

Analysis of Environmental Adaptation and Fruit Quality Variation in Zhejiang Citrus Orchards

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Abstract Zhejiang Province is an important citrus-producing region in China, where diverse climatic, soil, and topographic conditions strongly influence citrus growth and fruit quality. This study systematically analyzes the environmental adaptability of citrus orchards and the resulting changes in fruit quality under different ecological and cultivation conditions. The effects of temperature, precipitation, light, soil water availability, and nutrient status on citrus growth, physiological responses, fruit development, and quality formation are examined. Particular attention is given to the relationships between environmental factors and soluble solids, sugar-acid ratio, vitamin C, fruit appearance, and texture. A case study of a typical citrus orchard is further used to assess environmental responses and identify key factors driving quality variation. Based on these relationships, an environmental adaptability evaluation framework is proposed, together with integrated water and fertilizer management, microclimate regulation, and climate-adaptive cultivation strategies. The study provides a theoretical basis for improving citrus fruit quality, optimizing orchard management, and promoting climate-resilient and sustainable citrus production in Zhejiang Province.

Keywords Zhejiang Province; Citrus orchards; Environmental adaptability; Fruit quality; Climate-resilient cultivation

1 Introduction

Citrus is one of the world's most widely cultivated and economically important fruit crops, and in China it remains a pillar industry for many producing regions (Tang et al., 2026). China is also a major producer and exporter of diverse citrus fruits, and regional citrus industries increasingly depend not only on production scale but also on stable fruit quality, nutritional value, and market competitiveness. Within this broader context, Zhejiang is an important citrus-producing province in eastern China, with a long cultivation history, strong germplasm resources, and active varietal innovation represented by local and introduced cultivars grown in its production areas. Research in Zhejiang has already shown substantial inter-varietal differences in secondary metabolites, including flavonoids, phenolic acids, carotenoids, and limonoids, indicating that the province possesses rich citrus quality diversity and high potential for resource evaluation, breeding, and differentiated utilization (Zhang et al., 2026). At the same time, the performance of introduced hybrid citrus can vary among production areas, and even when cultivars share favorable flavor and nutritional traits, their actual field expression remains strongly shaped by local growing conditions. This is especially relevant in Zhejiang, where orchard environments are highly heterogeneous because of complex topography, monsoonal climate, differences in altitude and slope, and variation in soil conditions across producing counties, all of which can alter tree growth, fruit development, and quality formation (Yu et al., 2024). Recent climate projections further suggest that Zhejiang is one of the Chinese citrus regions in which future climate change could significantly improve overall fruit quality, highlighting the province as a valuable setting for studying environmental adaptation under both current and changing ecological conditions.

The quality of citrus fruit is formed through the combined action of genotype and environment, with climatic, edaphic, topographic, and biological factors jointly determining the accumulation of sugars, organic acids, pigments, phenolics, aroma compounds, and other nutritional substances. Among these drivers, temperature has long been regarded as the dominant climatic factor affecting citrus quality, especially through its influence on citric acid content, Brix-acid ratio, rind characteristics, flesh proportion, and fruit weight. More recent

orchard-scale studies also show that rainfall, cumulative temperature, and diurnal temperature range regulate key quality traits during different fruit developmental stages: high rainfall and lower heat accumulation tend to maintain higher acidity, whereas lower rainfall, higher cumulative temperature, and wider diurnal temperature range promote soluble solids accumulation (Dong et al., 2024). Evidence from regional and future-climate models further indicates that monthly diurnal temperature range is among the strongest determinants of citrus quality, while temperature, humidity, and seasonal thermal conditions can shape yield and ripening trajectories differently across production regions. Sunshine duration and agrometeorological heat indices likewise influence heterogeneity in fruit weight, total soluble solids, acids, and metabolites, and humid, low-light environments can depress yield efficiency relative to drier and warmer zones (Nawaz et al., 2020). However, climate alone does not explain all observed quality variation. Soil is the basic medium for water and nutrient uptake, and its physicochemical properties can exert effects on fruit shape, peel traits, and flavor that in some regions exceed those of meteorological or topographic factors. At a finer ecological scale, soil nutrient status and the rhizosphere microbiome also influence quality formation by altering nutrient transformation, nutrient availability, and specialized metabolism, including vitamin C, soluble solids, acidity, and peel monoterpenes. In addition, environmental variables such as light, temperature, pH, and humidity are linked to the synthesis of carotenoids, flavonoids, and vitamin C, providing a mechanistic basis for differences in nutritional quality among orchards and cultivars (Cui, 2024). Because many of these factors interact, contradictory relationships can emerge, especially for precipitation and acidity, depending on rainfall timing, intensity, and the stage of fruit development.

Against this background, a systematic analysis of environmental adaptation and fruit quality variation in Zhejiang citrus orchards is both scientifically necessary and practically important. Existing studies have clarified specific aspects of Zhejiang citrus resources, such as metabolite diversity among cultivars, but fewer studies have integrated meteorological, topographic, soil, and orchard ecological factors to explain why fruit quality differs across orchards within the province. The core scientific problem is therefore to determine how Zhejiang's heterogeneous ecological environments shape citrus adaptation and which environmental variables most strongly control variation in commercially important and nutritionally relevant fruit quality traits. A second question is whether the effects of climate, terrain, and soil act independently or in coordination, and whether their relative contributions differ among external traits, internal taste attributes, and functional metabolites. A third question concerns application: identifying the ecological ranges and orchard conditions most conducive to high-quality production would support cultivar zoning, orchard management optimization, and regional adaptation strategies under climate change. Accordingly, this study aims to characterize the current variation in fruit quality among representative Zhejiang citrus orchards, quantify the relationships between environmental factors and quality indices, and reveal the ecological basis of orchard adaptation in the province. The overall framework therefore links three components: first, characterization of Zhejiang citrus production contexts and orchard ecological backgrounds; second, comparative evaluation of fruit quality traits across orchards; and third, multivariate analysis of the associations between environmental variables and quality outcomes, so as to provide a scientific basis for superior-area identification, precision cultivation, and sustainable high-quality development of Zhejiang's citrus industry.

2 Ecological Environment and Production Conditions of Citrus Orchards in Zhejiang Province

2.1 Climatic resources and seasonal variation characteristics of citrus orchards

Zhejiang citrus orchards are situated in the humid subtropical monsoon zone, where citrus growth and fruiting are highly sensitive to seasonal temperature and precipitation patterns. For *Citrus reticulata*, the main climatic suitability range in China includes annual precipitation of 1 000-4 000 mm, precipitation in the driest quarter above 100 mm, and a mean temperature of the coldest quarter of 12°C-28°C, which is broadly consistent with the hydrothermal background of eastern and southeastern citrus regions. Zhejiang's production season typically experiences warm, rainy summers and cooler, relatively drier winters, and this seasonal alternation is favorable for both vegetative growth and later fruit maturation, although interannual fluctuations in rainfall and thermal accumulation can alter the stability of orchard performance (Jiao et al., 2024). At the national scale, projected

climate change has even been associated with significantly improved citrus quality in Zhejiang, indicating that the province occupies a relatively advantageous climatic position among China's citrus-producing regions.

Seasonal variation within the fruit development period is especially important because temperature, rainfall, sunshine, and diurnal thermal amplitude regulate sugar-acid balance and external fruit traits rather than simply total yield. A long-term orchard study showed that high rainfall and lower cumulative temperature during early fruit development increased titratable acidity, whereas lower rainfall, higher cumulative temperature, and a larger diurnal temperature range promoted soluble solids accumulation. Other regional analyses similarly found that temperature had the greatest effect on quality traits such as citric acid content, Brix/acidity ratio, rind thickness, flesh percentage, shape index, and fruit weight, while rainfall effects could differ by developmental stage and rainfall regime. Consistent with this, monthly mean diurnal temperature range in July has been identified as a dominant climatic control on citrus quality in China, while autumn temperature and humidity variables more strongly influence yield during growth and ripening stages (Wang et al., 2022).

2.2 Soil physicochemical properties, water availability, and nutrient conditions

The soil environment provides the material basis for citrus orchard adaptation because root growth, water uptake, and nutrient supply depend on pH, organic matter, texture, and available mineral elements. Evidence from major citrus regions shows that soil factors can exert stronger effects than meteorological and topographic factors on fruit flavor and fruit shape, underscoring the need to characterize orchard soils when explaining quality variation. In practice, citrus orchards often face nutritional imbalance rather than simple nutrient scarcity: in Hunan, widespread soil acidification was observed, while nitrogen, potassium, and boron deficiencies remained common despite relatively abundant organic matter. A Zhejiang case from Xiangshan County further showed that coastal saline-alkali orchards had higher soil pH, calcium, and magnesium but lower organic matter, nitrogen, iron, and boron than mountain and plain orchards, creating clear constraints on micronutrient availability and tree nutritional status (Figure 1).

Water availability interacts with these soil properties and strongly shapes citrus physiological performance across seasons and sites. In orange orchards from southwest China, transpiration responded not simply to rainfall amount but to the joint action of soil moisture and atmospheric demand, with the ratio of volumetric water content to reference evapotranspiration showing the strongest relationship to tree water use (Hou et al., 2023). Management studies also indicate that precise irrigation and fertilization by growth stage can improve soluble sugar, vitamin C, yield, and water-fertilizer productivity, whereas inefficient water and fertilizer supply limits stable high-quality production. Nutrient imbalance is another recurring issue in commercial orchards: magnesium deficiency has become a major limiting factor in Chinese citrus systems, and surveys in Southwest China found that unbalanced fertilization with excessive N, P, and K but negligible Mg input aggravated soil Mg depletion in most orchards. These findings imply that evaluating Zhejiang orchards requires attention not only to inherent soil properties, but also to seasonal soil water status and the match between fertilizer inputs and actual nutrient demand.

2.3 Site conditions and differences in cultivation management among major citrus-producing regions

Site conditions differ substantially among citrus-producing regions because orchards are distributed across mountains, hills, plains, and in some coastal zones, and these landform differences influence microclimate, drainage, soil development, and nutrient behavior. Topography is therefore not merely a background variable; it helps structure orchard ecological heterogeneity and can change how strongly fruit traits respond to soil and climate. In Xiangshan County, for example, fruit nutrient status differed across mountain, flat, and coastal saline-alkali land, and the Beni-Madonna cultivar was more sensitive than *C. unshiu* to topographic and soil constraints on nutrient uptake. In mountainous citrus areas more broadly, red soils with good permeability and relatively high organic matter are often considered favorable for citrus growth, but complex terrain also increases spatial variability in surface soil nutrients and complicates orchard monitoring and management.

Differences in cultivation management further enlarge regional variation in orchard performance. Across China, citrus planting remains strongly shaped by natural conditions, transportation accessibility, production scale, and the generally smallholder structure of mountain orchards, all of which affect technical efficiency and

standardization levels (Wu and Pu, 2026). Field and survey studies show that management choices such as fertilization balance, plastic-shed use, irrigation scheduling, and soil-cover or agroforestry practices can substantially alter soil quality and fruit performance: long-term plastic housing in coastal Zhejiang increased soil salinization and impaired iron uptake, while agroforestry and organic systems improved pH, soil carbon, porosity, and biological activity relative to conventional management. Even where climate is broadly suitable, excessive reliance on fertilizers and pesticides or expansion into less-adapted land can reduce sustainability and obscure true site suitability. For Zhejiang, this means that variation among major citrus-producing regions should be interpreted through the combined lens of landform, soil background, infrastructure, and orchard management intensity, rather than through climate alone.

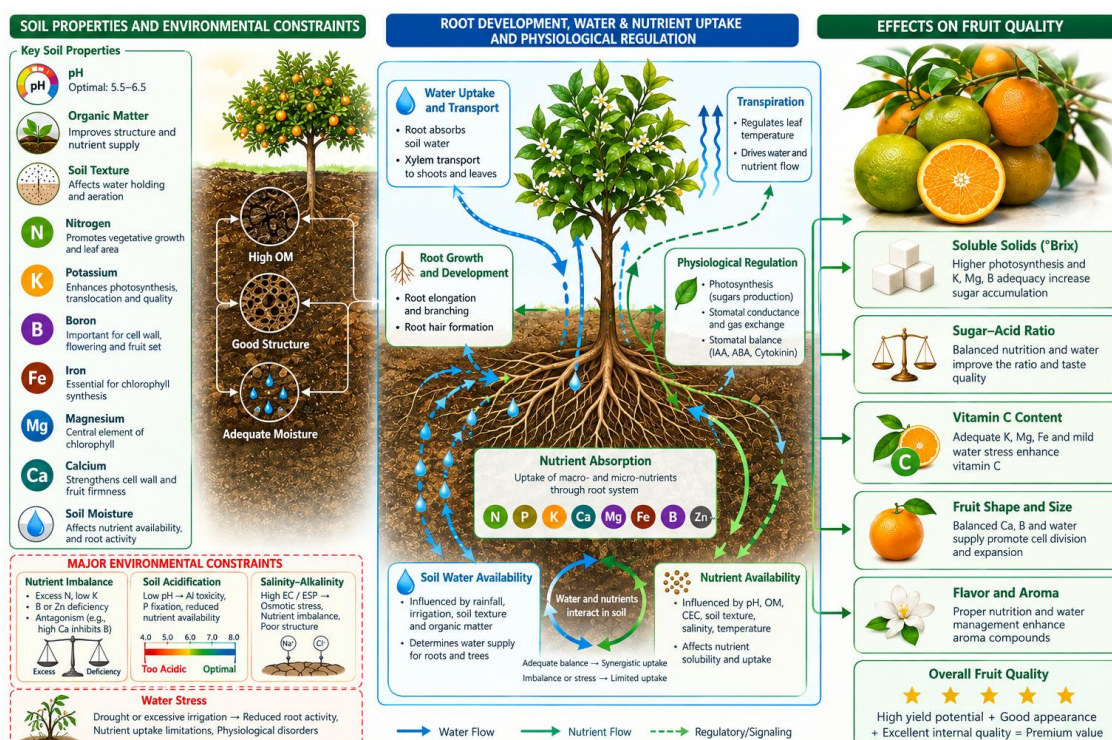


Figure 1 Conceptual framework illustrating the interactions among soil properties, water availability, nutrient uptake, citrus physiological responses, and fruit quality formation.

3 Environmental Adaptation Mechanisms of Citrus under Regional Conditions in Zhejiang

3.1 Regulation of citrus growth cycles by temperature, light, and precipitation

Under Zhejiang's subtropical monsoon conditions, citrus growth cycles are regulated by the joint action of thermal accumulation, seasonal rainfall, and light environment rather than by a single climatic factor. Temperature is especially important because citrus generally performs best within a moderate thermal range, while deviations from that range alter shoot growth, flowering, fruit set, and subsequent fruit development. Phenological evidence from mandarin further shows that budding depends on spring heat accumulation, flowering begins when effective temperature sums reach a threshold, and the full period from budding to fruit ripening varies with the annual water-thermal regime, indicating that seasonal temperature and precipitation together determine the timing and duration of developmental stages.

Light and precipitation then modulate how these temperature-driven stages are expressed in the canopy and fruit. Citrus is sensitive to photoinhibition, particularly when high spring irradiance follows a long low-light period, because its evergreen leaves and relatively low photosynthetic saturation make the photosynthetic apparatus vulnerable to sudden excess light (Naeem et al., 2024). At the same time, climatic variation in water supply affects reproductive development and fruit growth: changes in temperature and water stress at critical phenological stages reduce fruit set and size, increase acidity, and promote fruit drop, while flowering itself is known to be shaped by interactions between climatic cues and internal regulatory pathways.

3.2 Responses to water stress and abiotic stresses such as high and low temperatures

Water deficit is one of the main abiotic constraints on citrus adaptation, and its first effects are usually expressed through reduced stomatal conductance, lower leaf water status, and suppressed photosynthesis. Across rootstocks, stomatal closure functions as a major avoidance mechanism that limits water loss, but the speed and effectiveness of this response differ markedly among genotypes (Moreno-Lora et al., 2026). Drought tolerance is therefore not uniform: some rootstocks maintain relative water content and gas exchange better than others, and citrus plants can compensate through osmotic adjustment, antioxidant activity, and changes in biomass allocation between roots and shoots.

In Zhejiang orchards, drought responses are likely to interact with summer heat and episodic winter or early-spring cold, making stress combinations more relevant than single stresses alone. High temperatures disrupt photosynthesis, increase reactive oxygen species, and can impair flowering, fruit development, and fruit quality, while low temperatures lead to photosynthetic inhibition, chlorophyll degradation, altered water relations, and compatible solute accumulation (Hussain et al., 2023). Evidence from combined-stress studies further shows that drought and heat together trigger specific metabolic and antioxidant responses distinct from either stress alone, and moderate salinity or other concurrent stresses can modify whole-plant performance depending on stress intensity and duration.

3.3 Adaptive responses of roots, leaves, and whole trees to environmental changes

Adaptive responses begin in the root system because root architecture determines water and nutrient capture under fluctuating soil conditions. Under drought, citrus genotypes can maintain tolerance through deeper or more extensive roots, increased root length and surface area, and continued root growth supported by carbohydrate allocation, whereas susceptible genotypes show reduced root and shoot growth under stress (Modica et al., 2025). Rootstock-mediated metabolic adaptation is also important: different scion-rootstock combinations show distinct drought-response metabolites in leaves and roots, and some combinations appear able to buffer stress while preserving fruit-quality potential, which is highly relevant for selecting regionally adapted planting materials in Zhejiang.

Leaves and shoots are equally important because they are the organs directly exposed to high light, heat, and cold, and they determine whole-tree carbon gain and transpiration. Citrus aerial tissues respond through osmoprotective metabolite accumulation, antioxidant defense, and regulation of photosynthetic proteins, while heat-tolerant genotypes can maintain photosynthesis and water status through stronger expression of heat shock proteins and aquaporins. At the whole-tree level, grafting integrates these organ-level responses: rootstocks can transmit tolerance traits to the scion through vascular signaling, improve antioxidant capacity under drought-heat stress, and reconfigure scion metabolism through compounds such as raffinose, galactinol, salicylic acid, and proline, thereby enhancing environmental adaptation under complex orchard conditions (Balfagón et al., 2025). In sum, citrus environmental adaptation under Zhejiang's regional conditions depends on the coordinated regulation of phenology, stress physiology, and whole-tree integration, with rootstock-scion combinations playing a central role in stabilizing growth and fruit production across variable orchard environments.

4 Effects of Environmental Factors on Citrus Fruit Growth and Quality Formation

4.1 Effects of temperature and light on fruit enlargement, maturation, and color development

Temperature and light jointly regulate citrus fruit enlargement and ripening by influencing assimilate accumulation, acid catabolism, and pigment metabolism. Long-term field evidence shows that high temperatures alter the ripening process, affecting flavor, harvest timing, and market period, and that fruits in hotter climates often ripen faster because sugar accumulation and organic acid breakdown proceed more rapidly (Mesejo et al., 2024). However, excessively high temperature does not uniformly improve quality. In protected-cultivation mandarin, increasing daytime temperature reduced total free sugars under the strongest heat treatment, while combined day-night warming significantly lowered citric acid, indicating that thermal effects depend on both intensity and timing during development. This helps explain why fruit enlargement under warm conditions can be accompanied by weaker internal quality when heat exceeds the range favorable for balanced ripening.

Color development is even more tightly constrained by the temperature-light regime. Citrus peel coloration generally improves under cooler conditions, whereas high temperature inhibits chlorophyll breakdown and carotenoid biosynthesis; field and review evidence indicates that night temperatures below about 13°C with moderate daytime temperatures near 20°C promote color break and xanthophyll accumulation, while temperatures above 25°C delay normal orange coloration (Keawmanee et al., 2023). Light exposure further differentiates fruit within the canopy, because fruit growing outside the canopy develop brighter peel pigmentation than shaded fruit, and light deprivation reduces carotenoid accumulation and downregulates carotenoid biosynthetic genes in mandarin and sweet orange peels. For Zhejiang orchards, this means that late-season thermal decline and adequate canopy light are both necessary for synchronized maturation and commercially desirable coloration.

4.2 Regulation of sugar and organic acid accumulation by water availability and soil nutrients

Water availability regulates sugar and organic acid accumulation through both dilution effects and active metabolic adjustment. A climate-based orchard study showed that high rainfall and lower cumulative temperature during early fruit development promoted higher titratable acidity, whereas low rainfall, higher cumulative temperature, and a larger diurnal temperature range favored soluble solids accumulation. Mechanistic work on citrus water relations further found that moderate water-deficit stress during stage II increased fructose and glucose concentrations and raised soluble solids independently of fruit size, indicating that osmotic adjustment rather than simple dehydration can drive sugar enrichment. Yet the response is stage-specific: later water deficit does not necessarily increase sugars, and under some dry-climate conditions heat-water interactions can instead reduce juice content and maintain higher acidity.

Soil nutrients modify these water effects by controlling carbon allocation, acid metabolism, and final flavor balance. Available phosphorus showed strong positive associations with total soluble solids, titratable acidity, and vitamin C, indicating that intrinsic quality depends partly on soil nutrient supply rather than climate alone. Nutrient balance also matters more than simple abundance. Adequate supplementation of secondary nutrients and micronutrients improved nutritional value and the TSS/TA ratio, while fruit magnesium concentration was the only mineral significantly correlated with both sugars and organic acids, being negatively related to sugars and positively related to acids across six citrus cultivars. Nitrogen shows a similar optimum response: appropriate N increases fruit weight and soluble solids, but excessive N no longer improves yield and can weaken the sugar-acid balance at ripening.

4.3 Effects of orchard microclimate and environmental stress on fruit appearance, texture, and nutritional quality

Orchard microclimate shapes external appearance and internal nutritional quality by altering local light, humidity, and canopy temperature. Studies of canopy-position effects in citrus show that outer-canopy fruits receive greater irradiance and generally accumulate more total soluble solids, sugars, pigments, and antioxidant compounds than shaded inner-canopy fruits, with quality improving further as harvest maturity advances (Manzoor and Anjum, 2026). Similar microclimate patterns have been observed in tree-fruit canopies more broadly: higher light intensity is positively associated with fruit weight and soluble solids, while more humid, shaded canopy zones tend to maintain higher acidity and lower color development. These results indicate that fruit quality variation within Zhejiang orchards can arise not only from regional environment but also from canopy architecture and local exposure.

Environmental stress modifies appearance, texture, and nutritional composition in ways that can be either beneficial or detrimental depending on severity. Moderate stress can improve visible quality: reflective film mulching increased light in the middle and lower canopy, improved fruit coloring degree and excellent-fruit percentage, and reduced pericarp thickness, while moderate water deficit also improved appearance quality in citrus. By contrast, chronic nutritional excess or poorly regulated stress can degrade integrated quality. Excessive nitrogen enlarged fruit but reduced dry matter, impaired texture, and disrupted amino acid, sugar, organic acid, and ascorbate metabolism, whereas long-term grass mulching improved soil fertility and microbial activity while increasing vitamin C and reducing pericarp thickness (Xiong et al., 2026). In Zhejiang orchards, the key issue is

therefore not whether stress exists, but whether microclimate and management keep stress within a range that promotes color, texture, and nutritional quality without sacrificing fruit balance or storability. In sum, fruit growth and quality formation in Zhejiang citrus orchards depend on the coordinated effects of temperature and light on ripening, water and nutrients on sugar-acid metabolism, and microclimate and stress on appearance, texture, and nutritional traits (Figure 2).

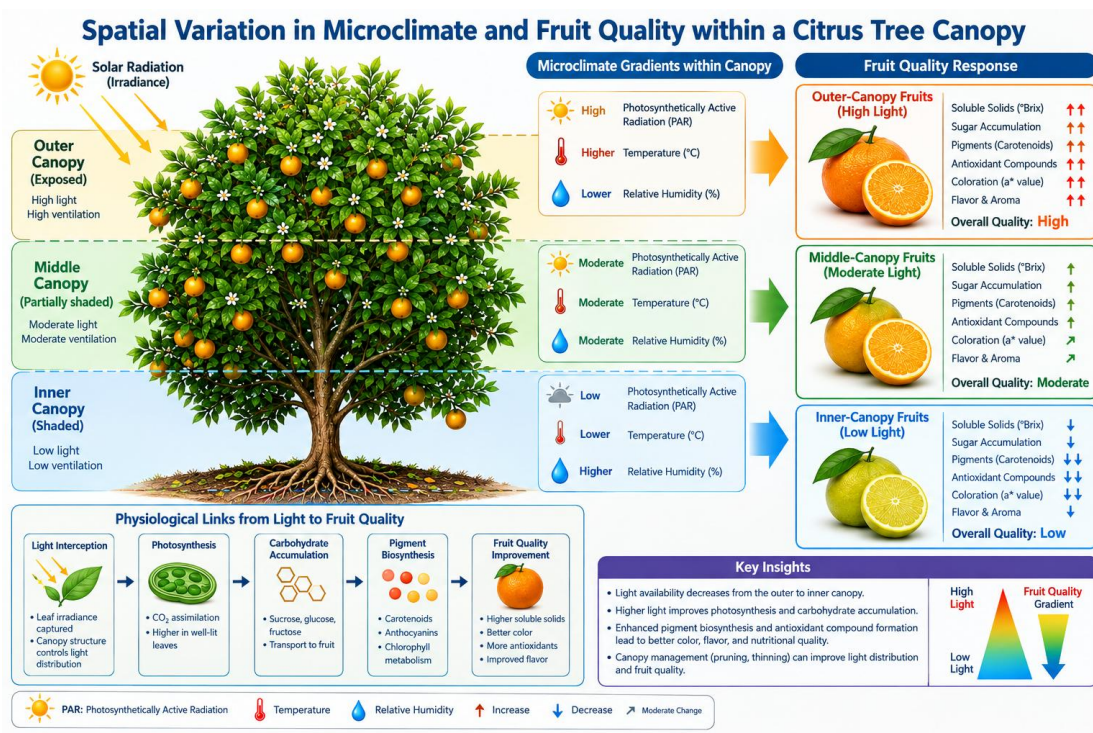


Figure 2 Spatial variation in citrus canopy microclimate and its effects on fruit quality

5 Spatiotemporal Variation in Citrus Fruit Quality in Zhejiang Province

5.1 Dynamic changes in fruit quality during different developmental stages

Citrus fruit quality in Zhejiang changes continuously from early expansion to full maturity, and the direction of change differs among traits. During fruit development, sugars and acids do not accumulate synchronously: sucrose usually increases steadily toward ripening, whereas citric acid tends to rise earlier and then decline during late maturation. This temporal divergence is one reason why the sugar-acid ratio increases sharply near harvest, even when absolute sugar accumulation becomes slower in late stages. Developmental studies further show that vitamin C and organic acids are often relatively high at earlier harvest stages and decline as maturity advances, while total soluble solids, juice pH, and total sugar content generally increase (Manzoor et al., 2023). Therefore, the temporal pattern of Zhejiang citrus quality should be understood as a coordinated shift from acid-dominated immature fruit to sweeter and more organoleptically acceptable mature fruit.

The dynamic nature of maturation also means that no single index can adequately define the optimal harvest stage across orchards or cultivars. Commercial maturity is commonly judged using soluble solids, titratable acidity, juice percentage, peel coloration, and especially the TSS/TA ratio, but their usefulness varies with genotype and local edaphoclimatic conditions. In newly developed citrus hybrids, titratable acidity and ascorbic acid were highest at early harvest stages and declined over time, whereas TSS, TSS/TA ratio, and BrimA generally increased toward later stages, confirming that harvest timing strongly alters both flavor and nutritional traits (Singh et al., 2023). In addition, cultivar-specific developmental trajectories can be substantial: in a fresh-sweet mutant of ‘Shatangju’, citrate content decreased significantly across development while vitamin C remained relatively stable, and the accumulation pattern of the major soluble sugars and the sugar/acid ratio also changed. For Zhejiang orchards, this implies that stage-specific quality evaluation should integrate internal composition and external maturity rather than relying on one threshold alone.

5.2 Differences in citrus fruit quality among different ecological regions

Marked spatial variation in citrus fruit quality is expected across Zhejiang because regional climate, terrain, and orchard environment modify both maturation and final harvest attributes. Comparative studies of Satsuma mandarin from Zhejiang, Hubei, and Hunan showed that quality parameters differed by both variety and region, and that color, juice yield, titratable acidity, total soluble solids, amino acids, and carotenoids were more strongly influenced by region than many other traits. This indicates that even within broadly suitable citrus zones, regional ecological conditions can shift the balance among appearance quality, flavor, and nutritional composition. Similar evidence from geographically stratified sweet orange populations showed significant variation in TSS, citric acid, vitamin C, and soluble sugar across sites, with altitude, temperature, and rainfall all contributing to these differences (Anand et al., 2022). Zhejiang's internal ecological heterogeneity therefore likely generates comparable regional differentiation in fruit quality among coastal, plain, hilly, and mountain orchards.

Spatial variation also appears at the cultivar and biochemical level, not only in standard juice traits. Multi-cultivar evaluations have shown large differences in TSS, TA, TSS/TA ratio, and vitamin C among citrus types, with some cultivars characterized by high sweetness and others by high acidity and high ascorbic acid. In Zhejiang germplasm, phytochemical profiling further revealed clear metabolite differentiation among locally important cultivars, and compound accumulation was shaped primarily by cultivar identity while still being influenced by climate, soil, and developmental stage. Broader regional work in China reached the same conclusion: differences among citrus varieties are significant, but origin, growing season, and environmental factors also help explain variation in total soluble sugar, acids, and antioxidant-related compounds (Guo et al., 2023). Taken together, spatial variation in Zhejiang citrus quality should be interpreted as the joint result of ecological region, cultivar composition, and orchard-specific growing conditions.

5.3 Relationships between environmental factors and quality indicators such as soluble solids, sugar-acid ratio, and Vitamin C

Among environmental drivers, temperature and rainfall show the clearest relationships with soluble solids and acidity during fruit development. A nine-year orchard study found that high rainfall and low cumulative temperature in young fruit promoted higher titratable acidity, whereas low rainfall, high cumulative temperature, and a high diurnal temperature range promoted soluble solids accumulation. At a broader scale, climate-model analysis identified the monthly mean diurnal temperature range in July as the strongest climatic determinant of citrus quality, and projected that fruit quality in Zhejiang may improve under future climate change relative to some other Chinese citrus regions. These results support the view that Zhejiang differences in TSS and sugar-acid ratio reflect not only varietal traits, but also the seasonal thermal and rainfall regime experienced during expansion and ripening.

Soil and nutrient conditions further regulate quality indicators by affecting sugar metabolism, acid degradation, and vitamin accumulation. Nitrogen nutrition strongly modulates internal fruit composition: an intermediate N supply produced the highest TSS and TSS/TA ratio with the lowest acidity at ripening, and fruit N concentration was positively correlated with sugars and vitamin components but negatively correlated with organic acids. Phosphorus had a similar directional effect, increasing soluble solids and sugars while decreasing titratable and citric acid through changes in sucrose and citrate metabolism. Mineral imbalance can also shift quality in more complex ways: fruit magnesium was significantly related to both sugars and organic acids, while excess soil copper increased vitamin C and peel color but often reduced the TSS/TA ratio (Mo et al., 2022). For Zhejiang orchards, the observed variation in soluble solids, sugar-acid ratio, and vitamin C is therefore best explained by the combined action of climatic regime and soil-nutrient status rather than by climate alone. In sum, citrus fruit quality in Zhejiang varies across both time and space, with developmental stage determining the trajectory of sugars, acids, and vitamin C, and regional environment shaping the final expression of those traits at harvest.

6 Case Study: Environmental Adaptability and Fruit Quality Responses in a Typical Citrus Orchard in Zhejiang Province

6.1 Study area, experimental design, and environmental monitoring methods

The case-study orchard was selected from a representative citrus-producing area in Zhejiang with a humid

subtropical monsoon climate, where annual heat and rainfall conditions fall within the broader climatic envelope typical of productive citrus regions in southern China. Similar orchard studies in subtropical monsoon zones have used uniform-cultivar commercial orchards to minimize genetic background effects and isolate environmental variation, which is appropriate for a Zhejiang case focused on environmental adaptation and fruit quality responses. In designing the field survey, the orchard can be divided into contrasting microsites or management units according to elevation, slope position, canopy exposure, or irrigation condition, because both topographic heterogeneity and orchard-scale environmental variation are known to alter soil properties and fruit-quality formation. To improve comparability, experimental trees should be similar in age, vigor, and fruit load, and fruits sampled for analysis should be uniform and free from visible disease or mechanical damage, which is consistent with established citrus orchard sampling protocols.

The monitoring framework should integrate meteorological, soil, and fruit observations across the main fruit development period. At the site scale, temperature, relative humidity, rainfall, solar radiation, and vapor pressure conditions are the most relevant climatic variables because they strongly influence fruit growth and final quality across production regions (Onwude et al., 2024). Soil monitoring should include pH, organic matter, moisture, and available nutrients in the main rooting zone, while periodic leaf sampling can be used to evaluate tree nutritional and physiological status. For field implementation, “S”-shaped or multi-point sampling layouts are suitable for capturing within-orchard variability, and soil can be collected from 0-40 cm depth for chemical analysis and moisture assessment. Where conditions permit, real-time monitoring can be strengthened by combining fixed sensors for soil temperature, moisture, and nutrients with remote or digital tools, since IoT-based systems and UAV-based sensing have both been shown to improve the timeliness and spatial precision of orchard environmental assessment (Figure 3).

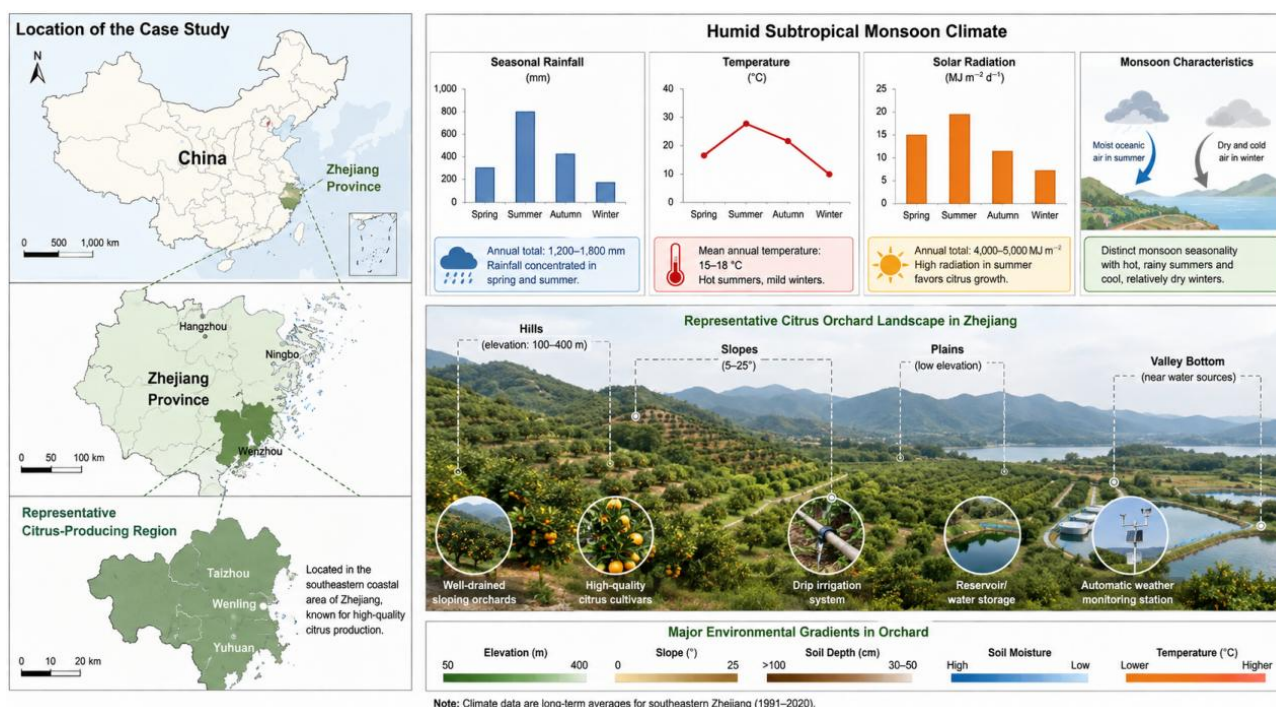


Figure 3 Geographical location and environmental characteristics of the representative citrus orchard case-study area in Zhejiang Province, China

6.2 Citrus growth and fruit quality responses under different environmental conditions

Under different environmental conditions within the orchard, citrus growth responses are expected to appear first in fruit enlargement, canopy physiological activity, and the rate of maturation. Comparative modeling across citrus regions has shown that weather variability alone can significantly change fruit diameter, fruit weight, rind thickness, total soluble solids, titratable acidity, and the Brix/acid ratio at harvest, confirming that even orchards of the same species can produce markedly different fruits under different growth environments (Onwude et al., 2024).

In warm and relatively dry microsites, fruits tend to enlarge faster and accumulate soluble solids more readily, whereas cooler or wetter conditions tend to maintain higher acidity during expansion. During the later maturation period, these differences are further expressed in peel coloration and juice composition, so spatial heterogeneity within a Zhejiang orchard can produce measurable differences in both commercial maturity and eating quality.

Tree physiological responses provide the mechanistic basis for these quality differences. High summer radiation and elevated leaf temperature can suppress photosynthesis in exposed canopy positions through stomatal limitation and photoinhibition, whereas treatments or microsites that lower leaf temperature and improve light distribution can increase stomatal conductance, photosystem efficiency, and final fruit quality (Gullo et al., 2020). Conversely, moderate shade or lower thermal load can improve leaf gas exchange and fruit external color, although in some cases it can slightly reduce soluble solids, showing that the response of quality traits is not always unidirectional. Water conditions also interact with these responses: periods of lower rainfall tend to favor soluble solids accumulation, while excessive rainfall or low cumulative temperature during fruit expansion delays acid decline and slows the improvement of the sugar-acid balance.

6.3 Relationships among environmental factors, tree physiology, and fruit quality and identification of key driving factors

The relationship among environment, tree physiology, and fruit quality in a typical Zhejiang orchard can be analyzed through correlation analysis, principal component analysis, and multivariate regression, using environmental variables as predictors and fruit traits as response variables. This approach has already been used successfully in citrus to quantify how meteorological, topographic, and soil factors together influence fruit quality, and it is especially useful where many drivers interact rather than acting independently. In a Zhejiang case study, response variables should include fruit weight, peel color, soluble solids, titratable acidity, sugar-acid ratio, and vitamin C, while physiological intermediates can include chlorophyll status, stomatal behavior, or leaf nutrient levels. Evidence from orchard-scale PCA further suggests that fruit weight and vitamin C can emerge as major discriminating variables among orchards even when planting conditions are broadly similar, indicating that quality differentiation is often structured by a few dominant traits rather than by uniform change across all indices.

Across existing citrus studies, the key driving factors are unlikely to be purely climatic. Soil-related variables often explain more variation in fruit flavor and shape than topographic or meteorological variables alone, and soil pH, organic matter, and available phosphorus repeatedly appear as important determinants of soluble solids, acidity, and vitamin C. Leaf nutritional status also links environment to fruit performance: long-term orchard surveys found that leaf N, P, K, and molybdenum significantly affected fruit weight and total soluble solids, while leaf phosphorus was closely associated with fruit acidity. At the same time, rootstock-mediated differences in water uptake, nutrient acquisition, and photosynthetic regulation can modify how trees respond to the same environment, so the final quality pattern reflects the combined action of habitat conditions, tree physiology, and plant material (Morales Alfaro et al., 2021). For a typical Zhejiang orchard, the most plausible conclusion is that temperature-moisture regime, soil fertility status, and canopy physiological performance together form the core driver system controlling environmental adaptability and fruit quality variation.

7 Evaluation of Environmental Adaptability and Mechanisms of Fruit Quality Formation in Zhejiang Citrus Orchards

7.1 Development of an evaluation indicator system for citrus environmental adaptability

An evaluation indicator system for citrus environmental adaptability in Zhejiang should combine climatic suitability, site and soil conditions, and management-related resilience indicators rather than relying on temperature alone. Existing adaptability studies commonly use annual mean temperature, accumulated temperature above 10°C, July and January temperatures, annual precipitation, and annual sunshine hours as core climatic inputs, with suitability classified into graded levels from most suitable to unsuitable. This structure is consistent with broader climatic suitability research showing that citrus suitability varies by growth stage and that flower bud differentiation, budding, and fruit maturity are the stages with relatively higher climatic risk, which supports a stage-specific rather than annual-average evaluation framework. For Zhejiang orchards, these climatic

indicators should be integrated with topography, elevation, drainage, and soil properties, because orchard establishment depends on the combined suitability of temperature, light, rainfall, soil texture, fertility, salinity, acidity, and permeability.

A more complete indicator system should also include production efficiency and environmental sustainability dimensions, because environmental adaptability in commercial orchards is expressed not only as survival or yield stability but also as input efficiency and quality consistency. Integrated assessment studies in citrus systems have shown that indicator sets can be organized around productive efficiency, biological regulation, and profitability, with variables such as seasonality, productive diversity, plant health control impact, and efficiency in water, nitrogen, and phosphate use contributing strongly to system performance (Martins et al., 2021). At a wider farm-to-supply-chain scale, multi-indicator frameworks such as LCA and SAFA further show that production, packaging, transport, nitrogen fertilizer use, and land occupation can materially affect environmental performance, although some comprehensive frameworks require adaptation for small and medium citrus farms. For Zhejiang, this means the final adaptability index should be hierarchical: climate suitability as the core layer, soil-site quality as the support layer, and resource-use efficiency, environmental risk, and management standardization as the application layer.

7.2 Interactive effects of environmental factors and mechanisms of fruit quality formation

Fruit quality formation in citrus is a multi-factor process in which climate, soil, and tree physiological regulation act together across development rather than independently. Reviews of citrus maturation emphasize that commercial and nutritional quality are shaped by interactions among light, temperature, rootstock selection, and plant nutrition, which alter both peel and pulp metabolism during maturation (Lado et al., 2018). Recent mechanistic work similarly shows that citrus fruit quality is governed by the interplay of ecological factors such as light, water, and temperature with soil factors, and that management practices influence quality largely by modifying soil pH, organic matter, and nutrient availability. In Zhejiang orchards, this interaction is likely especially important because monsoon rainfall, warm summers, and heterogeneous hill-plain landforms can simultaneously affect canopy microclimate, root-zone conditions, and nutrient uptake.

The mechanism of quality formation can therefore be understood as the coupling of source-sink relations, acid and sugar metabolism, and stress-responsive physiological adjustment. Multi-year field data show that rainfall and thermal accumulation jointly regulate soluble solids and acidity, with low rainfall and high cumulative temperature favoring sugar accumulation while wetter and cooler conditions slow acid decline. High summer heat can become detrimental when it exceeds the adaptive range, because days above 35°C are associated with reduced juice and sugar content and higher organic acids in dry climates. Soil and rhizosphere processes add a second layer of control: available phosphorus, soil pH, organic matter, and microbial community structure have all been linked to fruit weight, soluble solids, vitamin C, and titratable acidity, while some soil environments and microbiomes can promote peel monoterpene accumulation by activating stress-responsive and terpene-synthesis pathways (Su et al., 2023). These findings support a Zhejiang mechanism model in which fruit quality emerges from climate-driven carbon metabolism, soil-mediated nutrient supply, and biologically regulated secondary metabolism acting together.

7.3 Identification of key environmental thresholds and sensitive factors affecting citrus fruit quality

The most sensitive environmental factors affecting citrus fruit quality are temperature, rainfall regime, and diurnal temperature range, but their effects differ by developmental stage and quality trait. A nine-year field study found clear thresholds during early development: rainfall above 220 mm and cumulative temperature below 3 150°C increased titratable acidity, whereas rainfall below 220 mm, cumulative temperature above 3 150°C, and diurnal temperature range above 14°C promoted soluble solids accumulation. During fruit expansion, rainfall above 300-400 mm, cumulative temperature below 2 400°C, and diurnal temperature range below 10°C hindered acidity decline, while rainfall below 100 mm favored soluble solids accumulation. At the broader climatic suitability level, annual precipitation of 1 000-4 000 mm, precipitation in the driest quarter above 100 mm, and a mean temperature of the coldest quarter of 12°C-28°C define the principal environmental envelope for *Citrus reticulata* distribution, giving a useful outer boundary for Zhejiang suitability assessment.

Beyond these climatic thresholds, several sensitive factors strongly modify final fruit quality under orchard conditions. July diurnal temperature range has been identified as the dominant climatic determinant of citrus quality in China, while temperatures and humidity in September to November are more influential for yield during ripening. Soil chemical sensitivity is also evident: elevated soil copper can increase peel color and vitamin C but often lowers the TSS/TA ratio, showing that micronutrient excess can improve some traits while degrading flavor balance. Combined stresses are particularly important under climate change, because multiple concurrent stresses reduce photosynthesis, fruit set, fruit size, and sugar-acid balance more strongly than single stresses (Srivastava et al., 2026). For Zhejiang orchards, the most practical sensitive indicators are therefore summer and autumn thermal conditions, rainfall distribution during expansion and ripening, diurnal temperature range, soil pH and nutrient balance, and stress interactions that alter canopy physiology and fruit metabolic regulation. Overall, environmental adaptability and fruit quality formation in Zhejiang citrus orchards are best evaluated through a multi-layer indicator system that links climatic suitability with soil-site quality and management efficiency. Fruit quality then emerges from the interactive control of thermal, hydrological, nutritional, and biological factors, with several stage-specific thresholds providing a practical basis for orchard zoning and precision management.

8 Environmental Optimization and Fruit Quality Improvement Strategies for Citrus Orchards in Zhejiang

8.1 Soil environment regulation based on integrated water and fertilizer management

For Zhejiang citrus orchards, soil environment regulation should center on integrated water and fertilizer management that matches resource supply to phenological demand while reducing leaching and soil degradation. Evidence across citrus systems shows that optimized water and nitrogen management improves both productivity and fruit quality, while excessive irrigation and fertilization undermine resource efficiency and increase environmental risk. Drip irrigation combined with fertigation is especially useful because it aligns water and nutrients with root uptake, and nutrient-use efficiency under fertigation can reach about 90%, compared with 40%-60% under traditional basin irrigation (Ziogas et al., 2026). For Zhejiang's rainy hilly orchards, this implies that integrated scheduling should prioritize frequent, low-dose application, avoid one-time heavy fertilization, and adjust inputs according to rainfall, soil texture, and tree load rather than following uniform annual formulas.

The practical goal is not maximum input, but a stable rhizosphere environment that supports sugar accumulation, fruit enlargement, and tree vigor. Stage-based optimization studies show that moderate deficit irrigation combined with targeted fertilization can raise soluble sugar and vitamin C while maintaining yield, and precise irrigation-fertilizer thresholds can be defined for different growth stages. Soil-improving amendments can strengthen this system further: under moderate moisture, alginate oligosaccharide application increased yield, soluble sugar, sucrose, root growth, and water and potassium use efficiency while improving soil aggregation and organic carbon status. In addition, integrated soil fertility management that combines inorganic fertilizers with organic inputs and microbial inoculants is increasingly regarded as a climate-resilient path for fruit crops because it supports long-term soil health rather than short-term nutrient supply alone.

8.2 Orchard microclimate optimization through temperature, light, and water management

Microclimate optimization in Zhejiang orchards should focus on reducing summer heat stress, improving canopy light distribution, and stabilizing soil moisture during fruit expansion and ripening. Climate-response studies show that fruit quality is highly sensitive to rainfall, cumulative temperature, and diurnal temperature range: low rainfall and relatively high thermal accumulation favor soluble solids, whereas excessive rainfall and lower temperatures slow acidity decline. This means orchard management should not only supply water, but regulate when and where water is retained. Plastic or reflective mulching can help by modifying soil temperature, water potential, and within-canopy light, thereby improving orchard microenvironment and fruit quality. Under citrus conditions, moderate water deficit combined with high-performance film mulching improved yield, water-use efficiency, and fruit quality, indicating that water-saving strategies are most effective when paired with microclimate regulation rather than used alone (Zhong et al., 2025).

Canopy-level interventions are equally important because climate stress acts directly on leaves, peel coloration, and photosynthetic performance. Reviews on climate adaptation in citriculture identify shade netting, particle

films, automated climate regulation, and precision monitoring as practical tools for reducing excessive radiation and temperature stress while improving soil moisture management. Field evidence further shows that sunscreen protection can mitigate the combined effects of high temperature and water deficit, improving gas exchange, fruit quality, and orchard productivity even under limited irrigation (Santos and Filho, 2024). In parallel, reflective films or related light-management materials can enhance light distribution in the middle and lower canopy and accelerate coloration and ripening, which is especially relevant for dense-canopy orchards in humid eastern China. For Zhejiang, the most effective microclimate strategy is therefore a coordinated package of canopy pruning, reflective or protective surface materials, and regulated irrigation based on real-time monitoring.

8.3 Cultivar selection and adaptive cultivation strategies under climate change

Under climate change, cultivar and rootstock selection will increasingly determine whether Zhejiang orchards can maintain both environmental adaptability and fruit quality. Distribution modeling for *Citrus reticulata* indicates that suitable areas are shaped mainly by annual precipitation, precipitation in the driest quarter, and winter temperature, showing that cultivar deployment should be matched to local hydrothermal niches rather than expanded uniformly. Climate projections for China further suggest that citrus quality in Zhejiang is likely to improve under future conditions, but this advantage will depend on aligning cultivar traits with the region's changing diurnal temperature range and ripening-season climate. As a result, Zhejiang should prioritize cultivar combinations with stable sugar accumulation, peel coloration, and stress tolerance under warmer autumns and more variable rainfall, especially for late-maturing types.

Adaptive cultivation should also include rootstock choice, spatial restructuring, and climate-smart management of orchard systems. Stress-management reviews recommend using drought- and heat-tolerant rootstocks and combining them with nutrient regulation and exogenous biostimulants to maintain water status, reduce oxidative injury, and stabilize productivity under rising temperature and water stress. Broader climate-adaptation frameworks likewise emphasize adjusting citrus phenology, recalibrating inputs, and adopting precision agriculture, tolerant cultivars, and canopy-management systems as core responses to future abiotic stress (Bacelar et al., 2024). Mixed planting may also strengthen resilience in some landscapes, because mixed-species design has been proposed as a way to improve ecological stability and buffer climate risk in *Citrus reticulata* production regions. For Zhejiang orchards, the preferred strategy is therefore not a single resistant variety, but an adaptive production system built on matched cultivars, resilient rootstocks, and flexible management across different ecological zones. Overall, environmental optimization in Zhejiang citrus orchards should integrate soil fertility regulation, microclimate control, and climate-adaptive cultivar deployment. This combined strategy is more likely to improve fruit quality consistently than any single intervention alone.

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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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