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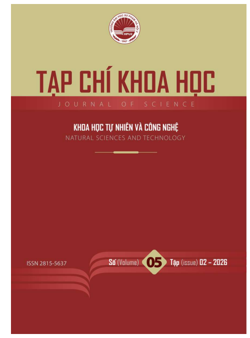


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# Evaluation of biochemical composition and sensory quality of ancient Shan tea trees (*Camellia sinensis* var. *assamica*) from Northern Vietnam

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## Abstract

The study evaluated the biochemical characteristics and sensory quality of ancient Shan tea (*Camellia sinensis* var. *assamica*) products in Northern Vietnam, specifically in Cao Bo-Tuyen Quang, Van Chan, and Cao Son-Lao Cai. The sensory quality was assessed based on appearance, water color, aroma, and taste. Meanwhile, the main biochemical compounds, including tannin, polyphenols, caffeine, amino acids, reducing sugars, and total soluble solids, were analyzed in 10 Shan tea tree individuals with the highest sensory scores. The results showed that the Shan tea samples achieved high sensory quality with an average total score of 16.22/20. There was also a very strong correlation among the sensory indicators ($r > 0.97$). PCA analysis indicated that the first principal component explained up to 98.36% of the total sensory variation, showing how well the overall tea quality structure is intergrated. The biochemical components among samples showed clear differentiation, especially for polyphenols and tannins. These findings suggest that secondary metabolites play a key role in shaping the unique quality of ancient Shan tea trees in Northern Vietnam. Overall, this study provides a scientific foundation for conservation, germplasm selection, and the development of high-quality Shan tea products linked to ecological and indigenous values.

***Keywords:*** Ancient Shan tea, biochemical composition, *Camellia sinensis* var. *assamica*, sensory evaluation, Northern Vietnam

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## 1. Introduction

Ancient Shan tea trees (*Camellia sinensis* var. *assamica*) are a native genetic resource with great economic and cultural value in the high mountainous regions of Northern Vietnam. These tea populations usually grow in natural or semi-natural conditions at high altitudes, where they are shaped by specific ecological conditions over a long time. The resulting tea products contain a rich mix of bioactive compounds that offer health benefits, especially antioxidant, anti-inflammatory, and antibacterial properties [1], [2]. The biochemical components of tea, particularly polyphenols, catechins, caffeine, amino acids, and soluble sugars, play a major role in deciding both the nutritional value and sensory quality of the tea products [3, 4].

In Vietnam, ancient Shan tea trees are highly valued for their long lifespan, natural adaptation to mountainous conditions, and tea liquor quality. These tea populations are mainly located in the high mountains of northern Vietnam, especially in provinces like Tuyen Quang and Lao Cai. The climate is cool year-round, humidity is high, the day-night temperature variation is large, and the soil is nutrient-rich, conducive to the accumulation of secondary metabolites in tea buds [5].

In recent years, the global demand for specialty and high-quality tea products has been increasing. Along with this, there is growing interest in the conservation and exploitation of native tea genetic resoures. Many studies show that tea quality depends heavily on genotype, ecological conditions, altitude, cultivation practices, and processing technology [6, 7]. Among these factors, genetics is a key to creating differences in the biochemical buildup and sensory quality of tea. Secondary metabolites in tea, especially polyphenols, catechins, and free amino acids, directly shape the product's taste, aroma, and health benefits [1, 3]. To date, few studies have simultaneously looked at both the biochemical and sensory traits of individual ancient Shan tea trees in the distinct ecological zones of Tuyen Quang and Lao Cai. However, differences in altitude and microclimate can greatly change how bioactive compounds accumulate and how the final tea tastes. Therefore, evaluating and comparing individual Shan tea trees from these two regions is necessary. Doing so helps identify superior genetic resources for breeding, conservation, and development of high-quality specialty tea varieties.

Sensory evaluation is an important tool that reflects overall tea quality through features such as leaf appearance, water color, aroma, and taste. These traits are closely related to the biochemical composition of the tea raw material. For example, catechin and caffeine mostly cause bitterness and astringency, while amino acids create the umami flavor and a sweet aftertaste [3]. Therefore, combining biochemical analysis with sensory testing gives a more complete picture of tea quality. This approach effectively helps select the best samples for processing premium tea.

Consequently, the study "Assessment of biochemical components and sensory quality of traditional Shan tea tree individuals in the Northern mountainous region of Vietnam" was conducted to provide the first comprehensive look at the main biochemical compounds and sensory quality of traditional Shan tea trees across two ecological regions in Northern Vietnam. The findings will offer the scientific basis for the conservation and sustainability using these traditional Shan tea genetic resources, while also guiding the development of high-quality specialty tea products in Vietnam.

## 2. Materials and methods

### *2.1. Plant materials and study locations*

The study focused on ancient Shan tea (*C. sinensis* var. *assamica*) populations across three mountainous areas in northern Vietnam, including Cao Bo commune (Tuyen Quang province), Van Chan commune, and

Cao Son commune (Lao Cai province) (Prior to July 1, 2025, they were part of Ha Giang, Yen Bai, and Lao Cai provinces). These sites sit at altitudes ranging from approximately 800 to over 1,500 m above sea level. They feature a subtropical highland climate, with large temperature differences between day and night as well as seasonal shifts in humidity. These conditions are ideal for ancient Shan tea populations to grow and thrive naturally or semi-naturally. We selected 36 tea individuals based on the criteria as clearly developed woody stems, stable growth, and being recognized by local communities as ancient trees. The trees were chosen evenly across the three locations to represent each ecological region. The geographic locations and physical traits of each tree have been published in Bui *et al.* (2025) [8].

### *2.2. Sensory evaluation*

Processed green tea samples were brewed according to TCVN 5086:1990 (ISO 3103:1980), Tea – preparation of liquor for use in sensory tests, to minimize variations caused by the brewing process [9]. And sensory attributes were evaluated using the scoring method described in TCVN 3218:2012 [10].

A team of five trained panelists scored each sample based on appearance, liquor color, aroma, taste, and aftertaste. Each feature was rated according to standard criteria. The overall sensory score was then calculated by adding up the individual scores after multiplying them by their assigned weights [10]. Finally, the scores from the five panelists were averaged for each sample and shown as mean ± standard deviation (SD).

### *2.3. Biochemical analysis*

The ten samples with the highest sensory scores, representing the three ecological regions (five LC.TT samples, two YB.SB samples, and three HG.LT samples), were selected for further analysis. Tea leaf samples were harvested following the standard plucking of one bud and two leaves at the same growth stage to minimize the influence of growth stage on chemical composition. After harvesting, the samples were steamed to stop oxidation, then dried and stored properly. Each sample is used for chemical analysis during the winter-spring growing season.

The biochemical parameters analyzed included total tannin content determined using the Leventhal method; total free amino acid content using a method of Papov; reducing sugar content determined using the Bertrand method; caffeine content determined by iodine titration as described by Vu *et al.* (2001) [11], soluble solids content according to TCVN 5610:2007 [12], and total polyphenol content determined according to TCVN 9745-1:2013 [13]. All biochemical analyses were performed three times, and the results are shown as mean ± standard deviation (SD) on a dry weight basis.

### *2.4. Statistical analysis*

Data was processed using R software (R Core Team, 2023). Descriptive statistics were used to find the mean and standard deviation of the measured variables. Principal component analysis (PCA) and variance analysis were used to evaluate factors affecting the sensory indicators. The correlation between sensory indicators was determined using Pearson's correlation coefficient. Additionally, multiple linear regression helped explain how gene types relate to variations of Shan tea. The threshold for statistical significance was set at $p < 0.05$.

## 3. Result and Discussions

### *3.1. Sensory quality analysis of Shan tea*

*Descriptive statistics of sensory attributes*

The sensory evaluation results for the 36 individual Shan tea trees are presented in Table 1. Overall, the tea samples scored high, with relatively little variation among them.

**Table 1.** Sensory quality of 36 Shan tea tree individuals.

| No | Parameter | Mean | Standard deviation |
|---|---|---|---|
| 1. | Appearance | 4.25 (x 0.6)* | 0.26 |
| 2. | Liquor color | 4.27 (x 1.0) | 0.20 |
| 3. | Aroma | 3.90 (x 1.2) | 0.22 |
| 4. | Taste | 3.94 (x 1.2) | 0.33 |
| 5. | Total score | **16.22**<br>* Coefficient according to TCVN 2012 [10] | 0.81 |

The average values of the indicators were: appearance 4.25±0.26, liquor color 4.27±0.20, aroma 3.90±0.22, and taste 3.94±0.33. The average total sensory score of the samples was 16.22±0.81 (on a scale of 20). The low standard deviation in all indicators shows a high level of consensus among the sensory quality assessment panel members and stability in quality assessment across samples. Taste had the highest variability (SD=0.33), indicating that it was the most sensitive indicator among samples. The total score had an SD of 0.81, demonstrating that significant quality differences still exist between samples, despite the overall high distribution. Ancient tea trees may accumulate higher levels of polyphenols, amino acids, and aromatic compounds. Tea derived from older trees tends to exhibit reduced bitterness and astringency, while showing more pronounced sweetness and umami characteristics, thereby contributing to an overall enhancement of sensory quality [14].

*Correlation structure among sensory attributes*

The Pearson correlation matrix among sensory attributes is presented in Table 2.

**Table 2.** Pearson correlation matrix of sensory attributes.

| No | Parameter | Appearance | Liquor color | Aroma | Taste |
|---|---|---|---|---|---|
| 1. | Appearance | 1.00 | 0.97 | 0.98 | 0.98 |
| 2. | Liquor color | 0.97 | 1.00 | 0.99 | 0.99 |
| 3. | Aroma | 0.98 | 0.99 | 1.00 | 1.00 |
| 4. | Taste | 0.98 | 0.99 | 1.00 | 1.00 |

All correlation coefficients were very high ($r > 0.97$). In particular, aroma and taste exhibited an almost perfect correlation, showing that these attributes vary synchronously across samples. Appearance and liquor color were also strongly correlated with the other attributes. These results demonstrate that sensory quality in Shan tea is highly integrated, with individual attributes not varying independently but rather changing coherently along a common quality axis.

*Principal component analysis*

Findings of principal component analysis (PCA) for the four sensory attributes are shown in Table 3.

**Table 3.** Proportion of variance explained by principal components.

| No | Principal component | Eigenvalue | Percentage of variance (%) | Cumulative percentage (%) |
|---|---|---|---|---|
| 1. | PC1 | 3.93 | 98.36 | 98.36 |
| 2. | PC2 | 0.04 | 1,12 | 99.48 |
| 3. | PC3 | ~0.02 | <1 | ~99.9 |
| 4. | PC4 | ~0.01 | <1 | 100.00 |

The first principal component (PC1) explained 98.36% of the total variance in sensory data, indicating that most variation among samples can be captured by a single underlying dimension. The second principal component (PC2) accounted for only 1.12% of the variance and does not represent a practically meaningful dimension.

This suggests that the sensory structure of the 36 Shan tea trees is strongly unidimensional, with differences among samples primarily reflecting overall quality levels rather than distinct separation among individual attributes.

*3.2. Biochemical characteristics of 10 selected Shan tea tree individuals*

Findings of biochemical composition analysis for 10 selected Shan tea trees, chosen based on their highest overall sensory scores, are presented in Table 4. Six parameters were analyzed, including tannin, total soluble solids, amino acids, reducing sugars, caffeine, and polyphenols.

**Table 4.** Major biochemical components in tea shoots of 10 studied Shan tea tree individuals.

| No | Samples | Tannin (%) | Total soluble solids (%) | Amino acids (%) | Reducing Sugars (%) | Caffeine (%) | Polyphenols (%) |
|---|---|---|---|---|---|---|---|
| 1. | HG.LT1 | 25.71±0.06 | 42.37±0.04 | 1.81±0.04 | 1.63±0.03 | 2.80±0.02 | 14.74±0.04 |
| 2. | HG.LT12 | 27.48±0.02 | 43.34±0.10 | 1.34±0.01 | 1.63±0.04 | 2.83±0.03 | 16.84±0.05 |
| 3. | HG.LT3 | 27.44±0.03 | 44.24±0.03 | 1.26±0.01 | 1.70±0.03 | 2.84±0.03 | 19.87±0.02 |
| 4. | LC.TT1 | 21.44±0.03 | 40.33±0.02 | 1.88±0.03 | 1.46±0.01 | 3.08±0.02 | 15.63±0.25 |
| 5. | LC.TT11 | 22.57±0.01 | 43.14±0.02 | 1.66±0.01 | 1.53±0.01 | 2.66±0.02 | 13.64±0.02 |
| 6. | LC.TT16 | 24.55±0.01 | 42.35±0.01 | 1.32±0.02 | 2.02±0.01 | 2.92±0.01 | 14.97±0.02 |
| 7. | LC.TT5 | 23.29±0.01 | 41.77±0.02 | 1.98±0.01 | 1.91±0.02 | 2.96±0.04 | 17.58±0.03 |
| 8. | LC.TT9 | 24.58±0.03 | 41.33±0.01 | 1.94±0.02 | 2.09±0.01 | 2.73±0.02 | 18.34±0.03 |
| 9. | YB.SB1 | 24.46±0.03 | 42.78±0.02 | 1.56±0.02 | 1.62±0.02 | 2.92±0.03 | 16.55±0.03 |
| 10. | YB.SB4 | 28.78±0.05 | 44.65±0.03 | 1.36±0.03 | 1.65±0.02 | 3.04±0.03 | 18.65±0.04 |

The results of biochemical composition analysis of Shan tea trees (*C. sinensis* var. *assamica*) revealed significant variation among samples in tannin, total soluble solids, amino acids, reducing sugars, caffeine, and polyphenols. These compounds are key determinants of sensory quality and the biological value of the final tea product [15].

Tannin content ranged from 21.44% to 28.78%. The highest values were observed in YB.SB4 (28.78%) and HG.LT12 (27.48%), while LC.TT1 exhibited the lowest content (21.44%). Tannin is the major group of polyphenols in tea leaves, contributing to the characteristic astringency and possessing strong antioxidant activity [16]. Differences in tannin content among genotypes reflect the influence of genetic factors on phenolic compound biosynthesis in tea leaves [17].

Total soluble solids ranged from 40.33% to 44.65%, with YB.SB4 and HG.LT3 showing the highest values (44.65% and 44.24%, respectively). This parameter is considered an important indicator of the extractability of flavor-related compounds during tea processing and infusion preparation [18]. Tea genotypes with higher soluble solids content generally produce better liquor quality due to higher levels of soluble compounds such as polyphenols, amino acids, and sugars [19].

Total amino acid content ranged from 1.26% to 1.98%. The highest levels were found in LC.TT5 (1.98%) and LC.TT9 (1.94%), whereas HG.LT3 had the lowest content (1.26%). Amino acids, particularly theanine, play a crucial role in contributing to umami taste and in softening the astringency of tea. Their accumulation in tea leaves is strongly influenced by genotype and growing conditions [20], [21].

Reducing sugar content ranged from 1.46% to 2.09%, with LC.TT9 (2.09%) and LC.TT16 (2.02%) showing the highest values. Reducing sugars contribute to mild sweetness and participate in Maillard reactions during processing, thereby influencing both color and aroma development in tea [22]. Variation in sugar content among samples may be associated with differences in carbohydrate accumulation and metabolic activity in the leaves.

Caffeine content ranged from 2.66% to 3.08%. LC.TT1 (3.08%) and YB. SB4 (3.04%) exhibited higher caffeine levels compared to other tree individuals. Caffeine is a characteristic alkaloid in tea, contributing to bitterness and providing stimulatory effects on the central nervous system [16]. Total polyphenol content varied from 13.64% to 19.87%. The highest levels were recorded in HG.LT3 (19.87%), YB.SB4 (18.65%), and LC.TT9 (18.34%). Polyphenols are the most important group of compounds determining the antioxidant capacity and health benefits of tea [16], [23].

Among polyphenols, catechins (EC, ECG, EGC, and EGCG) are the most abundant phenolic compounds in fresh tea leaves and green tea. They are the primary contributors to astringency, partly to bitterness, and play a major role in the antioxidant properties of tea [24], [25]. In addition, the relationship between catechin content, liquor color, and sensory quality suggests that a moderate catechin level, in combination with appropriate levels of amino acids and caffeine, results in a balanced astringency that is more favorably perceived by consumers [26].

Generally, tea grown at higher altitudes tends to accumulate flavonoids, amino acids and saccharides, which promote a sweeter and milder flavor [6], [27]. This phenomenon can be explained by the altitude-related changes in microclimate, including variations in temperature and humidity. The higher the elevation, the greater the diversity and abundance of microbial communities, which directly influence the biochemical composition of the tea [28], [29]; possibly due to the physiological adaptation mechanisms of the plants to low temperatures (cold stress) [6], the weaker light intensity (shaded conditions) also increases the amino acid content in tea [30], [31].

The summary of the indicators shows that the LC.TT group (Cao Son-Lao Cai) area demonstrates a clear advantage in biochemical balance, with high levels of amino acids and reducing sugars, moderate tannin and caffeine, and polyphenols sufficiently high to create flavor but not cause astringency. Meanwhile, the YB.SB group (Van Chan-Lao Cai) and the HG.LT group (Cao Bo-Tuyen Quang) tends to have higher polyphenol and soluble substance content, suitable for stronger-flavored tea or blending purposes, but less advantageous for high-grade tea orientation. These results are also consistent with many previous studies showing significant differences in the biochemical composition among tea genotypes due to genetic background influence and secondary metabolite accumulation capacity [15].

### *3.3. Relative distribution of biochemical parameters among 10 studied Shan tea tree individuals*

Heatmap analysis revealed clear differentiation in biochemical composition among the 10 selected Shan tea tree individuals in Figure 1. Standardization using z-scores enables relative comparison among variables with different measurement units, where positive values ($z > 0$) indicate concentrations above the overall mean of the dataset, while negative values ($z < 0$) indicate below-average levels.

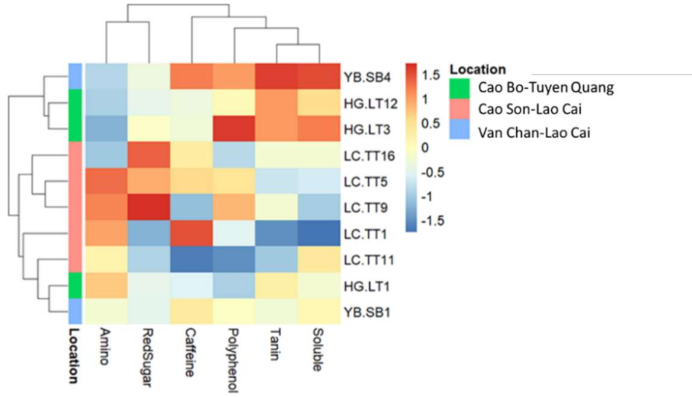


**Figure 1.** Heatmap biochemical traits (z-score) with location.

From a row-wise perspective, several samples exhibited notably high accumulation of key compounds. Specifically, YB.SB4 and HG.LT3 showed significantly higher polyphenol levels compared to the overall mean. These samples demonstrate strong potential for high-quality tea production, as polyphenols play a crucial role in shaping the flavor and taste profile of tea. LC.TT9 exhibited relatively high levels of reducing sugars compared to other samples. Reducing sugar content may contribute to moderating astringency and enhancing overall taste balance. In contrast, LC.TT11 displayed lower-than-average levels of both polyphenols and caffeine, indicating a comparatively less pronounced biochemical profile relative to other trees .

From a column-wise perspective, polyphenols and tannins showed the greatest variation among samples, whereas caffeine and total soluble solids exhibited narrower ranges of variation. This suggests that phenolic compounds may represent the primary source of variation distinguishing high-quality Shan tea tree individuals.

Overall, the heatmap highlights clusters of trees with similar biochemical profiles while also identifying samples with distinctive biochemical signatures. The results point to a potential relationship among tree age, biochemical composition, and sensory quality of tea. Previous studies have also shown that key secondary metabolites, such as flavonoids, phenolic acids, tannins, and catechins, vary significantly with tree age, reflecting gradual adjustments in metabolic pathways over the course of plant development [14]. These biochemical changes are accompanied by corresponding sensory modifications, where tea derived from older trees tends to exhibit greater sweetness, more pronounced umami characteristics, and reduced bitterness and astringency [32].

## 4. Conclusion

This study provides an initial analysis and evaluation of the biochemical components and sensory quality of ancient Shan tea populations in the northern mountainous region of Vietnam. The results showed that all Shan tea samples studied had high sensory quality scores; there was a close correlation between appearance, water color, aroma, and taste indicators. PCA analysis demonstrated that the variation in sensory indicators mainly centered on a single comprehensive quality axis, reflecting high consistency and strong linkage among the sensory attributes of ancient Shan tea. The Shan tea tree individuals exhibited significant diversity in biochemical composition, especially in phenolic compounds. Polyphenols and tannins are the two groups of compounds with the greatest variation, while caffeine and soluble substances tend to be more stable, indicating immense potential for selection and development of high-quality tea raw materials. Furthermore, the heatmap and biochemical analysis also showed that phenolic compounds are the most variable group among the studied tree individuals. The study also supports the hypothesis that the long-term growth process of ancient tea trees may be related to the regulation of secondary metabolism and the accumulation of compounds that determine tea quality. From there, it contributes to providing a scientific basis for the conservation of ancient Shan tea germplasm and guides the selection of high-value tea varieties associated with the ecological conditions of Northern Vietnam.

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**References**

[1] Z.-M. Chen and L. Chen, "Delicious and healthy tea: an overview," *Global Tea Breeding: Achievements, Challenges and Perspectives,* pp. 1–11, Jan. 2012, doi: 10.1007/978-3-642-31878-8_1.

[2] Q. V. Vuong, "Epidemiological evidence linking tea consumption to human health: a review," *Critical reviews in food science and nutrition,* vol. 54, no. 4, pp. 523–536, Nov. 2013, doi: 10.1080/10408398.2011.594184.

[3] Y. Hilal, U. Engelhardt, "Characterisation of white tea–Comparison to green and black tea," *Journal für Verbraucherschutz und Lebensmittelsicherheit,* vol. 2, no. 4, pp. 414–421, Nov. 2007, doi: 10.1007/s00003-007-0250-3.

[4] M. Obanda, P. O. Owuor, and R. Mang'oka, "Changes in the chemical and sensory quality parameters of black tea due to variations of fermentation time and temperature," *Food chemistry,* vol. 75, no. 4, pp. 395–404, Dec. 2001, doi: 10.1016/S0308-8146(01)00223-0.

[5] T. T. Pham and T. H. Nguyen, "Conservation and development of Ha Giang Shan Tuyet tea toward organic production," (in Vietnamese), *Journal of Human Geography and Sustainable Development,* vol. 3 (34) pp. 12 –21, 2021.

[6] M. Chen *et al.*, "Effects of low-temperature stress on cold resistance biochemical characteristics of dali and siqiu tea seedlings," *Horticulturae,* vol. 10, no. 8, p. 823, Aug. 2024, doi: 10.3390/horticulturae10080823.

[7] M. Adnan, A. Ahmad, A. Ahmed, N. Khalid, I. Hayat, and I. Ahmed, "Chemical composition and sensory evaluation of tea (*Camellia sinensis*) commercialized in Pakistan," *Pak. J. Bot,* vol. 45, no. 3, pp. 901–907, 2013.

[8] L. T. Bui *et al.*, "Morphological and genetic relationship of ancient Shan tea tree (*Camellia sinensis* var. *assamica*) from ecogeographical regions in Northern Vietnam," *Pertanika Journal of Science & Technology,* vol. 33 (4), pp. 1849–1868, Jun. 2025, doi: 10.47836/pjst.33.4.08.

[9] Vietnamese National Standard (TCVN) 5086:1990 (ISO 3103:1980), 1990, Tea- Preparation of liquor for use in sensory tests, (in Vietnamese).

[10] Vietnamese National Standard (TCVN) 3218:2012, 2012, Tea - Sensory analysis by presenting mark, (in Vietnamese).

[11] Vu Thy Thu *et al.*, Chemical compounds in tea and some common analytical methods used in tea production in Vietnam. Agricultural Publishing House, 2001 (in Vietnamese).

[12] Vietnamese National Standard (TCVN) 5610:2007 (ISO 9768:1994), Tea - Determination of water extract, (in Vietnamese).

[13] Vietnamese National Standard (TCVN) 9745-1:2013, 2013, Determination of substances characteristic of green and black tea - Part 1: Content of total polyphenols in tea - Colorimetric method using Folin-Ciocalteu reagent, (in Vietnamese).

[14] Z. Shi *et al.*, "Determining the influence of tree age on tea quality-related metabolites in Camellia tachangensis var. remotiserrata by integrating metabolomic and transcriptomic analyses", *Frontiers in Plant Science,* vol. 16, p. 1701011, Nov. 2025, doi: 10.3389/fpls.2025.1701011.

[15] F. Zaman *et al.*, "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,* vol. 9, no. 3, pp. 563–576, Jun. 2023, doi: 10.1016/j.hpj.2022.08.007.

[16] J. Kochman, K. Jakubczyk, J. Antoniewicz, H. Mruk, and K. Janda, "Health benefits and chemical composition of matcha green tea: A review," *Molecules,* vol. 26, no. 1, p. 85, Dec. 2020, doi: 10.3390/molecules26010085.

[17] L. Zhang *et al.*, “Volatile and flavour compounds analysis reveal quality constituents of Qianlin tea (*Camellia cuspidata*) to diversify tea products,” *Applied Food Research,* vol. 4, no. 2, p. 100624, Nov. 2024, doi: 10.1016/j.afres.2024.100624.

[18] J. Kong, X. Yang, X. Zuo, X. Su, B. Hu, and X. Liang, “High-quality instant black tea manufactured using fresh tea leaves by two-stage submerged enzymatic processing,” *Food Science and Human Wellness,* vol. 11, no. 3, pp. 676–685, May. 2022, doi: 10.1016/j.fshw.2021.12.025.

[19] J. Li *et al.*, “Characterizing the cultivar-specific mechanisms underlying the accumulation of quality-related metabolites in specific Chinese tea (*Camellia sinensis*) germplasms to diversify tea products,” *Food Research International,* vol. 161, p. 111824, Nov. 2022, doi: 10.1016/j.foodres.2022.111824.

[20] Q. Wang *et al.*, “L-Theanine metabolism in tea plants: biological functions and stress tolerance mechanisms,” *Plants,* vol. 14, no. 3, p. 492, Feb. 2025, doi: 10.3390/plants14030492.

[21] S. Deb *et al.*, “Neuroprotective attributes of L-theanine, a bioactive amino acid of tea, and its potential role in Parkinson's disease therapeutics,” *Neurochemistry international,* vol. 129, p. 104478, Oct. 2019, doi: 10.1016/j.neuint.2019.104478.

[22] X. Feng *et al.*, “New insights into the umami and sweet taste of oolong tea: Formation of enhancer n-(1-carboxyethyl)-6-(hydroxymethyl) pyridinium-3-ol (alapyridaine) in roasting via maillard reaction,” *Journal of Agricultural and Food Chemistry,* vol. 72, no. 15, pp. 8760–8773, Mar. 2024, doi: 10.1021/acs.jafc.3c09011.

[23] L. Chen, H. Wang, Y. Ye, Y. Wang, and P. Xu, “Structural insight into polyphenol oxidation during black tea fermentation,” *Food Chemistry: X,* vol. 17, p. 100615, Mar. 2023, doi: 10.1016/j.fochx.2023.100615.

[24] J. Moreira *et al.*, “Tea quality: An overview of the analytical methods and sensory analyses used in the most recent studies,” *Foods,* vol. 13, no. 22, p. 3580, Nov. 2024, doi: 10.3390/foods13223580.

[25] A. Parveen *et al.*, “The chemistry, sensory properties and health benefits of aroma compounds of black tea produced by *Camellia sinensis* and *Camellia assamica,*” *Horticulturae,* vol. 9, no. 12, p. 1253, Dec. 2023, doi: 10.3390/horticulturae9121253.

[26] A. Zheng *et al.*, “Key compounds responsible for the flavor diversity of Yongchun Foshou oolong tea of different grades and in different seasons,” *npj Science of Food,* vol. 10, no. 1, pp. 13–13, Dec. 2025, doi: 10.1038/s41538-025-00663-w..

[27] A. Bassiony *et al.*, “Differential accumulation patterns of flavor compounds in Longjing 43 and Qunti fresh leaves and during processing responding to altitude changes,” *Food Research International,* vol. 187, p. 114392, Apr. 2024, doi: 10.1016/j.foodres.2024.114392.

[28] C. Ren *et al.*, “Contrasting patterns of microbial community and enzyme activity between rhizosphere and bulk soil along an elevation gradient,” *Catena,* vol. 196, p. 104921, Jan. 2021, doi: 10.1016/j.catena.2020.104921.

[29] L. Xie, W. Li, X. Pang, Q. Liu, and C. Yin, “Soil properties and root traits are important factors driving rhizosphere soil bacterial and fungal community variations in alpine Rhododendron nitidulum shrub ecosystems along an altitudinal gradient,” *Science of the Total Environment,* vol. 864, p. 161048, Dec. 2022, doi: 10.1016/j.scitotenv.2022.161048.

[30] Y. Chen *et al.*, “Proteolysis of chloroplast proteins is responsible for accumulation of free amino acids in dark-treated tea (Camellia sinensis) leaves,” *Journal of Proteomics,* vol. 157, pp. 10–17, Mar. 2017, doi: 10.1016/j.jprot.2017.01.017.

[31] M. Wang *et al.*, “Effects of temperature and light on quality-related metabolites in tea [*Camellia sinensis* (L.) Kuntze] leaves,” *Food research international,* vol. 161, p. 111882, Sep. 2022, doi: 10.1016/j.foodres.2022.111882.

[32] P. Long *et al.*, “The effects of tea plant age on the color, taste, and chemical characteristics of Yunnan Congou black tea by multi-spectral omics insight,” *Food Chemistry: X,* vol. 21, p. 101190, Feb. 2024, doi: 10.1016/j.fochx.2024.101190.