

Article

Sprinkler Irrigation Improves Flavor and Sensory Quality of Ning Black Autumn Tea: A Comparative Analysis

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Abstract

Ning black autumn tea from Jiangxi, China, is often neglected by farmers due to quality decline under hot and arid autumn conditions. In this study, four soil moisture levels (T1–T4, ranging from 32.75% to 18.36%) were established through different sprinkler irrigation frequencies to investigate their effects on tea quality. T2 (27.98% soil moisture) exhibited the highest content of total free amino acids (13.77 mg/g), which was 13.33% higher than that in T4 (12.15 mg/g). Notably, T2 had the highest content of umami amino acids (6.75 mg/g) and the lowest content of bitter amino acids (3.07 mg/g) among all treatments. The total non-esterified catechin content in T2 (18.92 mg/g) was 2.74-fold higher than that in T4 (6.90 mg/g). Among the 55 volatile compounds identified, trans-nerolidol reached its highest odor activity value in T2 (11.77), contributing to a distinctive fruity and floral aroma. Sensory evaluation confirmed that T2 had the highest taste score (89.7), with significantly reduced bitterness and astringency, consistent with its enriched umami amino acids (6.75 mg/g) and lower bitter amino acids (3.07 mg/g). These findings demonstrate that maintaining soil moisture at approximately 28% through moderate sprinkler irrigation effectively balances flavor-related metabolites and improves autumn tea quality, offering a practical strategy to reduce resource waste and increase economic returns.

Keywords: Ning black tea; sprinkler irrigation; flavor substances; volatile compounds; tea quality



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1. Introduction

Black tea is one of the most widely consumed teas globally, with congou black tea being the predominant type produced in China, represented by renowned varieties such as Ning black tea, Keemun black tea, Yingde and Dianhong black tea [1]. Originating from Xiushui County, Jiangxi Province, Ning black tea is historically regarded as one of the earliest and most esteemed Chinese congou black teas. The quality of tea exhibits significant seasonal variations. Generally, spring tea is characterized by superior sweetness, flavor, and overall taste compared with autumn tea [2], which often lacks freshness and

exhibits more pronounced bitterness. Among the environmental factors contributing to this quality decline, water availability during the autumn growing season is particularly critical. Southern China frequently experiences recurrent periods of extreme heat and drought during the summer [3], which not only hinder the growth of tea trees but also adversely affect overall tea quality [4,5]. Such adverse conditions during the summer may exert residual effects on tea plants, potentially influencing the quality of the autumn harvest. Therefore, developing effective water management strategies is essential for optimizing the use of autumn tea resources.

Tea quality is largely determined by the accumulation of key metabolites, including polyphenols, catechins, free amino acids, caffeine, and volatile organic compounds [6–8]. These constituents not only contribute to the flavor profile but also influence the potential health benefits of tea [9–12]. The responses of these metabolites to water availability are complex and often contradictory. For instance, studies have shown that drought stress can significantly reduce catechin content in tea leaves under controlled conditions [13] and in field settings [14]. However, some studies have reported varying responses, with certain metabolites remaining unchanged under drought while others exhibited complex responses [15]. Notably, Scott et al. [15] further demonstrated that the induction of volatile metabolites by simulated herbivory was suppressed under severe drought but enhanced for certain compounds (e.g., methyl salicylate) under the same drought conditions, highlighting the complexity of water stress effects on tea quality. Moreover, some research suggests that the improvement in tea quality under field conditions does not show a significant correlation with the concentrations of theanine, catechins, and caffeine [16]. Beyond non-volatile components, the intricate aroma profile of tea is also influenced by water availability [14,15]. However, the precise effects of soil moisture content on the volatile composition of Ning black autumn tea remain largely unexplored.

Previous studies have predominantly focused on the impact of natural drought stress or have used simulated drought (e.g., polyethylene glycol treatment) on tea plants, often overlooking the potential of active water regulation through irrigation to improve tea quality. Furthermore, the majority of this research has concentrated on spring tea and has not accounted for variety-specific responses. Consequently, there is a lack of systematic evaluation of how controlled irrigation frequencies affect the processed quality of Ning black autumn tea, a variety with significant commercial and cultural value.

In this study, we aimed to investigate the effects of different sprinkler irrigation frequencies on the quality of Ning black tea processed from autumn fresh leaves. Fresh leaves from the *Camellia sinensis* “Ning black” cultivar subjected to varying soil moisture conditions were processed using standardized manufacturing procedures. High-performance liquid chromatography (HPLC) and headspace solid-phase microextraction coupled with gas chromatography–mass spectrometry (HS-SPME-GC-MS) were employed to comprehensively evaluate changes in both non-volatile (catechins, amino acids, caffeine, and theaflavins) and volatile components. This study seeks to elucidate the relationship between soil moisture management and the final tea quality, providing a scientific basis for optimizing irrigation strategies to enhance the quality of Ning black autumn tea.

2. Materials and Methods

2.1. Tea Samples and Stress Conditions

The study was conducted on a 60-year-old population of Ningzhou Population tea trees situated in the Jiujiang Xiushui Tea Science Research Institute tea garden within Xiushui County, Jiujiang City, Jiangxi Province, China (29.01° N, 114.52° E) in mid-August 2024. The experimental tea trees were planted in pairs, with a spacing of 1.5 m between rows and 0.33 m between plants within rows. The experimental area was divided into four

200 m² plots, each assigned to one of four irrigation treatments (one plot per treatment, $n = 1$). Treatments T1, T2, and T3 received sprinkler irrigation at different frequencies, while T4 served as a rainfed control (no supplemental irrigation). Due to land availability and the layout of the irrigation infrastructure, the plots were arranged in a fixed order rather than randomized. In the trial, a buffer of two rows was maintained between adjacent plots to prevent water drift.

Four treatments were implemented: Treatment 1 (T1): Daily irrigation, initiated at 08:00 local time, applied until soil moisture content reached field capacity. Treatment 2 (T2): Irrigation every 48 h, initiated at 08:00 local time, with irrigation applied until soil moisture content reached field capacity. Treatment 3 (T3): Irrigation every 72 h, initiated at 08:00 local time, with irrigation applied each time until soil moisture content reached field capacity. Treatment 4 (T4): Rainfed control (no supplemental irrigation). Meteorological data indicated an isolated 20 min rainfall on August 28, which partially replenished the topsoil moisture but did not significantly alter the irrigation schedule. Two days post-initiation of the experiment, the difference between dry and fresh soil was determined using the weight method, with the soil moisture quantified as a percentage of the total weight. Soil samples extracted from the 0–20 cm layer were dried in a 105 °C oven for 48 h. Each treatment plot was sampled at three random points, with the average moisture content representing the given treatment. The soil moisture contents of the four treatments were as follows: T1: 32.75% ± 1.80%, T2: 27.98% ± 0.93%, T3: 24.50% ± 0.79%, and T4: 18.36% ± 1.16%. The calculation of irrigation water volume refers to [7]. First, the water depth was calculated, and then the total amount of irrigation water was obtained based on the irrigated area.

In late September, 360 tea plants were randomly selected from each 200 m² plot and divided into three groups of approximately 120 plants each. All fresh leaves (one bud with two leaves) from each group were collected separately, with each group serving as one biological replicate (three replicates per treatment). The harvested leaves from each replicate were then processed into Ning black autumn tea by a seasoned expert with 30 years of experience, following the standard Ning black tea processing protocols (withering, rolling, fermentation, and drying). The resultant dry tea was stored in a sanitary, odor-free refrigerator at −20 °C for subsequent analysis of volatile metabolites and non-volatile constituents.

2.2. Sensory Assessment

A sensory assessment of black tea was carried out by a panel comprising five trained experts (two females and three males, aged 20–55 years), adhering to the protocols specified in GB/T 23776-2018 [17]. The assessment focused on dry tea appearance, liquor color, aroma, taste and infused leaf appearance. For the analysis, each tea sample (3.0 g) was steeped in 150 mL of boiling water for 4 min. To ensure objectivity, the samples were assigned random codes to ensure blinding during the evaluation process. The panelists documented their observations and scores for each sensory attribute in a detailed report.

2.3. Chemicals

Reagents and materials used in this study included catechin standards (≥98%), such as catechin (C), catechin gallate (CG), gallocatechin gallate (GCG), epicatechin (EC), epicatechin gallate (ECG), gallocatechin (GC), epigallocatechin (EGC), and epigallocatechin gallate (EGCG), along with gallic acid (GA, ≥99%), theobromine (TB, ≥98%), caffeine (CAF, ≥98%), and amino acids (≥98%), including L-asparagine (Asn), L-aspartic acid (Asp), L-alanine (Ala), γ-aminobutyric acid (GABA), L-arginine (Arg), L-cysteine (Cys), L-glutamic acid (Glu), L-glycine (Gly), L-histidine (His), L-isoleucine (Ile), L-leucine (Leu), L-lysine (Lys),

L-methionine (Met), L-phenylalanine (Phe), L-proline (Pro), L-threonine (Thr), L-tyrosine (Tyr), L-valine (Val), L-cystine (Cys-Cys), L-tryptophan (Trp), and L-theanine (The). These were purchased from Solarbio Technology Co., Ltd. (Beijing, China). High-performance liquid chromatography (HPLC)-grade acetonitrile ($\geq 99\%$) and methanol ($\geq 99\%$) were obtained from Merck Company (Darmstadt, Germany). Acetic acid, disodium ethylenediaminetetraacetate, ascorbic acid, triethylamine hydrochloride, and ethyl decanoate were sourced from Aladdin Biochemical Co., Ltd. (Shanghai, China), while disodium hydrogen phosphate and potassium dihydrogen phosphate were procured from Hushi Chemical Co., Ltd. (Shanghai, China). The AccQ-Tag amino acid analysis derivative kit was obtained from Waters Co., Ltd. (Milford, CT, USA), and n-alkane mixtures (C7–C40) were purchased from Sigma-Aldrich Trading Co. Ltd. (Shanghai, China). Distilled water was provided by the Hangzhou Wahaha Group Co. Ltd. (Hangzhou, China).

2.4. Extraction and Analysis of Non-Volatile Compounds from Tea Using UPLC

2.4.1. Catechins, Caffeine, and Theobromine

A 0.2 g sample of tea powder was placed in a 10 mL centrifuge tube, followed by the addition of 5 mL of 70% (*v/v*) methanol heated to 70 °C. The mixture was vortexed for 10 s and then shaken in 70 °C water bath for 10 min for extraction. Following this, the sample was vortexed again for 10 s and subjected to ultrasonic treatment in a water bath for 5 min. The mixture was then centrifuged at 10,000 rpm for 5 min, and the supernatant was transferred to a 10 mL volumetric flask. Prior to analysis, the solution was filtered through a 0.22 μm membrane. The analytical method was adapted and optimized based on procedures previously established in our laboratory [18]. For the high-performance liquid chromatography (HPLC) analysis, a system comprising the DGP-3600RS dual ternary pump, WPS-3000 autosampler, TCC-3 $\times$ 00 (RS) column oven, and DAD-3000 (RS) diode array detector (Ultimate 3000) from Thermo Fisher Scientific (San Jose, CA, USA) was utilized. Catechins, caffeine, and theobromine were separated and quantified using a gradient elution method on a Thermo Hypersil GOLD Phenyl column (250 $\times$ 4.6 mm, 5 μm), with DAD detection at 278 nm. Detailed procedural information is available in a previous study [18].

2.4.2. Amino Acids

A 40 mg sample of tea powder was weighed and mixed with 8 mL of ultrapure water, followed by vortex mixing for 10 s. Ultrasonic treatment was conducted at room temperature in a water bath for 30 min. The mixture was subsequently centrifuged at 4 °C and 10,000 rpm for 5 min, after which the supernatant was filtered using a 0.22 μm microporous membrane (Millipore, Merck KGaA, Milford, MA, USA). For amino acid derivatization, 10 μL of the filtrate was transferred to a derivatization tube and mixed with 70 μL of AccQ-Tag Ultra borate buffer, followed by the addition of 20 μL of AccQ-Tag derivatization reagent (Waters, Milford, CT, USA). The mixture was vortexed for 10 s, incubated at room temperature for 1 min, heated at 55 °C in an oven for 10 min, and then cooled to room temperature prior to analysis. Each sample was analyzed in triplicate. The analytical method was adapted and optimized based on procedures previously established in our laboratory [18]. For the separation of amino acids, a Thermo Synchronis C18 column (100 $\times$ 2.1 mm, 1.7 μm) was utilized. The column temperature was maintained at 35 °C. An FLD-3 $\times$ 00 (RS) fluorescence detector (Thermo Fisher Scientific, San Jose, CA, USA) was used for detection, with the detector temperature set to 45 °C. The detection settings were configured with an excitation wavelength of 250 nm and an emission wavelength of 395 nm. The xenon lamp (Thermo Fisher Scientific, San Jose, CA, USA) was operated in LongLife mode with a sensitivity of 3. The identification of individual amino acids

was achieved by comparing their retention times with those of standard compounds, while quantification was carried out using the regression equations derived from the corresponding calibration curves.

2.5. Extraction and Analysis of Volatile Compounds from Tea Using HS-SPME-GC-MS

The analytical procedure involved the addition of 1.5 g of powdered tea sample to a 20 mL headspace vial, along with 0.5 g of sodium chloride and 5.25 mL of distilled water. An internal standard, ethyl decanoate (20 µg/mL, 20 µL), was also included. After incubation with intermittent shaking, a DVB/CAR/PDMS fiber (50/30 µm, 1 cm; Supelco, Bellefonte, PA, USA) was inserted into the headspace at 70 °C for 30 min. The fiber was then subjected to thermal desorption in the GC-MS injection port at 250 °C for 5 min. Finally, volatile compounds were separated and identified using GC-MS techniques. The analytical protocols used in this study were adapted and optimized based on our previously published works [18,19].

2.6. Odor Activity Value (OAV) and Taste Activity Value (TAV) Calculation

The OAV was determined according to the equation below:

$$OAV_i = \frac{C_i}{OT_i}, \quad (1)$$

where C_i denotes the absolute content of volatile compounds, while OT_i refers to the odor threshold of these compounds in water.

The TAV was determined according to the equation below:

$$TAV = C/T, \quad (2)$$

where C denotes the concentration of taste components, whereas T signifies the corresponding taste thresholds.

2.7. Statistical Analysis

Data are presented as mean values along with their standard deviations (SD), based on three biological replicates per treatment (each obtained from approximately 120 tea plants within the same plot). One-way ANOVA was conducted using SPSS version 20.0 (SPSS Inc., Chicago, IL, USA) to compare differences in taste and aroma compounds of Ning black tea under varying moisture conditions. Principal component analysis (PCA), partial least squares discriminant analysis (PLS-DA), and variable importance in projection (VIP) scores were calculated using SIMCA 14.1 (Umetrics, Umeå, Sweden). The column charts were generated with GraphPad Prism 9.0 (GraphPad Software, LLC, San Diego, CA, USA). For heatmap analysis, TBtools version 2.056 (<https://github.com/CJ-Chen/TBtools>, accessed on 15 December 2023) was employed, with data standardization applied before plotting.

3. Results

3.1. Sensory Evaluation of Ning Black Autumn Tea

The sensory evaluation of Ning black autumn tea was performed under different soil moisture conditions to evaluate its appearance, liquor color, aroma, taste, and the characteristics of the tea leaf base (Table S1). The total sensory scores were 88.0, 89.4, 88.1 and 87.3 for T1, T2, T3 and T4, respectively, with T2 achieving the highest score. One-way ANOVA revealed significant differences in aroma and taste scores among treatments ($p < 0.05$). T2 exhibited superior aroma (89.6 ± 0.15) and taste (89.7 ± 0.13) scores, which were significantly higher than those of T1, T3 and T4 ($p < 0.05$) (Table S1). T2 was characterized by an obvious fruity and floral aroma, along with a mellow, slightly bitter and slightly astringent

taste. In contrast, T1, T3 and T4 displayed lower aroma and taste scores, with T1 showing a fruity and floral aroma but mellow, bitter, astringent and sourish taste, while T3 and T4 exhibited progressively more pronounced bitterness and astringency. For the appearance of the dry tea leaves, T2 (89.7 ± 0.31) scored significantly higher than T1 (88.5 ± 0.87) and T4 (87.6 ± 0.69) ($p < 0.05$). Liquor color scores were consistently high across all treatments, with T3 (88.7 ± 0.59) being significantly lower than T1 (89.5 ± 0.27), T2 (89.2 ± 0.37), and T4 (89.1 ± 0.31) ($p < 0.05$). The appearance of infused leaves showed minimal variation among treatments (ranging from 88.4 to 88.6), with no significant differences detected ($p > 0.05$).

These results suggest that variations in soil moisture influence the sensory quality of Ning black autumn tea, particularly in terms of aroma and taste attributes. To elucidate the chemical basis underlying these sensory differences, the contents of catechins, amino acids, caffeine and volatile compounds were analyzed by HPLC and HS-SPME-GC-MS.

3.2. Influence of Sprinkler Irrigation Frequency on Catechin, Caffeine, and Theobromine Content in Ning Black Autumn Tea

The concentrations of catechins, caffeine, gallic acid, and theobromine are shown in Figure 1. Catechins are classified into two categories based on their chemical structure and associated sensory properties: esterified catechins (catechin gallate [CG], epicatechin gallate [ECG], gallocatechin gallate [GCG] and epigallocatechin gallate [EGCG]), which are known for their pronounced bitter taste and strong astringency, and non-esterified catechins (catechin [C], epicatechin [EC], gallocatechin [GC] and epigallocatechin [EGC]), which exhibit milder bitterness and astringency.

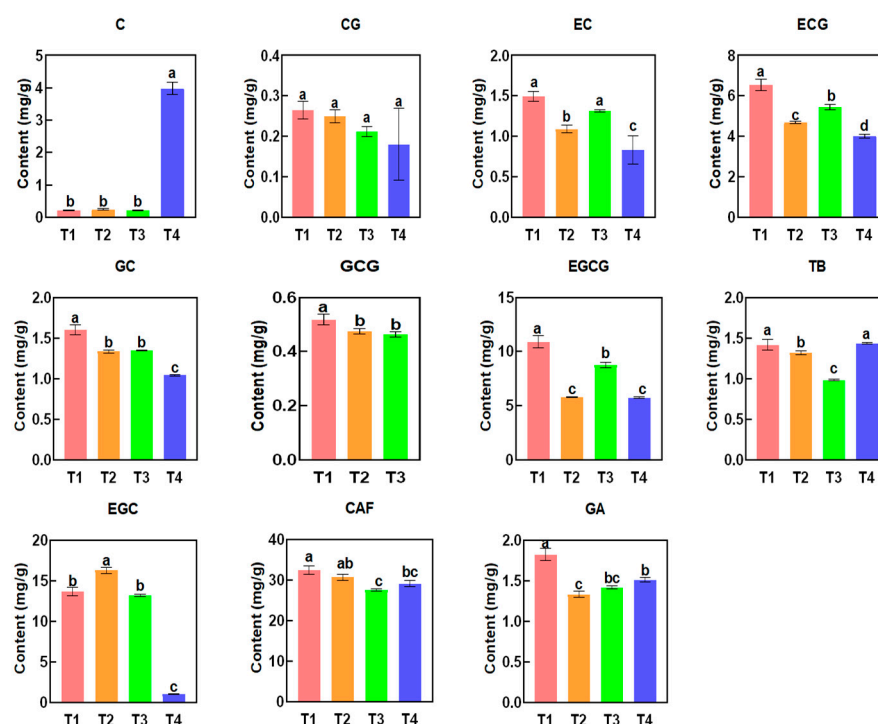


Figure 1. Contents of catechins, theobromine, caffeine, and gallic acid (mg/g) detected in Ning black autumn tea in T1, T2, T3 and T4 by HPLC. Different letters indicate significant differences at $p < 0.05$.

The contents of catechins under different sprinkler irrigation frequencies are presented in Table S2. The total content of non-esterified catechins was highest in T2 (18.92 mg/g) and lowest in T4 (6.90 mg/g), consistent with the sensory evaluation results that T2 exhibited a mellow, slightly bitter and slightly astringent taste, whereas T4 displayed more pronounced bitterness and astringency. In contrast, the total content of esterified catechins was highest

in T1 (18.34 mg/g), which corresponded to the more pronounced bitterness and astringency observed in T1 during the sensory evaluation.

Notable differences were observed in individual catechin monomers. The C content in T1 (0.2 ± 0.00), T2 (0.24 ± 0.02), and T3 (0.22 ± 0.01) differed significantly from that in T4 (3.98 ± 0.18) ($p < 0.05$). EGC and EGCG levels were significantly higher, with the EGC content peaking in T2 and exceeding that of T4 by a factor of 15.7, whereas the EGCG content was highest in T1, which was 1.89 times greater than that in T4. Furthermore, the gallic acid (GA) content peaked in T1, whereas the TB content was the highest in both T1 and T4 (Figure 1). Their ion chromatograms are shown in Figure S1.

3.3. Influence of Sprinkler Irrigation Frequency on Amino Acid Content in Ning Black Autumn Tea

Apart from the major flavor compounds, such as catechins and caffeine, trace amounts of free amino acids, flavonoids, organic acids, and various primary and secondary metabolites significantly contribute to tea quality. In this study, 21 amino acids were successfully identified in Ning black autumn tea by HPLC. The total amino acid contents in samples T1, T2, T3, and T4 were measured at 12.49 mg/g, 13.77 mg/g, 11.62 mg/g, and 12.15 mg/g, respectively (Table S3). The results indicated that the total amino acid content was highest in T2 and lowest in T3 (Table S3). Notably, the theanine (The) content in T2 exceeded that in the other three treatments by twofold (Figure 2). The classification of amino acids according to their taste characteristics follows well-established criteria documented in the literature. Specifically, umami amino acids (theanine [The], glutamic acid [Glu], and aspartic acid [Asp]), sweet amino acids (lysine [Lys], alanine [Ala], glycine [Gly], proline [Pro], and threonine [Thr]) and bitter amino acids (tryptophan [Trp], leucine [Leu], histidine [His], isoleucine [Ile], arginine [Arg], methionine [Met], tyrosine [Tyr], phenylalanine [Phe], and valine [Val]) were categorized based on previously reported taste thresholds and sensory properties [20–25]. The total contents of umami-associated amino acids in T1, T2, T3 and T4 were 6.02 mg/g, 7.93 mg/g, 5.60 mg/g, and 5.54 mg/g, respectively, while the total contents of sweet-associated amino acids were 1.24 mg/g, 1.18 mg/g, 1.20 mg/g and 1.31 mg/g, and the total contents of bitter-associated amino acids were 3.57 mg/g, 3.07 mg/g, 3.26 mg/g, and 3.70 mg/g, respectively (Table S3). Their ion chromatograms are shown in Figure S2.

3.4. Taste Activity Values (TAV) for Main Flavor Components of Ning Black Autumn Tea Under Different Sprinkler Irrigation Frequencies

The TAVs of the 30 flavor constituents of Ning black autumn tea was calculated (Table 1). Seven components exhibited TAVs >1 in specific tea samples, including EGC, EGCG, ECG, caffeine (CAF), GA, Glu, and γ -aminobutyric acid (GABA). Notably, the TAVs for the astringency-related catechins EGCG and ECG peaked in T1 with values of 2.503 and 1.138, respectively. ECG significantly influenced taste in T1. In addition, the TAV of the EGC reached its maximum in T2, with a value of 2.044. The elevated TAV of EGC in T2 demonstrated its critical role in balancing the bitterness and astringency typically associated with EGCG, thereby enhancing the overall taste quality of tea infusions. As amino acid content increased in this study, sensory attributes such as umami, sweetness, bitterness, and overall taste intensity also increased. Among the umami-related amino acids, Glu exhibited the highest TAV in T2, with a value of 3.962, thereby enhancing the umami taste profile. The TAV of GA exceeded 1 only in T1, with a value of 1.072, which influenced the acidity of the tea. Furthermore, the TAV of GABA was the highest among all flavor components across all treatments, reaching its maximum value of 11.045 in T4, which corresponded to the most pronounced astringency observed in this treatment (Tables 1 and S1).

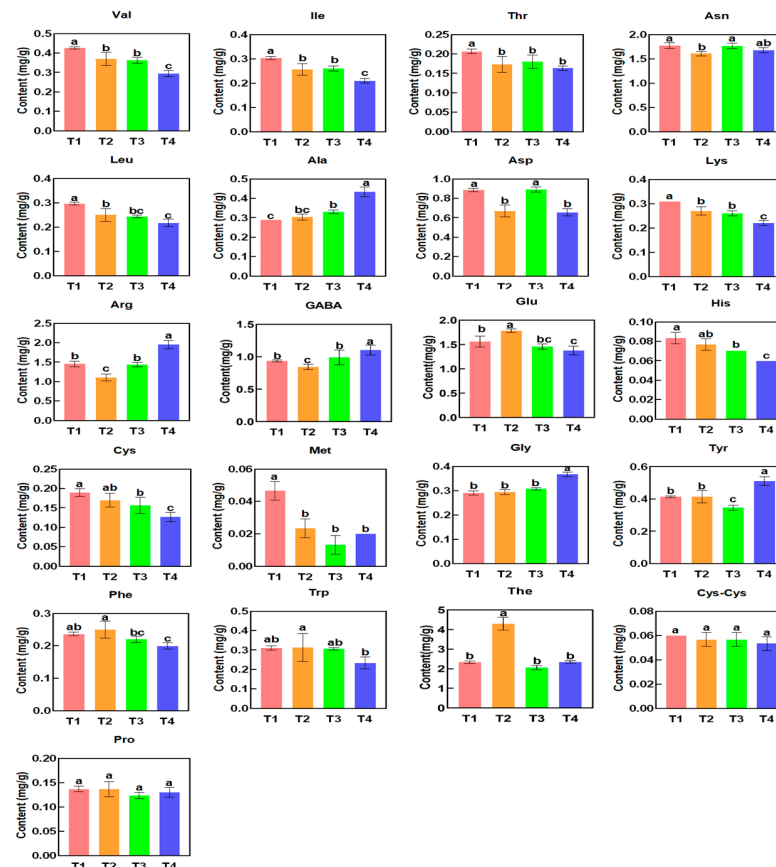


Figure 2. Contents of amino acids (mg/g) detected in Ning black autumn tea in T1, T2, T3 and T4 by HPLC. Different letters indicate significant differences at $p < 0.05$.

Table 1. TAV analysis of taste components in Ning black autumn tea under different sprinkler irrigation frequencies.

Compound	TAV				Threshold mg/L	Taste Characteristic
	T1	T2	T3	T4		
EGC	1.713	2.044	1.658	0.131	159.26	Astringent
C	0.036	0.041	0.037	0.669	119.01	Bitter, Astringent
EC	0.111	0.081	0.097	0.062	269.95	Astringent
EGCG	2.503	1.329	2.011	1.323	87.09	Bitter, Astringent
ECG	1.138	0.813	0.946	0.698	115.02	Bitter, Astringent
CAF	6.675	6.310	5.658	5.981	97.1	Bitter
GA	1.072	0.784	0.833	0.889	34.02	Sour, Astringent
GC	0.193	0.162	0.163	0.126	165.39	Astringent
TB					-	
GCG	0.058	0.053	0.052	0.000	178.76	Bitter, Astringent
CG	0.048	0.045	0.038	0.033	110.59	Bitter, Astringent
Asp	0.592	0.447	0.594	0.438	30	Umami
Glu	3.463	3.962	3.236	3.060	9	Umami
Asn	0.035	0.032	0.035	0.034	1000	Sour, sweet
His	0.009	0.008	0.007	0.007	191	Bitter
Gly	0.004	0.005	0.005	0.006	1300	Sweet
Arg	0.139	0.106	0.138	0.187	209	Bitter
Thr	0.002	0.001	0.001	0.001	2600	Sweet
Ala	0.010	0.010	0.011	0.014	600	Sweet
Pro	0.001	0.001	0.001	0.001	3000	Sweet, bitter
The	0.045	0.082	0.039	0.042	1045	Umami
Cys	0.191	0.168	0.157	0.128	20	Salty

Table 1. Cont.

Compound	TAV				Threshold mg/L	Taste Characteristic
	T1	T2	T3	T4		
Cys-Cys					—	—
Tyr	0.009	0.009	0.008	0.011	906	Bitter
Val	0.021	0.019	0.018	0.015	400	Bitter
GABA	9.355	8.444	9.927	11.045	2	Mouth-Drying
Met	0.003	0.001	0.001	0.001	300	Bitter
Lys	0.012	0.011	0.010	0.009	500	Sweet, bitter
Ile	0.007	0.006	0.006	0.005	900	Bitter
Leu	0.007	0.006	0.006	0.005	846	Bitter
Phe	0.005	0.006	0.005	0.004	900	Bitter
Trp	0.007	0.007	0.007	0.005	900	Bitter

TAV: taste activity value, the ratio of concentration to threshold value. A total of 3 g of tea powder was immersed in 150 mL of water. The taste characteristics and threshold values come from the same references [20–25]. —not mentioned in reference.

Despite significant variations in the levels of different amino acids (Figure 2), their TAVs were all below 1 (Table 1), suggesting that they had a negligible effect on the flavor profile of the tea. As a result, GABA, CAF, EGCG, and ECG were identified as the primary factors influencing the bitterness and astringency of Ning black autumn tea subjected to drought conditions. EGC appeared to mitigate bitterness and astringency, GA served as the primary acidic component, and Glu was the principal umami element. Tea subjected to treatment T1 may exhibit heightened bitterness and acidity than other treatments, with bitterness diminishing in T2, resulting in a more umami and sweet flavor profile. In contrast, the tea treated with T4 showed intensified astringency (Table S1).

3.5. Analysis of Volatile Aroma Components and Selection of Characteristic Compounds of Ning Black Autumn Tea Under Different Sprinkler Irrigation Frequencies

Aroma is a critical quality indicator in tea evaluation, and its characteristic profiles are determined by the diversity and concentrations of volatile organic compounds. A comparative analysis of the sensory evaluation data (Table S1) revealed that T2 exhibited enhanced floral and fruity characteristics, achieving significantly higher aroma scores than the other three samples. The aroma constituents of Ning black autumn tea were identified and analyzed using HS-SPME-GC-MS. A total of 55 volatile components were detected and classified based on their functional groups, with identification confirmed by comparison with the NIST database and retention indices. These components included 17 alcohols, six aldehydes, six ketones, seven hydrocarbons, five esters, 12 aromatic compounds, and two other compounds (Table S4). Across the four treatments, alcohols and esters emerged as the primary volatile components in Ning black autumn tea, with relative abundances ranging from 37% to 57% and from 32% to 43%, respectively. Aromatic compounds accounted for 10–13% of the total volatiles (Table S4).

To illustrate the contributions of various compounds to the quality of Ning black autumn tea, Sankey diagrams were used to illustrate the flavor profiles and variations in these compounds across the four treatments (Figure 3). The aroma components identified in the extracts of Ning black tea primarily included methyl salicylate, phenylethyl alcohol, geraniol, benzyl alcohol, and linalool, with concentrations ranging from 400 to 5200 µg/kg (Table S4; Figure 3). Additionally, compounds such as benzeneacetaldehyde, β-ionone, (Z)-3-hexen-1-ol, and benzaldehyde, as well as the oxidation products of linalool, including trans-linalool oxide (pyranoid), trans-linalool oxide (furanoid), and cis-linalool oxide, exhibited concentrations between 100 and 900 µg/kg (Table S4). Notably, most of these aromatic compounds were present at higher concentrations in T1 and T2 than in T3

and T4 (Figure 3). Furthermore, the floral compounds geraniol and phenylethyl alcohol, the almond-like compound benzaldehyde, and the wintergreen-like compound methyl salicylate reached their peak concentrations in T1, followed by T2 (Table S4). Total ion chromatograms (TICs) of the volatile compounds are shown in Figure S3.

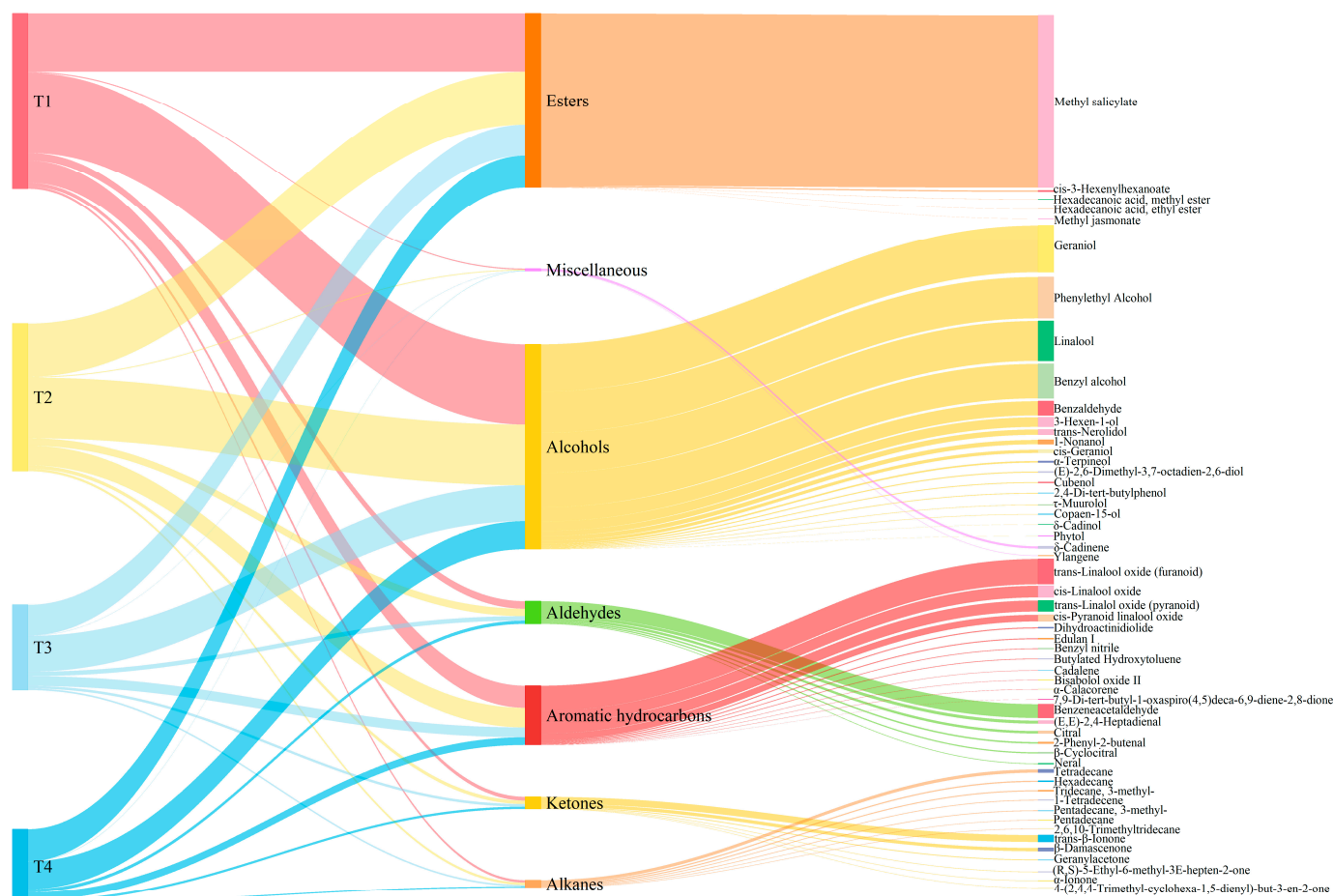


Figure 3. Sankey diagram based on the chemical classifications and content changes in different aroma components in T1, T2, T3 and T4.

Based on their absolute concentrations ($\mu\text{g}/\text{kg}$) determined by GC-MS, the ten most abundant aroma components—geraniol, methyl salicylate, linalool, trans-linalool oxide (pyranoid), phenylethyl alcohol, cis-linalool oxide, benzyl alcohol, trans-linalool oxide (furanoid), benzaldehyde, and benzeneacetaldehyde—exhibited significant accumulation in T1 and T2, contributing to the development of a distinctive aroma in Ning black autumn tea (Figure 4). However, because abundance alone does not necessarily reflect sensory importance, further OAV and VIP analyses were subsequently performed to identify the key odor-active compounds and their statistical contributions to the overall aroma profile. The VIP analysis further identified 13 compounds with $\text{VIP} > 1$ and $p < 0.05$ (Figure 5D), which did not fully overlap with the ten most abundant compounds. This discrepancy highlights an important principle in flavor chemistry: high-abundance compounds are not necessarily the most sensorially or statistically significant, as their importance also depends on factors such as odor thresholds, sample variability and correlation with sensory attributes. Conversely, certain low-abundance compounds may exert critical sensory effects due to their low odor thresholds or high discriminatory power.

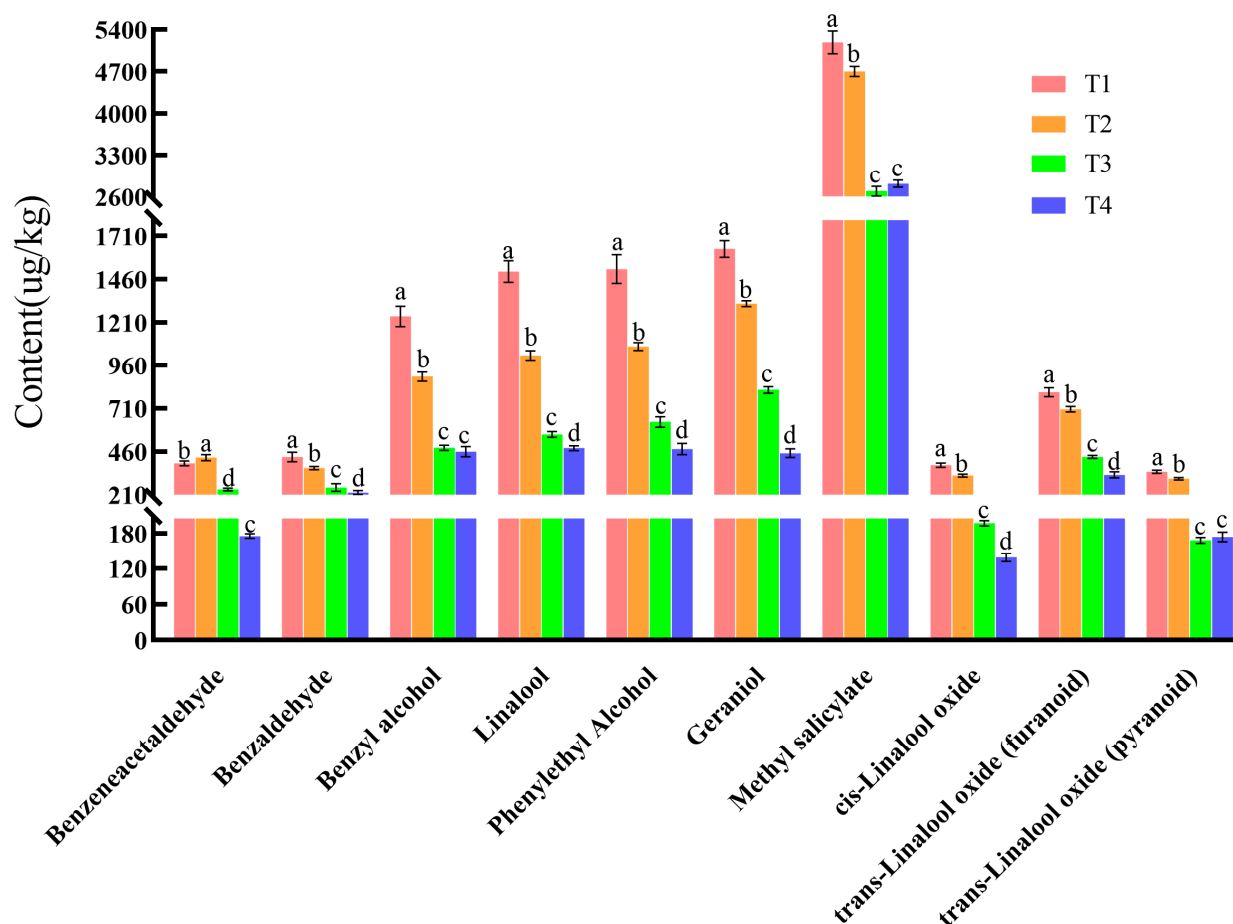


Figure 4. The contents of the top 10 abundant volatile compounds in Ning black autumn tea in T1, T2, T3 and T4. Different letters indicate significant differences at $p < 0.05$.

This study used multivariate statistical analysis to examine the similarities and differences among Ning black autumn tea samples subjected to various treatments, thereby identifying their key chemical constituents. The analysis included PCA and PLS-DA. The four treatment groups were clearly separated based on their aroma profiles, with PC1 and PC2 accounting for 69.4% and 14.5% of the total variance, respectively (Figure 5A). This categorization highlights the significant effect of sprinkler irrigation frequency on the aroma profile of Ning black tea. The PCA score plot (Figure 5A) showed clear separation of the four treatment groups, with T2 positioned distinctly from T1, T3 and T4 along PC1, indicating that moderate stress (T2) induced the most pronounced changes in the aroma profile. To further discriminate among treatments and identify the key aroma constituents responsible for group separation, PLS-DA was subsequently performed. Notably, the PLS-DA model effectively separated the samples into four clusters, which is consistent with the PCA findings (Figure 5B). After 200 cross-validations, the fit indices R^2X (cum) and R^2Y (cum) were determined to be 0.938 and 0.969, respectively, with a Q^2 of 0.959, indicating high explanatory and predictive capacity (Figure 5C). The intercepts of R^2 (0.0, 0.164) and Q^2 (0.0, −0.503) from the permutation test indicated that the model was not overfitted.

Furthermore, VIP was used to identify compounds that exhibited significant differences in their characteristic aroma profiles under various treatments, revealing 17 compounds with VIP values > 1 (Figure 5D). Subsequent refinement involved filtering compounds with VIP values > 1 and $p < 0.05$, resulting in the selection of 13 compounds: (R,S)-5-ethyl-6-methyl-3E-hepten-2-one, cis-3-hexenylhexanoate, geranylacetone, phytol, pentadecane, bisabolol oxide II, hexadecane, 3-methyl-pentadecane, hexadecanoic acid

ethyl ester, 1-tetradecene, trans-nerolidol, 4-(2,4,4-trimethylcyclohexa-1,5-dienyl)-but-3-en-2-one, and methyl jasmonate. The heatmap analysis depicted in Figure 6 demonstrate that most aroma compounds exhibited elevated concentrations in T2. For instance, compounds such as (R,S)-5-Ethyl-6-methyl-3E-hepten-2-one, known for its fresh aroma; geranylacetone, characterized by green and peppermint notes; pentadecane, noted for its floral aroma; 3-methyl-pentadecane, recognized for its roasted and sweet notes; and trans-nerolidol, which is characterized by fruity and floral notes, were predominantly abundant in T2 ($p < 0.05$). Hexadecanoic acid ethyl ester, which features fatty, rancid, waxy, fruity, and creamy notes, exhibited the highest levels in T4. In contrast, cis-3-Hexenylhexanoate, which exudes a fruity note, and phytol, which is characterized by floral, balsamic, powdery, and waxy notes, were the most prevalent in T3. Thus, the T2 treatment resulted in the accumulation of a diverse array of aromatic compounds.

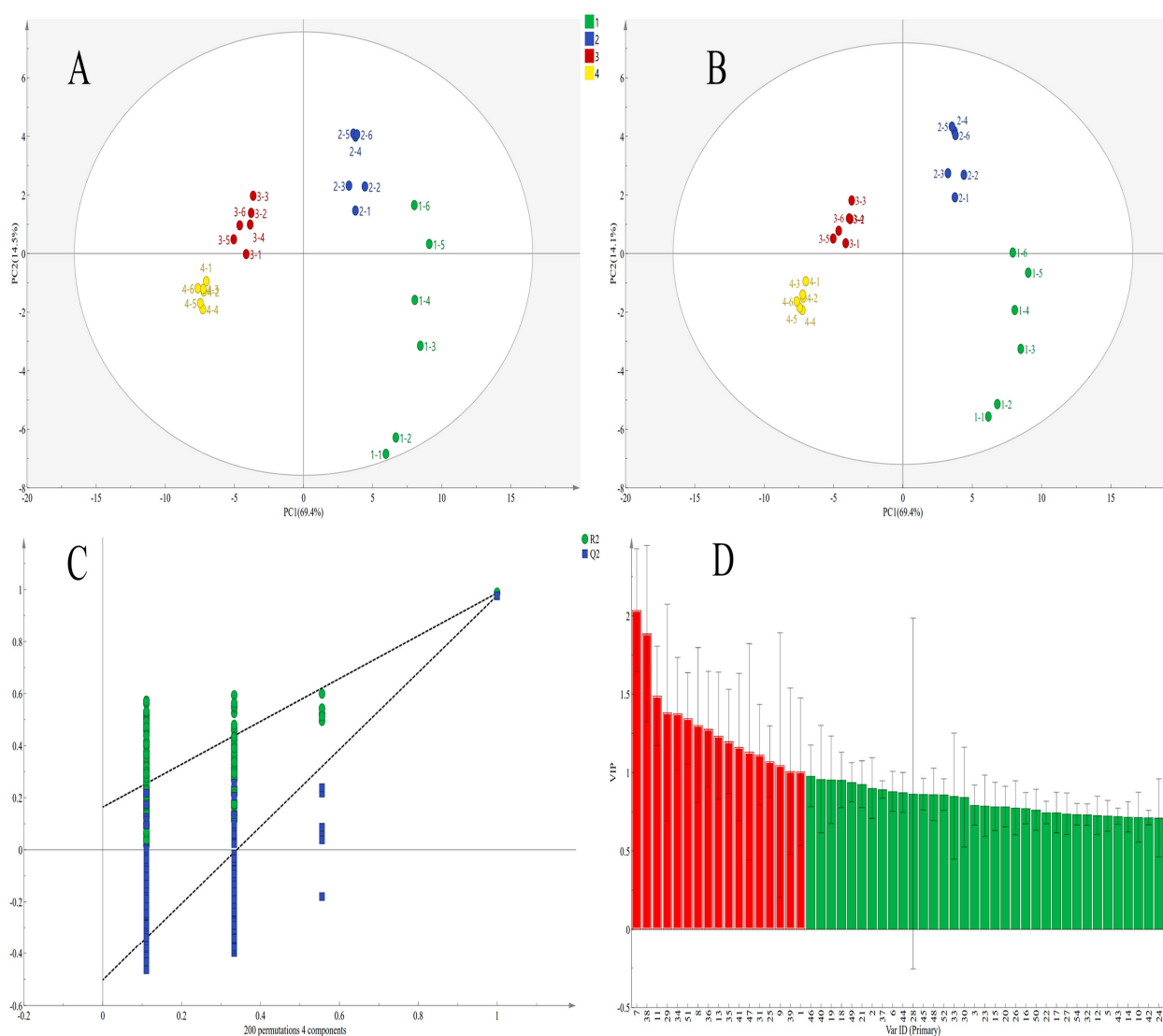


Figure 5. (A) PCA score plot of aroma compounds in Ning black autumn tea in T1, T2, T3 and T4. (B) PLS-DA score plot of Ning black autumn tea across T1, T2, T3 and T4. $R^2X = 93.8\%$, $R^2Y = 96.9\%$, and $Q^2 = 95.9\%$. (C) Cross-validation results of the PLS-DA model (200 permutations). The intercepts of R^2 (0.0, 0.164) and Q^2 (0.0, -0.503) indicated that this model was not overfitted. (D) VIP values of the 55 volatile components in Ning black autumn tea in T1, T2, T3 and T4. The numbers on the abscissa represent compounds, and the corresponding relationship between numbers and compounds is shown in Table S4; 1-1...1-6: T1; 2-1...2-6: T2; 3-1...3-6: T3; 4-1...4-6: T4.

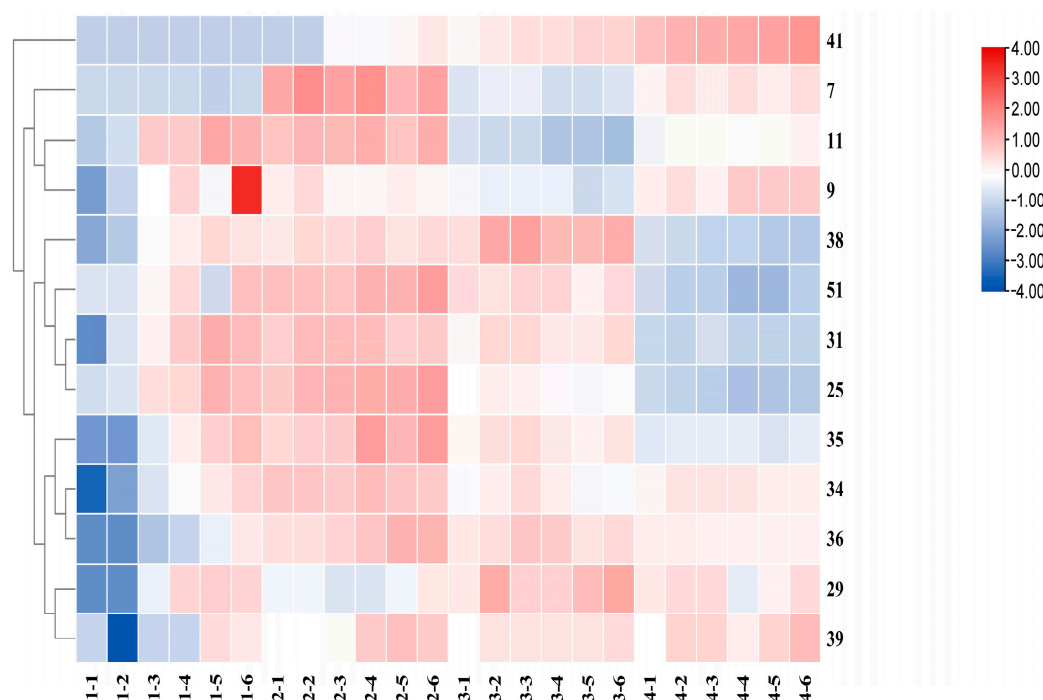


Figure 6. Heatmap of the 13 key volatile compounds ($VIP > 1$, $p < 0.05$) in Ning black autumn tea under T1, T2, T3 and T4. The x-axis indicates samples ($n = 6$), and the y-axis lists numerical identifiers for the compounds. The corresponding relationship between the numbers and compounds is shown in Table S4. Red and blue represent high and low contents, respectively.

3.6. Odor Activity Value (OAV) for Aroma Components of Ning Black Autumn Tea Under Sprinkler Irrigation Frequencies

Within the fields of food and plant sciences, OAV is a widely recognized parameter for assessing the impact of aroma compounds. The results of the sensory evaluation indicated that fruity and floral aromas in treatment T2 were prominent (Table S1). Among the 13 key volatile compounds identified, only trans-nerolidol and cis-3-hexenylhexanoate exhibited OAVs > 1 (Table 2). The OAVs of cis-3-hexenylhexanoate were > 1 across all treatments, with the highest value recorded in T3 (2.29), followed by T2 (1.88). These two treatments contributed significantly to the fruity aroma of Ning black tea (Table 2). Notably, the OAV of trans-nerolidol exceeded 10 in T2 (11.77), whereas the lowest value was observed in T4 (4.38), underscoring the substantial role of trans-nerolidol in imparting floral aroma characteristics to T2. Although the total aroma compound content in T2 was lower than that in T1 (Table S4), trans-nerolidol significantly contributed to the aroma profile of Ning black tea in T2. A higher OAV indicates that a compound plays a significant role in the aroma profile. The OAV of trans-nerolidol in T2 was the highest, whereas those in T1, T3, and T4 were 8.44, 6.87, and 4.38, respectively. The OAV results suggest that trans-nerolidol is a key aromatic volatile compound in T2. The sensory evaluation results showed that black tea treated with T2 exhibited floral and fruity aromas. This may be related to the contributions of cis-3-hexenylhexanoate and trans-nerolidol. The EI mass spectra of cis-3-hexenylhexanoate and trans-nerolidol are shown in Figure S4.

Table 2. OAV analysis of Principal volatile compounds responsible for aroma of Ning black autumn tea under different sprinkler irrigation frequencies.

NO. ^a	Name	Odor Characteristics	OT ^b (μg/kg)	OAV			
				T1	T2	T3	T4
39	Methyl jasmonate	Jasmine	70	<0.1	<0.1	<0.1	<0.1
11	Geranylacetone	Green, peppermint	60	0.33	0.41	0.19	0.27
25	trans-Nerolidol	Faint woody-floral, slightly rose apple aroma	15	8.44	11.77	6.87	4.38
29	Phytol	Floral, balsam, powdery, waxy	640	0.003	0.003	0.007	0.005
41	Hexadecanoic acid, ethyl ester	Fatty, rancid, waxy,	2000	<0.1	<0.1	<0.1	<0.1
36	Hexadecane	Alkane	13,000,000	<0.1	<0.1	<0.1	<0.1
38	cis-3-Hexenylhexanoate	Fruity fruity, creamy	16	1.52	1.88	2.29	1.21

^a: The numbers in the first column represent compounds. The corresponding relationship between numbers and compounds is shown in Table S4. ^b: Odor thresholds in water are based on the literature [26–31]. OAV: Odor activity value. The odor characteristics and threshold values come from the same references.

4. Discussion

The study provides a mechanistic understanding of how irrigation frequency affects the quality of Ning black autumn tea. The findings are derived from a single cultivar and location; therefore, further studies are needed to test their generalizability to other tea varieties and regions. Drought significantly affects the biosynthesis and accumulation of secondary metabolites in tea plants by modulating the expression of key genes in flavonoid, caffeine and amino acid metabolic pathways [13,14]. Among the various bioactive compounds, catechins are particularly responsive to water availability due to their well-characterized biosynthetic pathway. Catechins, which are the primary polyphenolic components in tea, play a role in imparting a bitter taste to the beverage [32]. Autumn-harvested tea generally contains higher levels of catechins than spring-harvested tea, primarily because of the accumulation of EGCG and ECG, which are known to contribute to the bitterness and astringency of tea [2]. Notably, EGCG and ECG demonstrate more pronounced bitterness and astringency than EGC and EC, with the latter primarily influencing the aftertaste [33–35]. In this study, the highest concentrations of EGCG and ECG were observed in T1, the treatment with the highest soil moisture (32.75%). This suggests that excessive water supply may favor the accumulation of esterified catechins, potentially by modulating precursor availability or the activity of key enzymes in the esterified catechin biosynthetic pathway, though the specific mechanisms require further investigation. The higher concentrations of ECG and EGCG in T1 and T3 ($p < 0.05$) would have intensified the bitterness of these teas compared with T2 and T4. Conversely, the increased levels of EGC in T2 ($p < 0.05$) likely contributed to a more balanced aftertaste, as EGC and EC elicit weaker bitterness and astringency than their esterified counterparts, while primarily contributing to the sweet aftertaste [35]. It is noteworthy that the catechin (C) concentration in T4 (3.98 mg/g) was substantially higher than those in T1–T3 (0.20–0.24 mg/g). This accumulation likely reflects a stress-induced metabolic response under severe drought (18.36% soil moisture), potentially involving the modulation of flavonoid biosynthesis genes [13,14]. However, despite this elevated C level, T4 exhibited the lowest overall non-esterified catechin content and the poorest sensory scores, indicating that the increase in a single monomer did not translate into improved flavor quality. This underscores the complexity of metabolic regulation under abiotic stress, where individual metabolite changes may not directly correspond to sensory attributes.

Transcriptomic studies have shown that the PEG-induced drought stress suppresses genes involved in catechin and caffeine biosynthesis [13,36] and reduces overall leaf quality [14], consistent with the overall trends observed in our study. However, the response is not uniform across all compounds: while most catechins declined with decreasing soil moisture, the increase in C under severe drought suggests that the flavonoid pathway may be rerouted toward specific monomers under extreme stress. Notably, CAF is a critical marker of tea quality, known for imparting bitterness [37], while also possessing stimulating, diuretic, and metabolism-accelerating properties. In this study, the CAF content was highest in T1, followed by T2, and lowest in T3 (Figure 1), with T4 remaining statistically unchanged from T3 ($p > 0.05$). This pattern aligns with previous findings [14], where drought inhibited caffeine synthesis-related gene expression. This progressive decline from T1 to T3 suggests that even moderate water stress can suppress caffeine accumulation, while the lack of a significant difference between T3 and T4 indicates that severe drought may not further reduce CAF beyond a certain threshold. Similar to the withering process in tea, during which catechins undergo enzymatic oxidation to theaflavins [38], this treatment also attenuated bitterness and astringency through the reduction in esterified catechins. The rise in EGC and the decline in EGCG in T2 appear to have contributed to neutralizing the bitterness, aligning with the findings from the sensory evaluation (Table S1).

Free amino acids not only define the basic taste profiles of tea infusions but also serve as precursors for aroma development [39–41]. Our research indicates that appropriate irrigation increases the total amino acid content, whereas water stress leads to a decrease, in agreement with earlier findings [14]. Among all the amino acids, The exhibited the highest concentration, particularly in T2. The is recognized as a key contributor to the umami taste of tea infusions [37]. Beyond its sensory role, its accumulation is highly responsive to environmental stress, as evidenced by a significant increase in the The content under shading treatments [42]. Therefore, the substantial accumulation of The in T2 may reflect a dual function: enhancing flavor quality while serving as a metabolic indicator of stress adaptation [42]. The higher total amino acid content in T2 may be linked to the physiological similarities between drought stress and leaf withering. A similar mechanism has been observed during green tea withering, where protein degradation contributes to amino acid accumulation [43], which may also explain the elevated The levels in T2. Notably, T2 exhibited the highest contents of sweet- and umami-tasting amino acids and the lowest content of bitter-tasting amino acids. This composition successfully mitigated the typical astringency linked to esterified catechins, thereby enriching the overall sweetness and umami notes of the tea infusion, aligning with the sensory assessments. The decreases in catechins and free amino acids observed under water deficit in our study are consistent with transcriptomic evidence showing drought-induced suppression of flavonoid and amino acid biosynthetic genes [14,36]. A similar declining trend in esterified catechins and total free amino acids has been reported during prolonged withering, where water loss activates degradative metabolism [44]. These findings collectively support the notion that water stress adversely affects the accumulation of key tea quality-related metabolites.

Drought represents a major environmental stress that restricts cellular development and expansion, disrupts plant growth, and reduces yield potential. Drought stress triggers the accumulation of osmotic adjustment compounds in various plant species [45] and enhances flavonoid accumulation as an antioxidant defense mechanism [46]. In tea plants specifically, catechins and free amino acids have also been reported to respond to water deficit [14,36]. Amino acids, caffeine, and catechins are the key flavor constituents of tea leaves, whose metabolic pathways are interconnected through the tricarboxylic acid (TCA) cycle (Figure 7). Drought stress significantly alters TCA cycle activity and amino acid metabolism [16,47,48], and amino acid accumulation generally facilitates osmotic

adjustment [48]. In this research, a gradual reduction in the levels of most amino acids was noted as the soil moisture content diminished (Figure 7). The, the predominant free amino acid in tea plants [49], peaked in T2, contributing to the highest total amino acid content observed in this treatment (Table S3). The is primarily synthesized from glutamate through the action of theanine synthetase, which plays a crucial role in promoting umami flavor [50]. Conversely, the Glu content was minimal in treatment T4, potentially because of the increased synthesis of Arg and GABA (Figure 7), suggesting a metabolic shift toward stress-responsive amino acids under severe drought. Notably, the trend for C differed from that of the other catechins, exhibiting the highest content in T4 (Figure 7). This divergence may be attributed to the inhibition of the conversion of C to other catechins under severe drought, resulting in a bottleneck that leads to C accumulation while other catechin intermediates decrease. EGC, along with EC, plays a crucial role in the sweet aftertaste of tea infusions [37]. The significant increase in EGC content in T2 contributed to balancing the bitter taste of esterified catechins, which corresponded with the sensory evaluation findings indicating flavors of mellowness, slight bitterness, and mild astringency. The overall decline in caffeine from T2 to T4 (30.64 mg/g to 27.47 mg/g) is consistent with the declining phase observed under severe drought stress in previous studies [4], particularly when soil moisture fell below 24%. In conclusion, the alterations in the metabolism of amino acids, catechins, caffeine, and theobromine identified in this study led to differences in the flavor profiles of tea infusions across varying soil moisture conditions, with moderate stress (T2) yielding the most favorable balance.

The sensory attributes of tea are primarily influenced by the variety and concentration of the volatile secondary metabolites. Drought conditions lead to a reduction in the total volatile compound content, significantly inhibiting the overall synthesis of volatile substances and consequently affecting tea quality [51]. Moderate soil moisture stress can stimulate the production of terpenoid aroma compounds [52] and promote the accumulation of quality-related components such as catechins and caffeine [4]. The mechanistic basis of drought-induced aroma formation shares certain features with that of withering during tea processing: moisture loss from leaf cells alters the activities of endogenous redox enzymes, which in turn promotes glycoside hydrolysis and the release of aroma components [52,53]. These results indicate that managing irrigation levels during the cultivation of tea plants could improve the quality of autumn tea products.

Floral and fruity aromas are crucial indicators of high-quality black tea. The sensory evaluation revealed that black tea subjected to T2 treatment displayed prominent floral and fruity fragrances. OAV was used to evaluate the influence of volatile compounds on tea aroma [54]. Compounds with an OAV greater than 1 are considered to have a noticeable impact on the aroma, while those with an OAV exceeding 10 are deemed to have a substantial contribution [55]. Notably, the OAV of trans-nerolidol was the highest (>10), indicating that it was the key aromatic compound in T2 treatment. This finding is consistent with sensory evaluation and confirms that moderate irrigation promotes the accumulation of this key volatile. The mechanisms underlying the effects of drought and wilting are comparable: drought stress reduces internal water potential, which subsequently boosts the content of volatile aromatic compounds. The aroma quality of tea is influenced by a select group of compounds, and the lack of specific critical compounds can considerably affect the overall aroma quality [54]. The content and OAV of trans-nerolidol were higher in blended varieties than in the Ningzhou population, contributing to enhanced floral and fruity aromas [43]. These findings suggest that T2 significantly promoted the synthesis of trans-nerolidol, resulting in more pronounced floral and fruity aromas. The biosynthesis of tea aroma, which is primarily derived from volatile organic compounds, is influenced by external environmental stress. Prior research has shown that both abiotic stresses (such

as changes in light intensity) and biotic stresses (such as pest infestations) during the growth of tea plants can notably stimulate secondary metabolic pathways, resulting in a higher accumulation of characteristic aromatic compounds [56–58]. Baldermann et al. [59] analyzed over 38 types of tea and identified trans-nerolidol, jasmine lactone, and indole as key aroma components that distinguish oolong tea. Notably, in oolong tea infusions, trans-nerolidol, which possesses floral and fruity aroma characteristics, is recognized as a critical aroma compound whose concentration directly affects aroma quality [26]. This study suggests that proper irrigation, by increasing the trans-nerolidol concentration, enhances the floral and fruity notes of Ning black autumn tea, giving it some of the aroma characteristics of oolong tea.

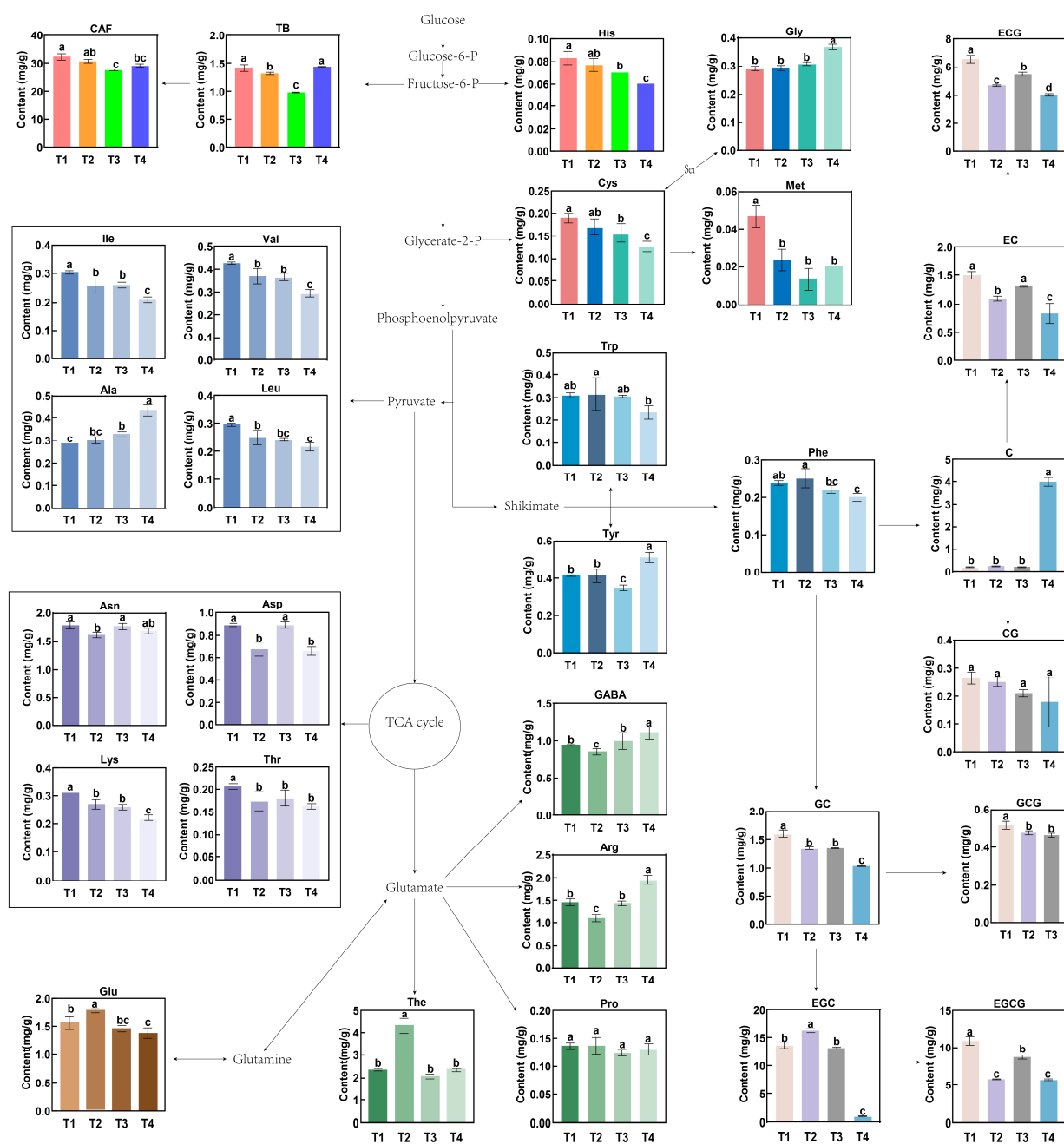


Figure 7. Systematic visualization of flavoring metabolites in Ning black autumn tea in T1, T2, T3 and T4. The bar graphs are constructed using quantitative values, with each bar representing samples T1, T2, T3, and T4 from left to right. Lowercase letters denote $p < 0.05$.

In this study, Ning black autumn tea, characterized by floral and fruity aromas, a refreshing taste, and slightly bitter and astringent flavors, was prepared by adjusting the irrigation frequency during autumn drought. Water is vital for plant growth and metabolic processes, affecting the production of secondary metabolites under different moisture levels. From a chemical composition standpoint, varying moisture levels lead to differences in the levels of non-volatile compounds in tea, such as amino acids, caffeine, catechins, and theobromine. Amino acids that impart sweet and umami flavors, along with non-esterified catechins, help mitigate bitterness and reduce astringency in autumn tea. Furthermore, an appropriate irrigation frequency enhances the floral and fruity notes of Ning black autumn tea through the accumulation of key volatiles such as trans-nerolidol.

Importantly, the observed trade-off between esterified (bitter) and non-esterified (milder) catechins under moderate water stress (T2) is likely governed by conserved biosynthetic pathways (e.g., flavonoid metabolism) that exist in most tea cultivars. Therefore, similar irrigation strategies may improve autumn tea quality in other varieties grown under analogous climatic conditions. Autumn drought is a common challenge in many tea-growing areas worldwide (e.g., Sri Lanka, Kenya, and Japan). Our results suggest that precision irrigation to maintain moderate soil moisture (around 28%, as in T2) could be a transferable strategy to balance flavor compounds and enhance the value of autumn harvests in those regions. The integrated analytical framework combining metabolomics and sensory evaluation can serve as a methodological reference for optimizing water management in other crops whose flavor quality is influenced by water availability. However, we acknowledge that the present study was conducted using a single plot per treatment without true field replication, and the plots were arranged in a fixed order rather than randomized. Therefore, the results should be interpreted as an exploratory case study rather than a definitive field validation. Nevertheless, the consistent trends across multiple independent analytical parameters (amino acids, catechins, volatiles and sensory evaluation) provide strong support for our conclusions. Therefore, we suggest that maintaining soil moisture at approximately 28% through moderate irrigation during tea cultivation can enhance its flavor and aroma, thereby improving the quality of autumn tea. These findings provide a practical irrigation strategy for tea producers to balance flavor compounds. This, in turn, increases the income of tea farmers and enterprises during the autumn season while reducing tea waste. Future multi-site and multi-year trials with true field replicates are required to confirm the applicability of this optimal irrigation strategy across different tea cultivars, environments and production systems.

5. Conclusions

In this study, we systematically investigated the effects of different sprinkler irrigation frequencies on the non-volatile and volatile compounds of Ning black autumn tea. The optimal soil moisture content for improving tea quality was identified as 27.98% (T2). Compared with the severely drought-stressed T4 (18.36%), T2 increased the total free amino acid content by 13.33% (from 12.15 mg/g to 13.77 mg/g). The total non-esterified catechin content in T2 was 18.92 mg/g, which was 2.74-fold higher than that in T4 (6.90 mg/g). Among the volatile compounds, the floral aroma contributor trans-nerolidol was most abundant in T2 (176.50 µg/kg), which was 2.69-fold higher than that in T4 (65.72 µg/kg). Sensory evaluation confirmed that T2 exhibited a distinct fruity and floral aroma, with a mellow, slightly bitter and slightly astringent taste.

To enhance the quality of autumn-harvested tea and increase its market value, we recommend maintaining soil moisture at approximately 28% during the late growing season through moderate sprinkler irrigation. This practice balances bitter (esterified catechins) and umami/sweet (amino acids) compounds while enriching desirable floral

volatiles. These findings provide a science-based irrigation strategy for revitalizing autumn tea production, reducing resource waste and improving the economic sustainability of tea farming. We acknowledge that our findings are primarily based on a single tea cultivar and one geographic location. Therefore, future multi-site and multi-cultivar studies are needed to validate the generalizability of our conclusions.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/horticulturae12070809/s1>, Table S1: Description of sensory evaluation in Ning black autumn tea under different sprinkler irrigation frequencies; Table S2: The content of catechins in Ning black autumn tea under different sprinkler irrigation frequencies (mg/g); Table S3: The content of amino acids in Ning black autumn tea under different sprinkler irrigation frequencies (mg/g). Table S4: Aroma compounds of Ning black autumn tea identified by GC-MS ($\mu\text{g/kg}$). Figure S1. HPLC-UV chromatograms of catechins, gallic acid, caffeine and theobromine in Ning black tea (T1–T4). Figure S2. HPLC-FLD chromatograms of amino acids in Ning black autumn tea (T1–T4). Figure S3. Total ion chromatograms (TIC) of volatile compounds in Ning black autumn tea samples (T1–T4). Figure S4. The EI mass spectra of representative volatile compounds (cis-3-Hexenylhexanoate and trans-Nerolidol) identified in the tea samples, with comparison to NIST library spectra (red: experimental spectra; blue: NIST reference spectra, as two examples). References [60–70] are cited in the Supplementary Materials.

Author Contributions: Y.G.: Conceptualization, Writing—original draft, Data curation. W.L.: Writing—review and editing, Data curation. L.C.: Investigation. Y.L., Y.F., G.W.: Methodology. Y.S.: Conceptualization, Data curation, Funding acquisition. L.Y.: Data curation, Methodology. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Medical Science and Technology Ethics Committee of Jiujiang University (protocol code JJUM20240090, approved on 20 April 2024).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The original contributions presented in this study are included in the article/Supplementary Materials. Further inquiries can be directed to the corresponding authors.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

C	Catechin
CG	Catechin gallate
GCG	Gallocatechin gallate
EGCG	Epigallocatechin gallate
EC	Epicatechin
ECG	Epicatechin gallate
GC	Gallocatechin

EGC	Epigallocatechin
GA	Alongside gallic acid
TB	Theobromine
CAF	Caffeine
Asn	L-asparagine
Asp	L-aspartic acid
Ala	L-alanine
GABA	Gamma-aminobutyric acid
Arg	L-arginine
Cys	L-cysteine
Glu	L-glutamic acid
Gly	L-glycine
His	L-histidine
Ile	L-isoleucine
Leu	L-leucine
Lys	L-lysine
Met	L-methionine
Phe	L-phenylalanine
Pro	L-proline
Thr	L-threonine
Tyr	L-tyrosine
Val	L-valine
Cys-cys	L-Cystine
Trp	L-tryptophan
The	L-theanine
HPLC	High-Performance Liquid Chromatography
HS-SPME-GC-MS	Headspace Solid-phase Microextraction coupled with Gas Chromatography–Mass Spectrometry
OAV	Odor Activity Value
TAV	Taste Activity Value

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