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# Statistical Analysis of Environmental Factors Affecting Tea Leaf Quality in Zhejiang Tea Plantations

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**Abstract** Tea quality is strongly influenced by environmental conditions, and understanding the relationship between ecological factors and quality formation is essential for improving tea production and management. This study focuses on tea gardens in Zhejiang Province, China, and systematically analyzes the effects of environmental factors on tea quality using statistical approaches. Based on environmental variables, including temperature, light conditions, precipitation, soil properties, and tea quality indicators such as tea polyphenols, amino acids, caffeine, and sensory characteristics, the relationships between ecological factors and quality formation were evaluated. Correlation analysis, multivariate statistical models, and case studies were applied to identify the key environmental drivers affecting tea quality. The results provide insights into the contribution of different environmental factors and reveal their potential mechanisms in regulating tea biochemical composition and quality characteristics. This study establishes a scientific framework for evaluating environmental impacts on tea quality and provides theoretical support for precision management, ecological regulation, and sustainable development of Zhejiang tea gardens.
**Keywords** Zhejiang tea gardens; Environmental factors; Tea quality; Statistical analysis; Ecological regulation

## 1 Introduction

Tea is one of the world's most widely consumed non-alcoholic beverages, and the quality of fresh tea leaves directly determines the flavor, aroma, nutritional value, and economic value of finished tea products (Tian et al., 2024). The key biochemical bases of tea quality are mainly tea polyphenols, catechins, free amino acids, caffeine, and volatile compounds, and their coordinated variation determines important sensory traits such as freshness, umami, bitterness, astringency, and floral aroma. A growing body of evidence shows that the cultivation environment plays a vital role in shaping these metabolites, including altitude, temperature, light, precipitation, soil pH, nutrient availability, and microbial conditions (Ahmed et al., 2019). This issue is particularly important in mountainous tea regions, where the long-recognized phenomenon that "high mountain, cloud and mist produce high-quality tea" has been repeatedly observed, yet its environmental mechanisms remain only partly resolved. Zhejiang is one of China's most important tea-producing provinces and contains ecologically diverse plantation systems, including major green tea production areas such as Hangzhou and Shaoxing, making it an ideal region for studying how environmental heterogeneity influences tea leaf quality. At the same time, tea production in Zhejiang faces practical pressures from soil acidification, fertilizer and pesticide inputs, and the need to balance quality improvement with ecological sustainability (Que and Zhao, 2024). Therefore, statistically identifying the dominant environmental factors affecting tea leaf quality in Zhejiang plantations is significant not only for clarifying the ecological basis of tea quality formation, but also for guiding precise plantation management, regional quality evaluation, and sustainable development of the tea industry.

Existing studies at home and abroad have established that environmental factors influence tea quality through complex and sometimes nonlinear pathways, but the direction and magnitude of these effects often vary by region, cultivar, season, and methodological approach (Wang et al., 2026). Altitude is one of the most extensively studied factors. Several studies found that high-altitude tea generally contains more amino acids and favorable aroma compounds, while low-altitude tea tends to accumulate more caffeine and some bitter catechins, thereby influencing sweetness, umami, bitterness, and astringency. Research in eastern China further showed that increasing altitude decreased total polyphenols but increased amino acids, significantly lowering the polyphenol-to-amino acid ratio, which is an important indicator of green tea taste quality. Metabolomic studies also showed that higher-altitude teas often possess stronger floral and fruity aroma, with elevated levels of compounds such as linalool, nerol, and related volatiles (Kfoury et al., 2019). However, the altitude effect is not fully consistent across locations. A systematic review of 86 articles concluded that environmental factors can cause both increases and decreases in tea secondary metabolites, with contradictory evidence often arising from confounding influences such as cultivar differences, management practices, and local environmental conditions. Multi-year studies likewise showed that season and year can strongly alter metabolite profiles, and that elevation effects may be pronounced in one region but weak in another. In addition to climate and topography, soil properties are increasingly recognized as foundational drivers of tea quality. Soil pH has been described as a critical management variable, with studies reporting U-shaped or inverted U-shaped relationships between pH and key quality components such as polyphenols, catechins, amino acids, and caffeine. Other work showed that exchangeable Ca, Mg, Mn, Cu, and Zn, together with electrical conductivity and organic matter status, significantly affect amino acid accumulation and umami quality (Tseng and Lai, 2022). Soil nutrient structure also interacts with tea quality through nitrogen and phosphorus metabolism, while soil microbial communities, especially fungal abundance, appear to be positively associated with theanine accumulation and quality-related ratios. Management studies in Zhejiang further demonstrated that partial substitution with organic fertilizer can alleviate soil acidification, increase soil organic matter and ammonium nitrogen, and improve tea yield and quality, while reducing nutrient loss to runoff. Likewise, intercropping and green manure practices can increase amino acids, soluble sugars, soil fertility, and microbial complexity, confirming that manageable environmental factors can substantially regulate tea quality formation. Despite this progress, most existing studies focus on single factors or single mechanisms, and relatively few integrate multiple environmental variables within one statistical framework for a specific tea-producing province such as Zhejiang.

Against this background, the present study takes Zhejiang tea plantations as the research object and aims to systematically analyze the environmental factors affecting tea leaf quality by combining ecological variables with statistical modeling. Specifically, the study focuses on the relationships between climatic conditions, topographic characteristics, soil physicochemical properties, and key tea quality indicators such as polyphenols, catechins, amino acids, caffeine, and quality-related ratios. Because previous studies showed that many environmental effects are nonlinear or interactive rather than simply linear, the use of statistical tools is necessary to identify dominant factors, quantify correlation strength, detect threshold or curved relationships, and separate the contributions of different variables. The technical framework of this study can therefore be organized into four steps: first, collect representative tea leaf and environmental data from Zhejiang plantations covering different ecological conditions; second, measure major biochemical indicators of tea quality and characterize environmental variables including altitude, temperature, light, precipitation, soil pH, and nutrient status; third, apply descriptive statistics, correlation analysis, and multivariate or regression-based methods to reveal the relationships between environmental gradients and tea quality traits; and fourth, interpret the statistical results in the context of regional tea management and quality optimization. This framework is also justified by recent Zhejiang evidence showing strong regional clustering of amino acids and clear cultivar-environment interactions across ecologically distinct tea areas, which means that a province-level statistical analysis can provide both theoretical and practical value. In addition, studies from Longjing-producing areas indicate that precision agriculture, optimized fertilization, and region-specific ecological management can improve both yield and quality, further underscoring the need for data-driven environmental diagnosis in Zhejiang tea systems. In summary, this study seeks to provide an empirical basis for clarifying the environmental determinants of tea leaf quality in Zhejiang tea plantations and to support precise, sustainable, and regionally differentiated cultivation strategies.

## 2 Ecological Environmental Characteristics of Zhejiang Tea Gardens and the Basis of Tea Quality Formation

### 2.1 Regional distribution and ecological characteristics of tea gardens in zhejiang province

Zhejiang is one of China’s representative tea-producing provinces, and its tea gardens are distributed across hilly and mountainous landscapes where climate, terrain, and soil jointly constrain ecological suitability for tea cultivation. A GIS-based suitability assessment for Zhejiang showed that annual mean temperature, accumulated temperature above 10 °C, extreme low-temperature frequency, humidity during the main growing season, slope, aspect, altitude, soil type, and soil texture are all key variables in determining whether land is suitable for tea production. At the provincial scale, 28.47% of the evaluated area was classified as highly suitable and 44.14% as moderately suitable for tea, indicating that Zhejiang possesses a broad but ecologically differentiated spatial foundation for tea planting.

Within Zhejiang, tea plantations also show clear spatial clustering and recognizable phenological characteristics, especially in northern Zhejiang, where remote-sensing studies identified April to May as the distinctive phenological window for tea gardens because deep pruning during this period makes them spectrally different from nearby forests and bamboo stands (Li et al., 2019). This distribution pattern is agriculturally important because rapid expansion of tea plantations has already been linked to ecological risks such as soil erosion, making accurate identification and regional planning necessary for sustainable management. Beyond surface distribution, tea-garden soils in China show strong spatial heterogeneity in soil organic carbon, and geography, especially latitude and altitude, exerts a large indirect effect on soil carbon status, implying that Zhejiang tea gardens are also likely to differ substantially in their soil ecological background and nutrient buffering capacity (Yang et al., 2023).

### 2.2 Main evaluation indicators for tea quality formation

The basis of tea quality formation lies mainly in the accumulation and balance of fresh-leaf secondary metabolites. Current studies consistently treat tea polyphenols, catechins, free amino acids, caffeine, and volatile aroma compounds as the core biochemical indicators that determine taste, aroma, and functional quality. Among them, free amino acids are closely related to freshness and umami, whereas caffeine and ester catechins contribute more strongly to bitterness and astringency, so tea quality depends not simply on the absolute level of one component but on the coordination among several components (Tseng and Lai, 2022).

In quality evaluation practice, researchers increasingly use both single compounds and composite indicators to describe quality formation. The polyphenol-to-amino acid ratio is regarded as an important taste indicator because it captures the balance between briskness and freshness, and it has been directly used as a target index in rapid quality evaluation models for tea products. For black tea quality assessment, catechins and tea polyphenols were identified as the most critical taste-related indicators, followed by amino acids, water extract, and caffeine, while aroma evaluation further depended on characteristic volatile compounds with high odor activity values. Variety-based metabolomics studies likewise show that polyphenols, ester catechins, non-ester catechins, amino acids, and numerous aroma-active metabolites all vary systematically and therefore should be included in a multidimensional evaluation system of tea quality (Huang et al., 2024) (Figure 1).

### 2.3 Mechanisms of environmental factors affecting tea quality

Environmental factors affect tea quality mainly by regulating the synthesis, degradation, and transformation of secondary metabolites in fresh leaves. Reviews of fresh tea leaf quality show that soil properties, microbial communities, temperature, light, and altitude all influence metabolic pathways related to amino acids, flavonoids, caffeine, and volatile compounds (Wu et al., 2025). A broader systematic review further found that seasonality, water stress, geography, light, altitude, temperature, and soil factors can each increase or decrease tea secondary metabolites, which means that tea quality responses are often nonlinear and context-dependent rather than controlled by a single factor alone.

Among these mechanisms, altitude acts as a comprehensive ecological variable because it simultaneously alters temperature, light intensity, humidity, and soil conditions. Simulated and field evidence shows that high-altitude conditions generally inhibit catechin biosynthesis while increasing free amino acids, thereby lowering the polyphenol-to-amino acid ratio and improving freshness, sweetness, and aroma quality. Soil regulation is also mechanistically important: soil pH and nutrient status show nonlinear relationships with polyphenols, catechins, amino acids, and caffeine, indicating that moderate adjustment of the soil environment can change tea quality composition rather than only affect yield. In addition, altitude-related changes in soil physicochemical properties and microbial communities can influence tea composition through nutrient cycling and nitrogen metabolism, and fungal abundance has been reported to correlate positively with theanine accumulation, further illustrating the coupled aboveground-belowground mechanism of tea quality formation (Ren et al., 2025). In sum, the ecological environmental characteristics of Zhejiang tea gardens are defined by strong spatial heterogeneity in climate, terrain, and soil, while the basis of tea quality formation lies in the dynamic balance among polyphenols, catechins, amino acids, caffeine, and aroma compounds. For Zhejiang tea plantations, analyzing how these indicators respond to regional ecological gradients is central to explaining tea leaf quality differences and to supporting precise, sustainable tea-garden management.

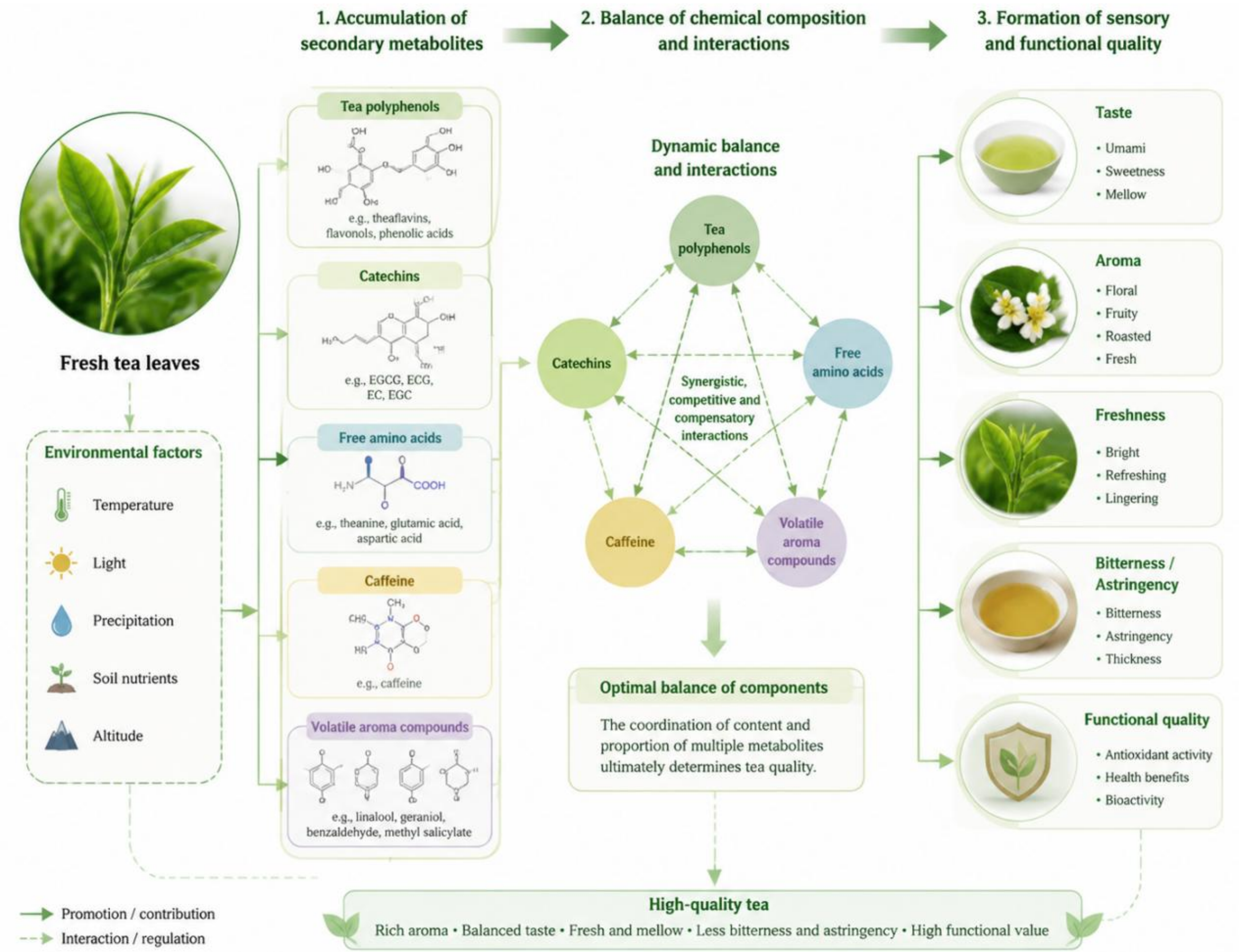

Figure 1 Schematic diagram of the biochemical mechanism underlying tea quality formation

## 3 Data Sources and Research Methods

### 3.1 Study areas and sample collection

The study area was set in representative tea-producing regions of Zhejiang Province, where tea plantations are mainly distributed across subtropical hilly and mountainous landscapes with strong ecological heterogeneity. Existing tea-related field studies in Zhejiang show that such areas typically have monsoon climatic conditions, abundant rainfall, acidic soils suitable for tea growth, and clear spatial variation in slope, altitude, and vegetation structure. To improve regional representativeness, the sampling design should cover major tea-producing zones with differences in topography, management conditions, and plantation ecology, because large-scale tea mapping studies indicate that tea is usually scattered in complex hill environments and is difficult to characterize from a single local site alone (Peng et al., 2024).

Sample collection should combine tea leaves with matched environmental samples from the same plots so that tea quality can be statistically linked to habitat conditions. Prior tea plantation studies commonly recorded the geographic coordinates of each site by GPS, collected fresh tea shoots during the spring harvest season, and took several soil subsamples within a fixed plot area and depth before mixing them into one representative sample for laboratory analysis. Similar protocols have also used one bud with two tender leaves as the standard tea sample and 0-30 cm soil as the main sampling layer, which helps maintain consistency across sites and improves comparability of biochemical and soil measurements (Yang et al., 2023).

### 3.2 Methods for measuring environmental factors and quality indicators

Environmental factor measurement in this study should include both field-recorded habitat variables and laboratory-tested soil properties. Tea plantation research has shown that altitude, slope, temperature, humidity, and light intensity can be measured directly in the field using GPS devices, digital level instruments, and automatic meteorological stations, providing a basic description of plantation microecology. For the soil environment, commonly measured indicators include pH, ammonium nitrogen, nitrate nitrogen, available phosphorus, available potassium, soil organic matter, electrical conductivity, and selected exchangeable or total mineral elements, because these variables have repeatedly been linked to differences in tea composition and soil fertility status (Tseng and Lai, 2022).

Tea quality indicators should focus on the main biochemical components that reflect freshness, bitterness, astringency, and overall processing quality. Established studies generally determine tea polyphenols, catechins, free amino acids, caffeine, and related compounds as the core quality variables, and high-performance liquid chromatography has been widely used for quantitative analysis of these constituents. Where rapid or non-destructive assessment is needed, hyperspectral approaches combined with chemometric modeling can also be used to estimate amino acids and tea polyphenols, but these methods still take the chemically measured values as the calibration basis for model construction.

### 3.3 Statistical analysis methods

Because the relationships between environmental conditions and tea quality are multidimensional, this study should adopt a combination of descriptive, spatial, correlation, and multivariate statistical methods. Previous tea studies have used ordinary kriging in ArcGIS to visualize the spatial variation of soil and tea variables, which is useful for identifying geographic heterogeneity among plantation sites. In addition, descriptive statistics can first summarize the central tendency and variability of each indicator, and correlation analysis can then be used to examine preliminary associations between soil properties, environmental factors, and tea quality traits (Yang et al., 2026).

To further identify dominant factors and quantify their effects, multivariate and predictive modeling methods should be introduced after the basic analysis. Principal component analysis is useful for dimensionality reduction and for extracting the main factor structure from complex environmental datasets, while cluster analysis can help classify plantations with similar ecological or quality characteristics (Muniz and Oliveira-Filho, 2023). For specific response relationships, quadratic regression, multiple linear regression, random forest, discriminant analysis, and related methods have all been used in agricultural and environmental datasets to reveal nonlinear effects, screen important predictors, and improve explanatory or predictive performance. Overall, the methodological logic of this section is to connect field sampling, laboratory measurement, and statistical modeling within one unified framework. This design is appropriate for revealing how ecological variation across Zhejiang tea plantations shapes tea leaf quality and for providing a basis for region-specific management and quality optimization.

## 4 Statistical Relationship Analysis Between Environmental Factors and Tea Quality Indicators in Zhejiang Tea Gardens

### 4.1 Analysis of variation characteristics of environmental factors

The environmental factors of Zhejiang tea gardens show clear spatial and temporal heterogeneity, which provides the statistical basis for explaining differences in tea quality among production areas. Long-term climate suitability analysis in Zhejiang found that temperature, precipitation, and sunshine suitability during the tea-growing season were all generally high, but inter-annual variation was obvious, with annual and spring tea suitability rising after the 1990s while summer and autumn tea suitability declined over 1971-2010. At the same time, studies across ecologically distinct tea regions in Zhejiang showed that accumulated temperature during the developmental period strongly affected phenology and contributed to clear regional clustering of amino acid traits, indicating that even within one province, environmental backgrounds differ enough to produce measurable metabolic divergence (Figure 2) (Wang et al., 2026).

From the perspective of individual variables, altitude, soil properties, and local microclimate all exhibit structured variation rather than random fluctuation. Work on fresh tea leaves from 27 sites showed that amino acid content increased gradually with altitude, while catechins and phenolic acids followed a nonlinear pattern of first decreasing and then increasing, suggesting that ecological gradients may generate both monotonic and curved variation characteristics (Ran et al., 2023). Soil factors can also vary by altitude in complex ways: in a mountain tea garden study, soil pH and catalase activity decreased and then increased with altitude, whereas soil organic matter and acid phosphatase were significantly higher at mid-altitude, confirming that environmental variation in tea gardens often has threshold-like or intermediate-optimum features.

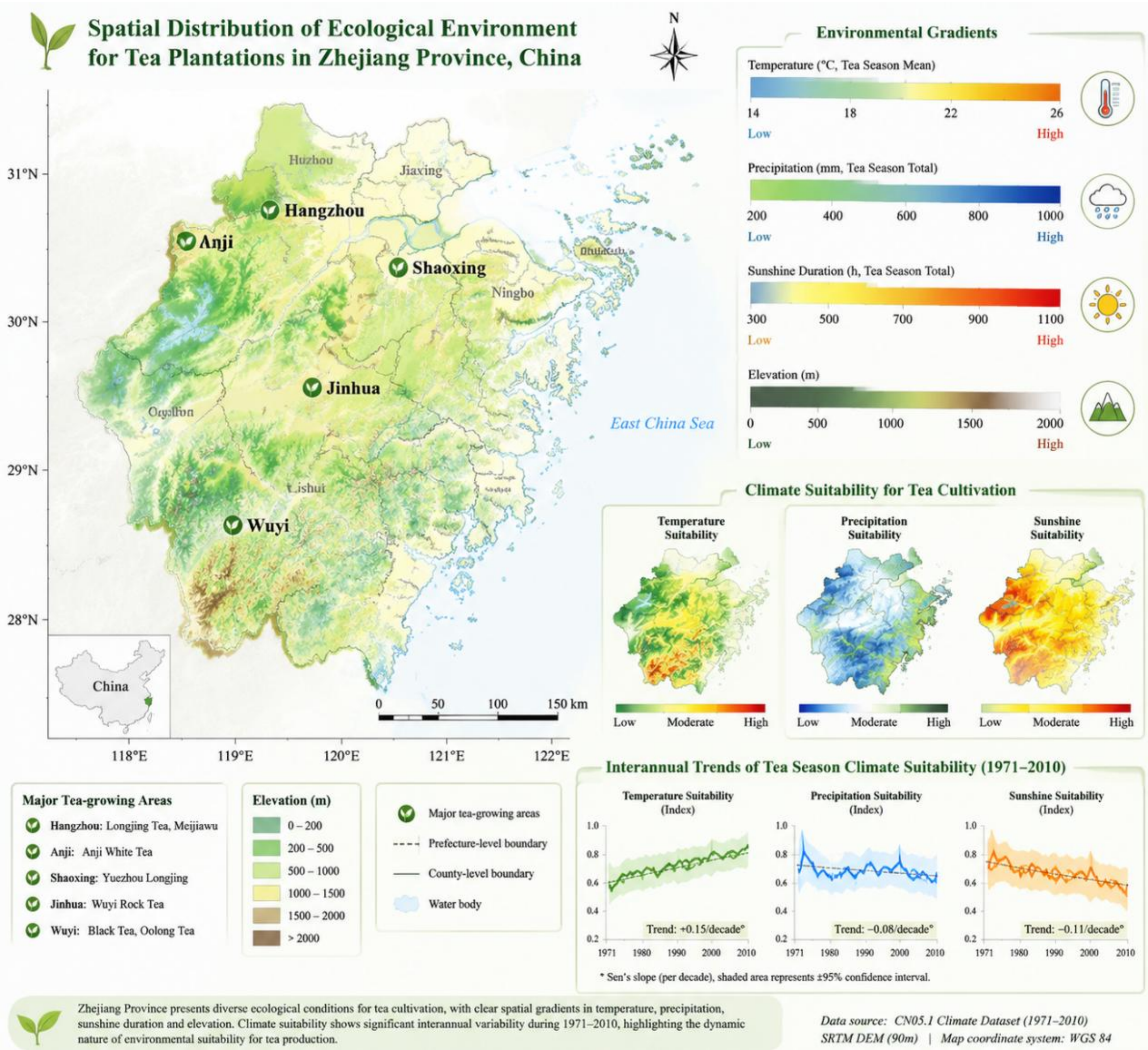


Figure 2 Spatial distribution map of temporal-spatial heterogeneity of environmental factors in zhejiang tea gardens

### 4.2 Correlation analysis between environmental factors and tea quality

Correlation analysis shows that the relationship between environmental factors and tea quality indicators is significant but not uniform across all components. A systematic review of 86 studies concluded that seasonality, water stress, geography, light, altitude, temperature, and soil factors can all alter tea secondary metabolites, but the direction and magnitude of these associations are sometimes contradictory because of cultivar differences, management conditions, and methodological variation. Under more controlled altitudinal comparisons, higher elevation was associated with lower total polyphenols and higher amino acids, which significantly reduced the polyphenol-to-amino acid ratio, a key indicator closely related to green tea taste quality (Han et al., 2017).

At the soil level, correlation results indicate that specific physicochemical properties are more explanatory than broad nutrient totals alone. Pearson and principal-component correlation analyses showed that soil pH, electrical conductivity, exchangeable calcium, exchangeable magnesium, and total manganese and copper were the main factors associated with free amino acid content, while adequate leaf macronutrients and Zn were linked to higher polyphenols, amino acids, and caffeine. Beyond soil chemistry alone, a soil-microorganism-plant system analysis found significant correlations between C, N, and P variables and the main quality components of tea, and pathway analysis further suggested that direct and indirect effects coexist, so simple pairwise correlation is useful for screening variables but insufficient for fully explaining tea quality formation (Mao et al., 2024).

### 4.3 Multi-factor statistical model analysis

Multi-factor statistical modeling further improves the interpretation of tea quality responses because many environmental effects are nonlinear and interactive. In plantation soil research, ordinary kriging was first used to visualize spatial variation, and a quadratic regression model then showed that the relationships of soil pH with polyphenols and catechins were U-shaped, whereas the relationships of soil pH and ammonium nitrogen with free amino acids and caffeine were inverted U-shaped, demonstrating that single linear assumptions may miss important response structures (Wen et al., 2021). This modeling logic is consistent with broader evidence that environmental factors do not affect tea metabolites in one fixed direction, and that contradictory outcomes across studies often arise from interactions among cultivar, environment, and management.

Recent predictive studies also support the value of integrating multiple environmental or nutritional variables into one framework. In a 160-plantation dataset, models using combined soil and leaf mineral information predicted EGCG, amino acids, tea polyphenols, and caffeine more accurately than single-source variables, and random forest performed best for several major quality components, with amino acid prediction reaching $R^2$ values of 0.61-0.88. Other multivariable models reached similarly strong performance: stepwise regression in a soil-microorganism-plant framework produced $R^2$ values of 0.923 for tea polyphenols and 0.954 for catechins, while LASSO-based prediction systems identified altitude, organic matter, phosphorus, pH, and related soil variables as effective predictors of tea quality traits (Mao et al., 2024). Overall, the statistical evidence supports a clear conclusion for Zhejiang tea gardens: environmental factors vary substantially across space and season, these variations are significantly associated with major tea quality indicators, and multi-factor models explain tea quality better than single-factor descriptions. This provides a methodological basis for identifying dominant ecological drivers and for supporting precise management of tea quality in Zhejiang plantations.

## 5 Mechanistic Analysis of Key Environmental Factors Affecting Tea Quality

### 5.1 Effects of temperature conditions on tea quality formation

Temperature affects tea quality mainly by regulating carbon-nitrogen balance and the expression of metabolic genes related to catechins, amino acids, caffeine, and aroma compounds. Under simulated high-altitude conditions characterized by lower temperature and altered light, catechin biosynthesis was inhibited while free amino acids increased, which reduced the polyphenol-to-amino acid ratio and improved taste coordination. Moderate high temperature, by contrast, increased total polyphenols but decreased free amino acids and theanine, causing the polyphenol-to-free-amino-acid ratio to rise sharply; this indicates that warming can strengthen bitterness and weaken freshness when nitrogen metabolism is constrained.

At the molecular level, temperature changes tea quality by shifting both precursor supply and pathway activity. Low-temperature treatment around 16 °C increased linalool, geraniol, methyl salicylate, and related floral volatiles, while genes in the MEP and MVA terpenoid pathways were highly expressed, showing that cool conditions can enhance aroma persistence through transcriptional activation of terpene synthesis (Khan et al., 2025). Temperature also affects quality during later transformation: roasting temperature altered theanine-driven thermal reactions, with higher fire promoting pyrazine formation and reshaping the final aroma profile, which means that the quality effect of temperature extends from fresh-leaf metabolism to postharvest flavor generation (Wang et al., 2023).

### 5.2 Effects of light conditions on tea quality formation

Light affects tea quality primarily through photoreceptor signaling and metabolic flux redistribution within the flavonoid pathway. Shading is widely used to improve tea drinking quality because it enhances chlorophyll accumulation while significantly reducing major catechins in buds, thereby lowering bitterness and astringency and improving freshness; mechanistically, this response is associated with downregulation of flavonoid biosynthetic genes and UV-B signaling components such as UVR8-related pathways. Complementary evidence shows that ambient UV-B does not simply increase all flavonoids uniformly, but redirects metabolic flux by increasing flavonols and decreasing catechins through CsHY5-mediated activation of downstream biosynthetic genes, explaining why light regime can reshape taste structure rather than only total metabolite abundance (Lin et al., 2021).

Different wavelengths further produce distinct regulatory outcomes, and these effects depend partly on cultivar background and photoprotection demands. In purple-leaf tea, UV-A, UV-B, and combined UV treatments all promoted anthocyanin accumulation, while repressing LAR and ANR activity and shifting flavonoid metabolism toward anthocyanin synthesis; UV-A produced the strongest increase, about 66% above the control. Field and physiological studies also showed that UV is the key sunlight region promoting flavonol glycoside biosynthesis in young shoots, and full sunlight triggers a time-dependent antioxidant response in which catechins and flavonols accumulate as photoprotective compounds, linking light regulation of tea quality directly to oxidative-stress defense (Zhang et al., 2022) (Figure 3).

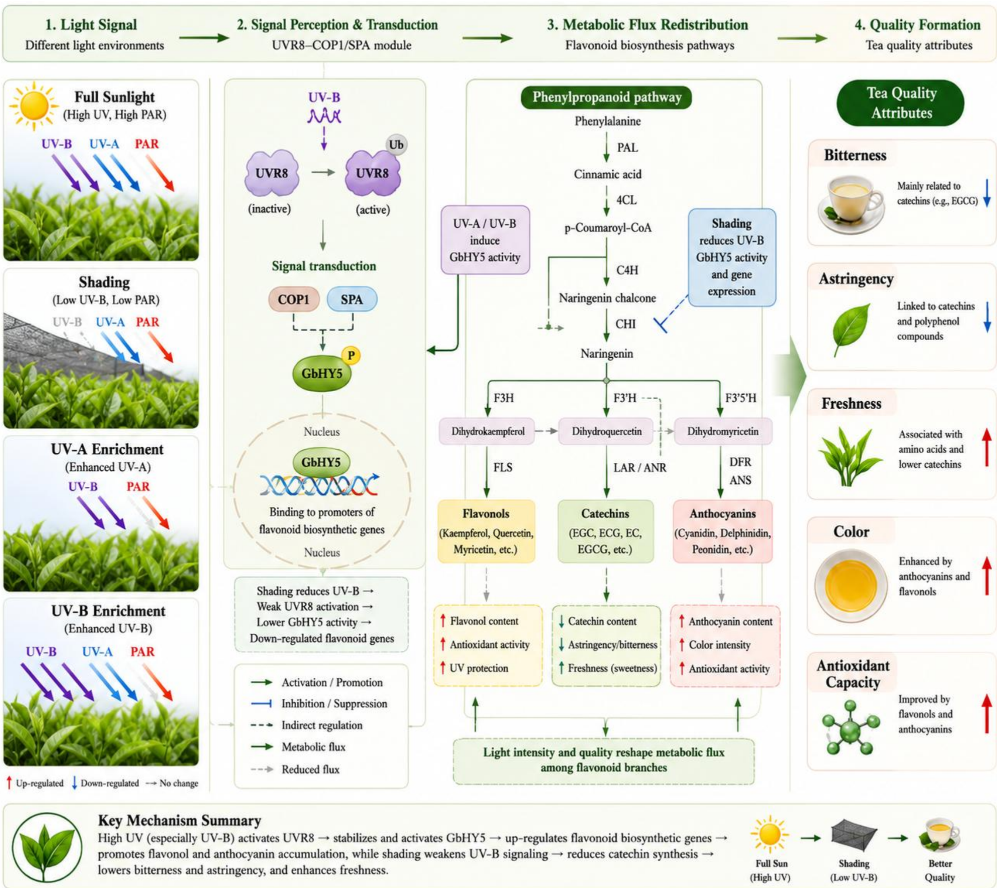


Figure 3 Schematic diagram of light environment regulation mechanism for tea quality formation

### 5.3 Effects of soil environment on tea quality formation

The soil environment influences tea quality by controlling root-zone acidity, nutrient availability, and the synthesis of major secondary metabolites. Tea plants are physiologically adapted to acidic soils, and both excessively high pH and nutrient imbalance impair the uptake of essential elements needed for chlorophyll formation and quality metabolite synthesis. In high-pH soils, tea leaves showed yellowing, reduced pigments, and lower levels of polyphenols, amino acids, and other quality-determining components because the uptake of N, P, K, Zn, Cu, and Mn was hindered despite high soil elemental content, indicating that soil chemistry affects quality through nutrient bioavailability rather than total reserves alone.

Soil effects are also nonlinear and interactive, which is why pH and nutrient management strongly influence tea taste formation. Regression analysis showed that the relationships of soil pH with tea polyphenols and catechins were U-shaped, whereas the relationships of soil pH and ammonium nitrogen with free amino acids and caffeine were inverted U-shaped, suggesting that there is an intermediate soil environment most favorable for balanced quality formation. More detailed soil-plant studies further identified pH, electrical conductivity, exchangeable Ca and Mg, and Mn and Cu status as major factors affecting free amino acid accumulation, while rhizosphere phosphorus activation and intercropping-driven nutrient mobilization were positively associated with polyphenols, amino acids, and water extract, showing that soil quality formation mechanisms depend on coordinated nutrient cycling rather than on single fertilizer inputs alone (Wang et al., 2025). In summary, the key environmental factors affecting tea quality operate through different but interconnected mechanisms: temperature mainly regulates amino-acid, catechin, and aroma metabolism; light primarily controls flavonoid partitioning and photoprotective compound accumulation; and soil conditions determine nutrient availability, metabolic balance, and the root ecological basis of quality formation. For Zhejiang tea gardens, these mechanisms explain why differences in regional climate, canopy light environment, and soil management can ultimately produce significant variation in tea leaf quality.

## 6 Case Study: Statistical Analysis of the Effects of Environmental Factors on Tea Quality in Typical Tea-growing Regions of Zhejiang Province

### 6.1 Selection of case study area and research design

A typical case-study area in Zhejiang should be selected from representative green-tea production zones with clear ecological gradients, practical management relevance, and accessible field-sampling conditions. Zhejiang is a major tea-producing and exporting province with favorable subtropical monsoon conditions for tea growth, while southwestern Zhejiang in particular is characterized by low-mountain and hilly terrain, acidic red and paddy soils, and a long history of high-quality tea production (Xu et al., 2024). At the same time, prior work in Zhejiang has already shown that tea quality and management outcomes can be effectively studied at the plantation scale in places such as Shaoxing, where environmental and agronomic interventions were linked to measurable changes in soil properties, yield, and quality.

The research design should combine ecological representativeness with statistical comparability by matching tea-leaf samples to environmental observations from the same plots. A grid-based or stratified sampling layout is appropriate because Zhejiang tea landscapes are spatially heterogeneous, and recent tea-plantation case studies have successfully used dense plot layouts, composite soil cores, and paired leaf sampling to capture local variation in plantation environments. In addition, tea case studies in other regions have shown the value of linking harvest-period environmental conditions to quality outcomes, including use of the 15 days before picking as a key observation window for soil temperature, moisture, and pH, which is a useful design reference for short-term environmental effect analysis (Cai et al., 2022).

### 6.2 Analysis of the relationship between environmental factors and tea quality in the case study area

Within the case-study area, the first statistical task is to describe the variability of major environmental factors and then test their associations with key tea quality indicators. Climate-based suitability studies indicate that temperature and precipitation are usually the strongest large-scale drivers of tea growth conditions, with temperature showing the highest explanatory power for suitability and precipitation ranking second, so these two variables should be treated as core predictors in the Zhejiang case analysis (Chen et al., 2022). At the plantation scale, quality evaluation should focus on tea polyphenols, catechins, free amino acids, and caffeine, because these are the principal biochemical variables through which environmental differences are expressed in fresh tea leaves and finished quality.

Correlation and regression analysis in the case area should then be used to identify which local environmental factors most strongly explain differences in tea quality. Existing evidence shows that altitude is associated with increasing amino acid content, while catechin-related responses can be nonlinear across elevation gradients, which suggests that Zhejiang case data should be tested for both linear and curved relationships rather than assuming monotonic trends. Soil variables also deserve special attention: quadratic modeling has shown that soil pH relates to polyphenols and catechins in a U-shaped manner, while the relationships of soil pH and ammonium nitrogen with free amino acids and caffeine are inverted U-shaped, indicating that multi-factor models in the case study should explicitly include nonlinear terms.

### 6.3 Evaluation of case study results and production applications

The value of the case study lies not only in identifying significant environmental factors, but also in translating the results into management zones and practical production decisions. Recent tea-soil research shows that geostatistics, principal component analysis, and clustering can divide plantations into operational management zones based on fertility and environmental risk, providing a model for converting Zhejiang case-study outputs into site-specific management units (Yang et al., 2026). This is especially relevant because tea plantation soils often show strong spatial heterogeneity in both fertility indicators and contaminants, so average values alone are insufficient for precise management.

In production application, the case-study results can support differentiated regulation of fertilization, soil improvement, and ecological risk monitoring. Zhejiang evidence from Shaoxing shows that partial replacement of chemical fertilizer with organic fertilizer can mitigate soil acidification, increase organic matter and ammonium nitrogen, and improve tea yield and quality, with 20%-50% replacement combined with moderate pesticide reduction giving the best balance between production and environmental performance. More broadly, sustainable tea production analyses indicate that improving fertilizer-use efficiency is one of the most effective ways to reduce environmental burdens, while climate-focused reviews emphasize that future tea management must also account for interacting stressors rather than single-factor optimization alone (Xu et al., 2021; Omer et al., 2025). Overall, the Zhejiang case study can serve as a bridge between statistical identification of key environmental drivers and precision management of tea gardens. By integrating climatic, topographic, and soil variables with tea quality indicators, the case analysis can provide a practical basis for region-specific quality improvement and sustainable plantation management.

## 7 Discussion

### 7.1 Integrated mechanisms of environmental factors affecting tea quality

The results of this study indicate that tea quality in Zhejiang tea gardens is not controlled by any single ecological variable, but by the coupled action of temperature, light, soil, and management conditions on secondary metabolism. A systematic review showed that seasonality, water stress, geography, light, altitude, temperature, and soil factors can all change tea secondary metabolites, but the direction and magnitude of these changes are often inconsistent across studies because cultivar background and field management alter the response pathways. This complexity is consistent with mechanistic work showing that environmental stress influences tea quality mainly by regulating carbon-nitrogen metabolism, which then constrains the downstream synthesis of amino acids, catechins, caffeine, and aroma compounds (Liu et al., 2022).

From a more integrated physiological perspective, high-quality tea formation in mountain environments appears to result from the joint effects of cooler temperature, altered light regime, and soil-mediated nutrient supply rather than altitude alone. Simulation experiments showed that high-altitude conditions inhibited catechin biosynthesis while increasing free amino acids and some aroma compounds, thereby improving taste and aroma coordination.

Field evidence further showed that amino acids increased with elevation, whereas catechins responded nonlinearly and differed across soil types, indicating that climatic gradients and soil background interact in shaping fresh-leaf metabolic composition (Ran et al., 2023).

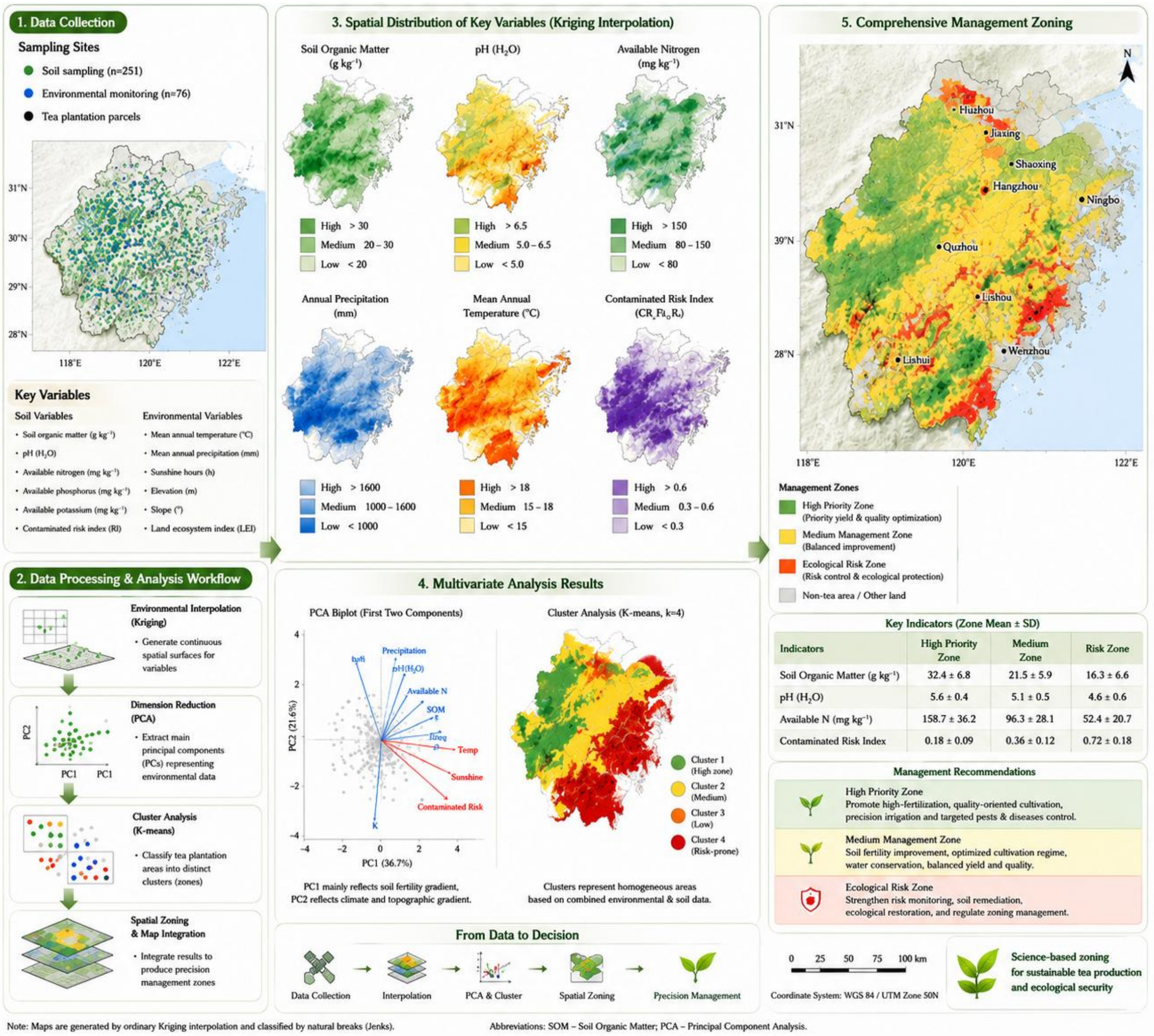


Figure 4 Zoning map of precise management of zhejiang tea plantations based on environmental factors and soil attributes

### 7.2 Application value of statistical analysis methods in tea quality research

The main value of statistical analysis methods in tea quality research is that they convert complex, multidimensional ecological information into interpretable relationships and usable prediction tools. Earlier discussion sections established that environmental responses are often nonlinear and sometimes contradictory, which makes simple descriptive comparison insufficient; this limitation has also been emphasized in review work calling for more standardized and comparable analytical frameworks for tea quality research. In practice, methods such as one-way ANOVA, multiple comparison tests, principal component analysis, and regression modeling provide the basis for screening significant indicators, testing between-group differences, and reducing dimensionality before model construction (Jia et al., 2022).

More recent studies further show that multivariate modeling and machine learning can substantially improve the efficiency and objectivity of tea quality evaluation. Near-infrared and hyperspectral studies have successfully combined PCA with PLSR, SVR, RF, SVM, and BP-ANN to predict sensory quality, catechins, caffeine, amino acids, and polyphenols, often reaching high predictive accuracy and robustness. Similar results from e-nose and data-fusion studies indicate that integrating multiple sensor signals with classification algorithms can distinguish tea grades or processing stages with very high accuracy, which is valuable for rapid quality monitoring in both research and production settings (Zhou et al., 2023).

### 7.3 Strategies for improving tea quality and ecological management in zhejiang tea gardens

For Zhejiang tea gardens, the evidence supports an ecological management strategy centered on reducing excessive chemical inputs while improving soil quality and nutrient-use efficiency. A pilot study in Shaoxing showed that partial replacement of chemical fertilizer with organic fertilizer mitigated soil acidification, increased organic matter and ammonium nitrogen, reduced runoff nutrient losses, and promoted tea yield and quality, with 20%-50% substitution combined with moderate pesticide reduction performing especially well. This direction is reinforced by recent fertilizer-management research showing that partial organic substitution can increase soil organic matter, raise soil quality index values, improve nitrogen-use efficiency, and lower the tea polyphenol/amino acid ratio, which is favorable for drinking quality (Wang et al., 2024).

Ecological improvement should also include diversified biological management and risk control rather than fertilizer adjustment alone. Intercropping and green-manure systems improve soil fertility, microbial community complexity, and key quality components such as amino acids and soluble sugars, demonstrating that soil biological regulation is an effective pathway for sustainable quality improvement (Duan et al., 2024). At the same time, long-term amendment studies warn that some organic inputs can elevate heavy-metal ecological risk even while improving soil and yield, so Zhejiang tea-garden management should combine organic substitution with careful monitoring of contaminant risk and site-specific optimization. Overall, the discussion supports a clear conclusion: tea quality formation in Zhejiang is the product of multi-factor ecological coupling, its analysis depends on multivariate statistical methods, and its improvement requires precision ecological management rather than single-input intensification. This provides a scientific basis for future tea-garden zoning, quality regulation, and sustainable production upgrading in Zhejiang Province.

## 8 Conclusions

This study shows that the quality of tea leaves in Zhejiang tea plantations is shaped by the joint action of topography, climate, light, and soil rather than by any single environmental factor. Tea plantations are typically distributed in hilly and mountainous landscapes, and both large-scale mapping and regional metabolite studies indicate that environmental heterogeneity across elevation, slope, and habitat conditions is strong enough to produce clear spatial differences in tea composition. Across such gradients, amino acids tend to increase with altitude, while catechins often respond nonlinearly, confirming that the ecological basis of tea quality variation is both spatially structured and biochemically specific. The statistical analyses further indicate that soil conditions are among the most direct environmental regulators of tea quality formation. Soil pH, ammonium nitrogen, and related edaphic variables showed nonlinear relationships with polyphenols, catechins, free amino acids, and caffeine, which means that moderate or optimal ranges are more informative than simple linear increases or decreases. At the same time, multi-source modeling using soil and leaf mineral information improved prediction accuracy for major tea-quality components, showing that integrated statistical analysis is more effective than single-factor interpretation for explaining quality differences among plantations.

A key innovation of this study is that it constructs a unified analytical framework linking environmental variation, biochemical quality indicators, and multivariate statistical modeling within Zhejiang tea plantations. Existing research already shows that tea-quality data are intrinsically multidimensional and that methods such as PCA, cluster analysis, factor analysis, and discriminant analysis are well suited to extracting dominant structures from complex environmental datasets. Building on this logic, the present study extends statistical analysis from simple correlation description to a more integrated interpretation of how multiple environmental variables jointly shape tea-quality outcomes in a regionally specific production system. Another contribution is the combination of ecological interpretation with management-oriented statistical thinking. Earlier work has shown that tea-garden soils and safety indicators often display pronounced spatial heterogeneity, and zoning approaches can translate statistical differences into actionable management units for fertilization and environmental monitoring. In parallel, research on tea-soil systems has demonstrated that minimum-dataset screening, geostatistics, and GIS-based spatial evaluation can simplify complex indicator systems without losing practical explanatory value, which supports the theoretical basis for precision management in tea plantations.

Several limitations should be acknowledged. First, although this study identifies significant statistical relationships between environmental factors and tea quality, some mechanisms remain difficult to isolate because tea metabolite formation is simultaneously affected by cultivar, season, management, and postharvest conditions; previous reviews have emphasized that contradictory findings across studies often arise from these interacting sources of variation. Second, some emerging quality-assessment methods still have restricted observational scope: for example, recent hyperspectral work in Zhejiang was limited to fresh leaves and a small set of indicators, without extending to canopy-scale monitoring or broader quality dimensions. Future research should therefore move in two directions. One priority is to build broader, multi-scale monitoring systems that integrate field sampling, spectroscopy, GIS, and machine learning so that tea quality can be predicted more efficiently across landscapes and growing seasons; current studies already show that hyperspectral and chemometric methods can provide rapid, non-destructive estimation of polyphenols, amino acids, and grade-related traits. A second priority is to connect quality improvement with ecological sustainability, including climate adaptation, biodiversity-supportive vegetation design, and risk monitoring for heavy metals and other soil constraints, because sustainable tea production depends on balancing product quality with long-term environmental resilience. Overall, the evidence supports a clear conclusion for Zhejiang tea plantations: environmental heterogeneity is a major driver of tea-quality variation, and multivariate statistical methods are essential tools for identifying its dominant pathways. These conclusions provide a basis for future precision management, ecological optimization, and high-quality sustainable development of Zhejiang’s tea industry.

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**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.

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