., Liu X., Cheng X., Li Y., and Liu L., 2023, Shading effects revisited: Comparisons of spring and autumn shading treatments reveal a seasonal-dependent regulation on amino acids in tea leaves, Beverage Plant Research, 3: 1-9.
https://doi.org/10.48130/BPR-2023-0005