

Modeling the Effects of Temperature on Peach Fruit Yield and Quality

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Abstract Peach production is highly sensitive to variations in air temperature; as a critical climatic factor, temperature plays a pivotal role in the phenological development of peach trees, yield formation, and the regulation of fruit quality. Focusing on the mechanisms by which temperature influences peach yield and quality, this paper systematically analyzes its regulatory effects across different growth stages—specifically, the temperature response characteristics observed during bud break and flowering, fruit development, and the ripening process. Building upon this foundation, and by integrating meteorological data with orchard production records, a predictive model for peach yield and quality based on temperature indicators was constructed. This model places particular emphasis on incorporating variables such as accumulated temperature, extreme heat events, and seasonal temperature fluctuations, while employing a hybrid approach that combines statistical analysis with machine learning techniques for modeling and optimization. Through model performance evaluation and sensitivity analysis, key temperature thresholds and dominant factors influencing yield and quality were identified, thereby further elucidating the mechanisms by which heat stress and low-temperature impacts contribute to yield loss and quality deterioration. Case studies demonstrate that the developed model effectively predicts regional trends in peach yield and quality, exhibiting high applicability and stability. The findings of this study provide a theoretical basis for orchard temperature management, variety selection, and disaster risk management; furthermore, they offer technical support for the advancement of precision agriculture and intelligent decision-support systems, holding significant implications for enhancing the climate adaptability and production efficiency of the peach industry.

Keywords Peach yield prediction; Temperature stress; Fruit quality modeling; Growing degree days; Precision agriculture

1 Introduction

Temperature is a primary abiotic factor shaping peach growth, fruit set, and postharvest value, and its role is becoming more critical under ongoing climate change. Experimental warming studies with early- and low-chill cultivars show that moderate increases in temperature can accelerate development and, in some cases, enhance photosynthesis and fruit mass, whereas stronger warming reduces photosynthetic performance, floral bud differentiation, and subsequent yield (Lee et al., 2022). Temperature during fruit development also alters key quality traits—such as size, sweetness, coloration, and firmness—with high temperatures often hastening maturity but compromising desirable attributes like fruit weight and soluble solids content. These responses highlight the need to understand and predict how temperature regimes across seasons and regions translate into changes in both yield and fruit quality.

Despite extensive physiological and agronomic work, quantitative models linking temperature to integrated peach yield and quality outcomes remain limited. Process-based “virtual fruit” models capture fruit mass and sugar dynamics and are sensitive to environmental drivers, yet they often treat temperature only implicitly through generic weather terms rather than explicitly parameterizing its effects on growth and compositional traits. Recent climate-driven phenological and epidemiological models have projected climate-change impacts on peach blooming, disease pressure, and yield losses at national scales, but they primarily target phenology and disease, not detailed fruit quality responses (Lee et al., 2020). As a result, growers and breeders lack predictive tools that jointly represent how intra- and inter-seasonal temperature variability influences both quantitative yield and multiple quality dimensions.

At the same time, emerging statistical and machine learning approaches demonstrate the feasibility of robust peach yield prediction when temperature and other climatic variables are explicitly incorporated. Yield models calibrated on multiyear orchard data in subtropical climates, using inputs such as chilling hours, mean temperature, and leaf nutrient status, have identified chilling and temperature as dominant predictors, with machine learning methods (e.g., Random Forest) outperforming multiple linear regression (Moura-Bueno et al., 2026). Parallel work in subtropical regions using growing degree-days (GDD) to characterize fruit development shows that thermal accumulation strongly differentiates cultivars in terms of fruit size and mass, underscoring the central role of temperature metrics for explaining variability in agronomic performance. However, these data-driven models rarely integrate detailed fruit-quality indicators, and are seldom evaluated under projected future temperature scenarios.

The present study addresses these gaps by developing and testing models that explicitly quantify the effects of temperature on peach fruit yield and quality. Building on controlled-environment and field evidence that high and low temperature regimes differentially affect photosynthesis, growth, and key quality traits, the study formulates the hypothesis that specific temperature indices (e.g., mean temperature, GDD, extreme heat indicators) are systematically associated with both yield components and multi-dimensional quality attributes, and incorporating these indices into statistical and machine learning frameworks significantly improves the prediction of combined yield-quality outcomes compared with models using generic climate covariates. By integrating physiological knowledge with modern modeling techniques, the research aims to identify temperature thresholds and response patterns critical for maintaining yield and quality, compare alternative modeling strategies for capturing these relationships, and provide a transferable framework to support cultivar selection, orchard climate adaptation, and precision management decisions in current and future temperature regimes.

2 Temperature Regulation of Peach Phenology and Fruit Development

2.1 Temperature effects on bud break and flowering dynamics

Bud break and flowering in peach are governed by the interaction of winter chilling and subsequent heat accumulation. Studies across many cultivars show that increasing chilling accumulation generally reduces the heat requirement and days to flowering, but the strength of this chilling-heat trade-off differs with the cultivar's chilling requirement; high-chill genotypes respond strongly to small increases in chilling, whereas low-chill types show weaker reductions in heat requirement (Yan et al., 2024). Classic work demonstrated an exponential decline in heat needed for floral budbreak as chilling increases, with insufficient chilling leading to extended, asymmetric budbreak and greater sensitivity to spring temperature variation.

Across wide climatic gradients, the timing of rest completion and the balance between chill and heat strongly shape bloom dates. Multi-site trials of peach and nectarine in Europe found that in colder sites, rest was completed earlier and bloom time was more tightly controlled by spring heat accumulation, while in warmer sites delayed or incomplete rest made bloom timing more sensitive to winter temperatures (Drogoudi et al., 2023). Long-term modeling shows that warming winters in major peach regions are already reducing chill accumulation, shifting the relative roles of chilling and forcing and complicating the prediction of budbreak and bloom under climate change (Yan et al., 2024).

2.2 Heat accumulation and fruit development rate

After bloom, heat accumulation is a primary driver of fruit development rate and the length of the fruit development period (FDP). Thermal-time models using growing degree hours with cultivar-specific base, optimum, and critical temperatures have been shown to predict harvest dates within 1-4 days across cultivars with FDPs ranging from 70 to 150 days, and are especially accurate when based on heat accumulated in the first 25-52 days after bloom. Analyses of spring temperature effects indicate that high early-season heat (GDH30) accelerates phenological development and shortens the period from full bloom to a reference developmental stage, but can reduce fruit size at that stage because trees cannot supply resources rapidly enough to match the higher growth potential.

Fruit growth response to temperature is stage-dependent. Under controlled conditions, peach fruit developed typical double-sigmoid growth, with higher temperatures (up to 30 °C) increasing growth rates and shortening the duration of early stages (S1-S2), thereby reducing total development time by more than two weeks compared with cooler regimes. However, the same high temperatures slowed late-stage expansion (S3) and reduced final fruit size, weight, and soluble solids, indicating that while elevated temperatures speed development and advance maturity, they can compromise key quality traits if thermal conditions exceed optimal ranges during critical growth phases.

2.3 Temperature stress impacts on reproductive success

Reproductive processes in peach are particularly vulnerable to temperature extremes around bloom. Controlled-environment studies with ‘Hakuho’ showed that constant temperatures of 25°C-30 °C greatly accelerated bud burst and flowering but reduced flower size, impaired embryo sac development, and markedly lowered fruit set, indicating that temperatures above about 25 °C disrupt normal reproductive organ development and fertilization success. Field and greenhouse comparisons in ‘Granada’ revealed that pre-bloom and bloom high temperatures advanced dormancy break and bloom but delayed female gametophyte development, induced anomalies in male gametophytes, and resulted in low pollen viability, poor synchrony of fertilization, and reduced yield.

More detailed analyses of the progamic phase show contrasting temperature sensitivities of male and female functions. Within a moderate range, increasing temperature accelerates pollen germination and pollen tube growth and increases the number of tubes reaching the style base, but simultaneously causes a sharp decline in stigmatic receptivity, first for supporting tube penetration, then germination, and finally pollen adhesion. Additional work comparing cultivars under subtropical fluctuations found that high temperatures (≥ 25 °C) during bloom reduced *in vitro* pollen germination and the proportion of normal pollen grains, with stronger negative impacts on fruit set in ‘Granada’ than in ‘Maciel’, highlighting genotype-specific vulnerability of reproductive success to heat episodes at flowering.

3 Temperature Impacts on Peach Yield Formation Mechanisms

3.1 Growing degree days and yield accumulation relationships

Growing degree-based thermal indices provide a mechanistic link between temperature, developmental timing, and yield formation in peach. In subtropical field conditions, cultivars with higher growing degree day (GDD) requirements during fruit development (“Biuti”) achieved larger fruit size and mass, whereas low-GDD cultivars (“Tropical”) showed smaller fruits, indicating that greater thermal accumulation supports longer growth phases and higher yield potential. Similarly, cultivar comparisons in a sub-temperate Himalayan zone showed that mid- and late-season cultivars requiring 1500-1900 GDD produced higher yields and better quality traits (TSS, sugars) than early cultivars with lower GDD, underscoring that cultivar-specific GDD thresholds structure both yield and quality outcomes.

Process-based and simulation approaches further embed growing degree metrics into yield formation. The PEACH tree growth and yield model uses growing degree hours (GDH) accumulated during the first 30 days after bloom to estimate the length of the fruit growth period; incorporating this GDH-harvest date relationship markedly improved predictions of harvest timing and yield across years and locations compared with earlier degree-day formulations. Empirical analyses of spring temperatures also show that high early GDH accumulation shortens the interval from full bloom to a reference date, increasing instantaneous growth rates but ultimately reducing reference-date fruit size when resource supply cannot keep pace with rapid phenological advancement, demonstrating that thermal time can both promote and constrain yield formation depending on seasonal context.

3.2 Heatwaves and yield reduction mechanisms

Short-term heat stress around harvest exerts distinct and sometimes counterintuitive effects on peach yield formation. A regional analysis for South Korea, using municipal yield data and thermal indicators around the ‘Cheonjungdo Baekdo’ harvest window, found that a higher number of hot days (>30 °C) and elevated minimum temperatures during fruit development significantly increased the probability of low-yield years, implicating

prolonged heat exposure and warm nights in yield reduction. Yet higher maximum temperatures earlier in the growth period were associated with improved productivity, and cumulative heat intensity above 30 °C around harvest showed a negative association with low yield, highlighting complex, stage-dependent responses to heat events.

Controlled-environment experiments reveal physiological mechanisms through which excessive heat depresses fruit yield and size. For the low-chill cultivar ‘KU-PP2’, growth at 30 °C accelerated early fruit expansion and shortened the development period by up to 18 days but substantially reduced final fruit weight and soluble solids compared with 20 °C, effects attributed to diminished photosynthetic capacity under sustained high temperature. Related work on ‘Mihong’ shows that moderate warming (+3.4 °C) can increase photosynthesis, stomatal density, and tree yield, while stronger warming (+5.7 °C) reduces photosynthetic rates and floral bud differentiation, thereby lowering current yield and compromising yield potential in the following year, illustrating how heatwaves that push temperatures beyond optimal thresholds can damage both current and subsequent crops (Lee et al., 2020).

3.3 Seasonal temperature variability and yield stability

Interannual variability in seasonal temperatures modulates both phenology and yield stability in peach orchards. In Moroccan Sais Valley conditions, years with higher temperatures during flowering and fruit growth showed earlier bloom and maturity but significantly lower fruit weight, suggesting that warmer seasons may compress developmental periods and reduce assimilate accumulation per fruit. Long-term observations in a warm Tunisian production area similarly indicate that exceptionally warm winters with low chill accumulation delay and desynchronize flowering, increase bud abscission, and reduce yield and fruit quality when chilling falls below cultivar-specific thresholds, demonstrating that warm-winter anomalies destabilize reproductive success and commercial output.

At broader spatial scales, process-based phenology models that couple chilling, forcing, frost risk, and growing degree days show that climate warming will shift the thermal niche of peach cultivation, with earlier bloom and easier ripening but increasing risk of insufficient winter chill in traditional warm regions. Analysis of historical low-yield events in the U.S. Midwest and Southeast further identifies “false spring” patterns—early GDD accumulation followed by hard freezes—as major drivers of regional peach crop failures, and uses surface temperature thresholds and GDD tracking to build a decision-support tool capable of predicting major yield reductions, emphasizing how seasonal temperature sequences rather than single extremes determine yield stability.

4 Temperature Regulation of Peach Fruit Quality Attributes

4.1 Temperature effects on sugar and acid metabolism

Storage and handling temperature strongly shape sweetness-acidity balance in peach by altering sugar and organic acid metabolism. Non-chilling storage around 12 °C allows normal ripening, maintaining flavor development and preventing chilling injury, whereas storage at 4 °C, although effective at slowing softening, induces off-flavors and increased bitterness linked to the accumulation of specific bitter flavonoids and related metabolites (Muto et al., 2022). Low-temperature stress can also trigger metabolic reprogramming of carbohydrates: during cold storage, sucrose and other soluble sugars often change in parallel with chilling symptoms, reflecting their dual roles as flavor components and stress protectants.

Regulation of sucrose metabolism under cold and temperature-related treatments is central for both flavor and chilling tolerance. Hot-air and methyl jasmonate treatments before storage at 5 °C increased sucrose and sorbitol contents compared with controls, associated with higher sucrose phosphate synthase activity and lower acid invertase activity, suggesting that moderate temperature stress combined with elicitors can maintain sweetness while enhancing chilling resistance (Figure 1). Similarly, salicylic acid pretreatment prior to 4 °C storage raised total soluble sugars, largely via sucrose accumulation, and modified expression of sucrose-related genes, while simultaneously activating cold-response transcription factors and reducing internal browning, indicating that temperature-driven sugar metabolism is tightly coupled to stress signaling and quality preservation.

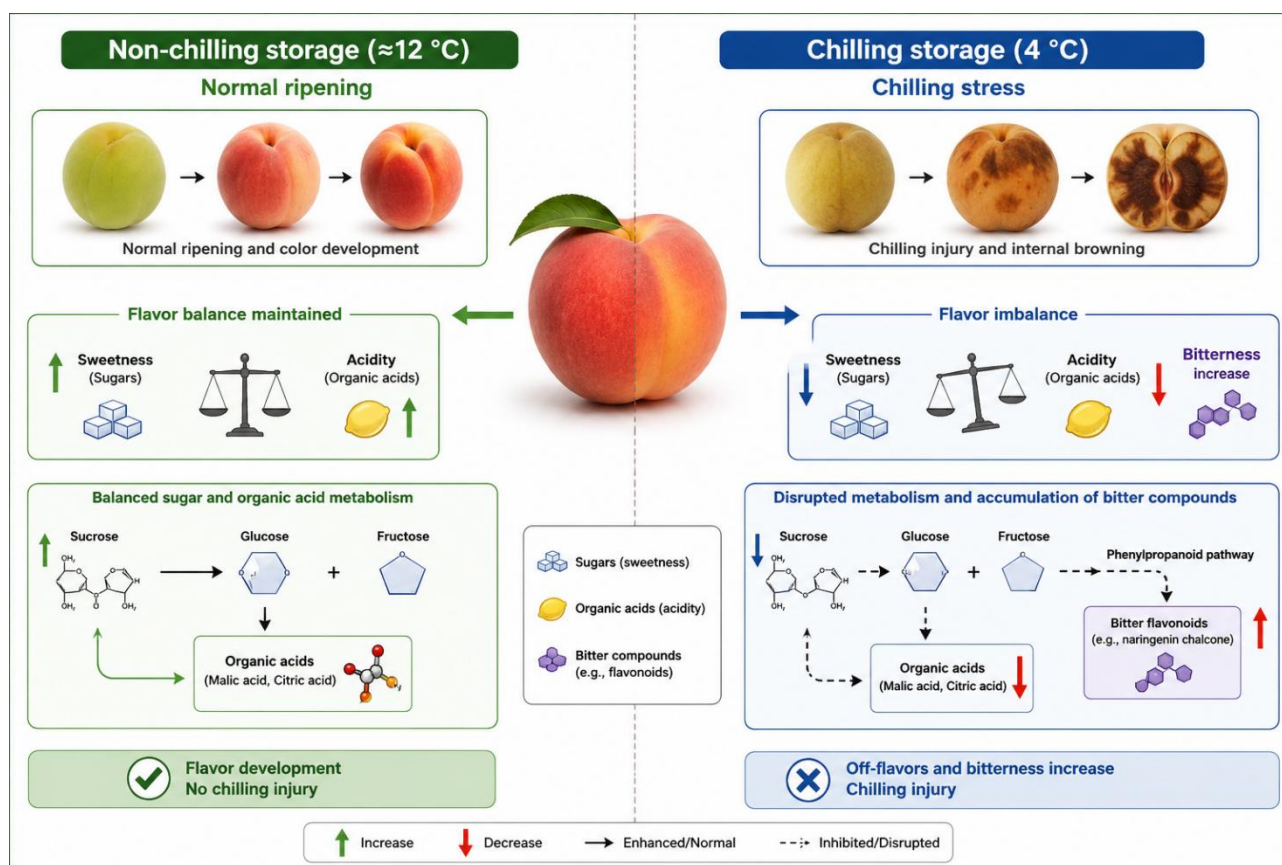


Figure 1 Effects of storage temperature on flavor balance and metabolic regulation in peach fruit

4.2 Influence on fruit size, firmness, and texture

Temperature during on-tree development controls final size and basic texture attributes. In controlled environments, increasing growth temperature from 20 °C to 30 °C accelerated early fruit expansion and shortened the development period but reduced final fruit weight, size, and sweetness, indicating that high developmental temperatures hasten maturity at the expense of key quality traits. Under projected climate-change scenarios with elevated CO₂, moderate warming (+3.4 °C) increased photosynthesis, carbohydrate content, and fruit weight, whereas stronger warming (+5.7 °C) decreased photosynthetic performance and was associated with poorer physiological status and reduced fruit quality in the subsequent year, emphasizing that beneficial temperature windows are narrow (Lee et al., 2022).

Postharvest temperature interacts with cell wall metabolism to determine firmness and textural defects. In stony-hard peaches, storage at intermediate temperatures (8°C-15 °C) induced substantial softening and strong expression of a polygalacturonase gene, whereas storage at 0 °C or 20 °C for extended periods prevented subsequent softening at 10 °C, suggesting that specific temperature ranges activate pectin-degrading machinery independently of ethylene (Tatsuki et al., 2021). Conversely, in melting-flesh peaches, low-temperature storage at 6 °C, compared with 25 °C, inhibited softening by maintaining cell wall integrity: low temperature reduced the accumulation of water- and ion-soluble pectin and suppressed activities and expression of polygalacturonase, pectate lyase, and pectin methylesterase, effects linked to cold-induced CBF transcription factors that repress pectin-degradation genes (Guo et al., 2026).

4.3 Temperature-driven changes in aroma and phytochemicals

Aroma and phytochemical profiles of peach are highly temperature-dependent during storage and ripening. Cold storage at 1 °C for 7 d significantly affected firmness, acidity, phenolics, vitamin C, and carotenoids across cultivars, with some sensory attributes (bitterness, astringency, crunchiness) increasing as firmness and acidity rose, while perceived harmony and sweetness were more closely related to °Brix, β-carotene, and specific volatiles than to simple acidity measures (Muto et al., 2022). In another study, low-temperature storage at 0.5 °C

and 5.5 °C increased aldehydes and alcohols during storage but shifted ester and lactone evolution to subsequent shelf life, with cultivar differences in chilling injury linked to differential accumulation of antioxidants and osmoprotectants such as sorbitol, putrescine, and phenolics (Brizzolara et al., 2018).

Moderately low temperatures during ripening can enhance phenolic accumulation and modify volatile pathways in the field. For a protected-origin peach, correlation analyses showed that cooler ripening conditions were associated with higher levels of phenolic compounds, particularly flavonoids and anthocyanins, while expression of a lipoxygenase gene (PpLOX1) co-varied with climate variables and LOX-derived volatiles, indicating coordinated temperature regulation of antioxidant and aroma biosynthesis. Under postharvest cold storage at 0 °C, controlled-atmosphere conditions improved sensory quality by reducing internal browning and retaining higher levels of esters and lactones; several LOX-pathway volatiles and associated biosynthetic genes were positively correlated with consumer acceptability, underscoring how temperature-atmosphere regimes modulate both aroma and perceived eating quality (Liu et al., 2022).

5 Construction of Temperature-Based Peach Yield and Quality Models

5.1 Selection of temperature indicators and feature engineering

Constructing temperature-based models for peach yield and quality begins with identifying thermal indicators that best capture phenology and fruit development. Reviews of temperature indices in temperate fruit production emphasize chill units, growing degree days (GDD), and growing degree hours (GDH) as core descriptors for dormancy release, flowering, and development, together with indices for extreme events such as frost and heat stress. In subtropical peach orchards, cultivar comparisons show that GDD accumulation during fruit development is closely linked with fruit size and mass, with higher GDD requirements associated with larger fruit, guiding the choice of development-stage-specific thermal sums as model inputs.

Feature engineering must also reflect cultivar-specific thresholds and the timing of thermal exposure. Nonlinear GDH models that incorporate base, optimum, and critical temperatures predict harvest dates within 1-4 days for cultivars with very different fruit development periods, illustrating the value of calibrated, cultivar-dependent heat-response parameters. Phenological work in sub-temperate regions further demonstrates that GDD from dormancy break to harvest differentiates early, mid, and late cultivars and is strongly associated with yield and sugar content, suggesting that cumulative heat over well-defined BBCH stages can be transformed into compact, phenology-anchored predictors for yield and quality models.

5.2 Integration of physiological and meteorological data

Accurate temperature-based models require integrating meteorological variables with physiological or structural indicators of tree status. A multi-year study on ‘Esmeralda’ peach combined meteorological indices (chilling hours, GDD, rainfall) with foliar mineral composition and previous-season yield, showing that chilling hours and GDD dominated feature rankings for yield and several quality traits, while leaf nutrients and carryover effects refined predictions (Nava et al., 2022). Similarly, a peach yield prediction study using 208 trees under subtropical climates found that hours of chilling and mean temperature, together with leaf K and N, were the most relevant predictors of yield in machine learning models, highlighting the importance of jointly representing climate and plant nutritional status (Moura-Bueno et al., 2026).

Physiological integration is also needed to capture how temperature affects photosynthesis and fruit growth potential. Controlled phytotron experiments on the early cultivar ‘Mihong’ under elevated temperatures and high CO₂ showed that moderate warming (+3.4 °C) increased photosynthetic rate, fruit weight, and carbohydrate content, whereas stronger warming (+5.7 °C) reduced photosynthesis, floral bud differentiation, and expected subsequent yield (Figure 2) (Lee et al., 2022). Temperature-controlled studies on ‘KU-PP2’ similarly demonstrated that higher growth temperatures accelerate early fruit expansion but reduce final fruit size and sweetness at 30°C, implying that model inputs should include not only simple thermal sums but also phase-specific temperature descriptors linked to physiological processes such as photosynthetic capacity and source-sink balance.

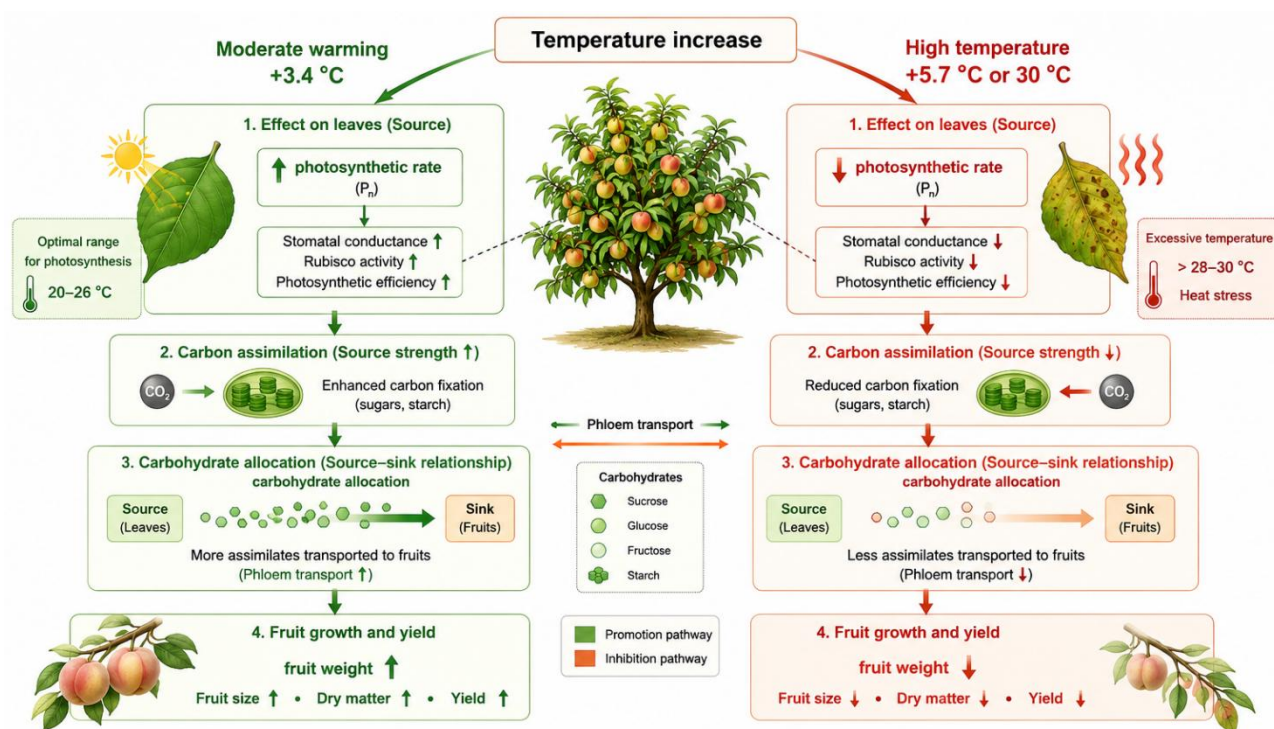


Figure 2 Effects of temperature variation on photosynthesis and source-sink dynamics in peach trees under controlled environments

5.3 Development of statistical and machine learning models

Once temperature indicators and physiological covariates are defined, they can be embedded in statistical and machine learning frameworks. For bud and bloom phenology, models combining chill accumulation (Dynamic model) with growing degree sums have predicted bud development stages across major Spanish peach regions with errors of about four days, outperforming forcing-only models and providing physiologically consistent thresholds for chill and heat. At finer scales, chill-heat models for individual cultivars have been fitted using sequential chill and GDH accumulation to estimate budbreak timing, offering simple yet robust tools for linking winter-spring temperatures to the onset of reproductive development (Cifuentes-Carvajal et al., 2023).

For yield-focused modeling, multivariate machine learning approaches appear especially promising. In ‘Esmeralda’ peach, k-nearest neighbors and stochastic gradient descent models trained on meteorological indices, foliar nutrients, and prior yield achieved accuracies up to 1.00 for several yield and quality indices, with chilling hours and degree-days emerging as top-ranked features (Nava et al., 2022). A broader yield prediction study comparing Random Forest, multiple linear regression, and support vector machines found that Random Forest provided the best performance, and identified hours of chilling, leaf K and N, and mean temperature as the most influential variables, confirming that nonlinear ML models can effectively learn complex temperature-nutrition-yield relationships when supported by well-engineered temperature indicators (Moura-Bueno et al., 2026).

6 Evaluation and Optimization of Temperature-Driven Prediction Models

6.1 Model performance comparison and selection

Evaluation of temperature-driven peach yield and quality models requires systematic comparison of alternative model structures and learning algorithms. For peach yield, a study comparing Random Forest, Multiple Linear Regression, and Support Vector Machine found that Random Forest achieved the highest predictive accuracy when using climatic, soil, and leaf nutrient data, with chilling hours and mean temperature among the most influential predictors (Moura-Bueno et al., 2026). Similarly, temperature-based phenology models for peach bloom (developmental rate, chill day, and new chill day models) were assessed with MAPE, R^2 , and RMSE, and the new chill day model provided the best compromise between bias and precision across cultivars and sites, illustrating the value of multi-metric model comparison for temperature-driven processes.

Beyond peach, crop modeling research highlights the need to balance accuracy and interpretability when selecting prediction models. An interaction regression framework for corn and soybean yielded lower relative RMSE than state-of-the-art machine learning methods while explicitly decomposing yield into contributions from weather, soil, and management, demonstrating that carefully regularized regression with interaction selection can outperform black-box models and provide mechanistic insight on temperature effects (Ansarifar et al., 2021). Phenology-guided deep learning for soybean showed that incorporating heat-related predictors and phenological-stage windows in a Bayesian CNN architecture substantially improved yield prediction relative to benchmark models, underscoring that model choice should reflect both temperature process representation and the temporal structure of response variables (Zhang and Diao, 2023).

6.2 Error decomposition and robustness testing

For temperature-driven crop models, decomposing prediction errors helps clarify limitations in both structure and parameterization. In a grapevine phenology-yield model calibrated with a frequentist framework, the joint objective function based on normalized RMSE revealed that no single parameter vector minimized errors for both phenology and yield simultaneously, and yield RMSE exhibited much larger spread than phenology RMSE, indicating structural or parameter constraints in capturing yield responses to weather variability (Yang et al., 2024). Follow-up uncertainty analysis showed that fruit-setting parameters were the dominant contributors to yield prediction variability, illustrating how error decomposition can pinpoint biologically meaningful leverage points for improving reproductive and yield submodels.

Robustness of phenology and yield simulations to temperature extremes and calibration data coverage has been explicitly tested in multi-model rice phenology assessments. Using six model structures and leave-one-out cross-validation, regional simulations of maturity dates achieved RMSE of 2-4 days, but evaluation errors were larger than calibration errors, especially in areas with frequent high-temperature episodes, where divergent model responses increased structural uncertainty. Decomposition of total uncertainty into parameter and structural components showed that parameter variability dominated overall uncertainty in most regions, except in high-temperature zones where structural differences in temperature response functions were more important, emphasizing that robustness testing must consider both parameter and model-form uncertainties across temperature regimes.

6.3 Sensitivity and uncertainty analysis of temperature variables

Sensitivity and uncertainty analyses provide a quantitative basis for prioritizing temperature-related variables and parameters in peach yield and quality models. Global sensitivity analysis of a fertigation crop model (HORTSYST) using Sobol indices identified nine key parameters-including minimum and maximum optimal temperatures and radiation-use efficiency-as most influential on photo-thermal time, dry matter production, and transpiration, guiding calibration toward the subset of parameters that control temperature and radiation responses. In the same framework, parameters showed stage-dependent importance, with more parameters affecting outputs early in fruiting than late in the season, suggesting that temperature sensitivities should be evaluated for specific phenological windows when modeling fruit crops.

Other dynamic crop models combine variance-based sensitivity analysis with uncertainty propagation to understand climate effects on yield. For *Lycium barbarum* in WOFOST, Morris and extended FAST methods demonstrated that parameters related to CO₂ assimilation, leaf area expansion, and thermal time during specific periods had the largest impact on simulated yield, and sensitivity rankings were consistent across climate sites, supporting the transferability of temperature- and development-related parameter priors across regions. A similar strategy in a grapevine soil-plant-atmosphere model quantified prediction uncertainty as the spread of nRMSE across hundreds of thousands of parameter vectors, then used parameter-wise reductions in uncertainty to identify those most responsible for yield and phenology variance, providing a template for implementing global sensitivity and uncertainty analysis in peach temperature-yield-quality models.

7 Identification of Critical Temperature Thresholds in Peach Production

7.1 Optimal temperature ranges for key growth stages

Critical temperature thresholds for vegetative and reproductive development can be described using basal (minimum and maximum) temperatures and thermal sums for successive phenological phases. For 14 peach and one nectarine cultivar, minimum basal temperatures of about 8°C-10 °C were identified for pruning-sprouting and sprouting-flowering, 12°C-14 °C for flowering-fruiting, and 12°C-14 °C for ripening, while maximum basal temperatures were about 28°C-34 °C depending on the phase. These values imply that temperatures below phase-specific bases do not contribute to development, whereas temperatures above the upper limits do not further accelerate progress and may predispose to stress, providing practical bounds for “effective” temperature ranges during each stage.

Thermal-time models further refine optimal temperature concepts by combining cultivar-specific base, optimum, and critical temperatures. A non-linear growing degree hour (GDH) model using a base of 7.5 °C, an optimum of 26 °C, and a critical temperature of 38.5 °C accurately predicted harvest dates (1-4 d error) for cultivars with fruit development periods from 70 to 150 d, and an early forecast could be obtained from GDH accumulated in the first 25-52 d after bloom. Together, these results indicate that peach development proceeds most efficiently within a broad band from the low teens up to the mid-20s °C, with diminishing or saturating developmental gains as temperatures approach the upper 20s and mid-30s °C.

7.2 High-temperature stress thresholds and yield loss

Experimental warming under future-climate CO₂ has clarified high-temperature thresholds for physiological decline. For ‘Mihong’, a modest rise of +3.4 °C above local averages (with 700 μmol/mol CO₂) increased photosynthetic rate, carbohydrate content, and fruit weight, whereas a +5.7 °C scenario reduced photosynthesis, caused chlorophyll loss, decreased floral bud differentiation, and lowered floral bud density, leading to expected yield reduction in the following year (Lee et al., 2022). These responses suggest that warming within roughly +3-4 °C may still fall within an expanded “optimal” window, while sustained warming approaching +6 °C crosses a physiological threshold where vegetative dominance and early defoliation compromise reproductive potential.

At the orchard and regional scale, heat indicators around harvest identify damaging thresholds for yield. In South Korea, a logistic model using municipal yield data showed that a higher number of days above 30 °C and elevated minimum temperatures during fruit development significantly increased the probability of low-yield years, although higher maximum temperatures earlier in the growth period were linked to improved productivity. The positive association between counts of >30 °C days and low yield, combined with the experimental evidence of performance declines near +6 °C warming, indicates that both the intensity and persistence of temperatures above about 30 °C define critical stress thresholds for peach yield formation.

7.3 Low-temperature injury and recovery mechanisms

On the cold side, storage temperature tightly controls the onset of chilling injury (CI) symptoms and associated membrane damage. During postharvest storage, peaches kept at 4 °C rapidly developed CI, with enhanced expression of membrane lipid metabolism genes, accumulation of phosphatidic acid, and shifts in diacylglycerol and triacylglycerol profiles, whereas storage at 0 °C delayed CI by maintaining higher levels of phospholipids and promoting fatty acid desaturation and unsaturation. These findings indicate that, paradoxically, “moderate” low temperatures around 4 °C may be more injurious than near-freezing 0 °C, and that maintenance of unsaturated membrane lipids is a key protective mechanism at very low temperatures.

Pre-storage conditioning and acclimation treatments define additional functional thresholds for cold tolerance and recovery. Low temperature conditioning at 8 °C for 5 d before 0 °C storage increased ethylene production, accelerated softening, reduced internal browning, and led to higher fatty acid content, desaturation, and phospholipid levels compared with constant 0 °C storage (Song et al., 2022). Similarly, priming ‘June Gold’ fruit for 48 h at 20 °C before 40 d at 0 °C suppressed CI symptoms relative to fruit transferred directly to 0 °C, with distinct proteomic and metabolomic signatures indicating altered cold responses and a possible role for

branched-chain amino acids in tolerance. Collectively, these studies show that both the absolute low temperature (0°C vs 4°C) and short exposures to intermediate “priming” temperatures (8°C-20 °C) critically determine whether cold acts as damaging stress or as a signal that triggers protective acclimation pathways.

8 Case Study on Temperature-Driven Yield and Quality Variations in Peach Orchards

8.1 Study area climate and orchard characteristics

The case study focuses on subtropical orchards in southern Brazil, where ‘Maciel’ and ‘Chimarrita’ peaches are grown under contrasting microclimates but broadly similar humid subtropical conditions with variable winter chill and warm springs. A database of 208 trees captured spatial variation in soil properties, leaf nutrient status, and localized weather, allowing climate variables such as chilling hours and mean temperature to be related to yield at tree scale (Moura-Bueno et al., 2026). In parallel, field work in Brazilian subtropical regions characterized fruit development of four cultivars across the season, using growing degree days (GDD) to describe the temperature regime governing fruit growth and size.

These subtropical environments are characterized by relatively mild winters that can constrain chill accumulation and by warm, often rapidly heating, springs and summers that drive fast GDD accumulation (Moura-Bueno et al., 2026). Under these conditions, cultivars such as ‘Tropical’ require lower GDD and produce smaller, lighter fruit, whereas ‘Biuti’ demands higher GDD and attains larger size, illustrating how local thermal regimes interact with genotype to shape orchard yield potential and quality profiles. Such climate-cultivar interactions frame the design of temperature-driven prediction models in the study area.

8.2 Application of temperature-based predictive models

In the Brazilian orchards, peach yield was modeled by combining climatic indicators with tree- and soil-level covariates. Random Forest, Multiple Linear Regression, and Support Vector Machine were trained using hours of chilling, mean temperature, and leaf and soil nutrient data; Random Forest gave the highest predictive performance, and chilling hours emerged as the single most relevant predictor of yield, followed by leaf K and N and mean temperature (Moura-Bueno et al., 2026). This structure embeds temperature both as a direct driver (chill and in-season means) and as a proxy for longer-term site suitability, while allowing nonlinear effects and interactions (Figure 3).

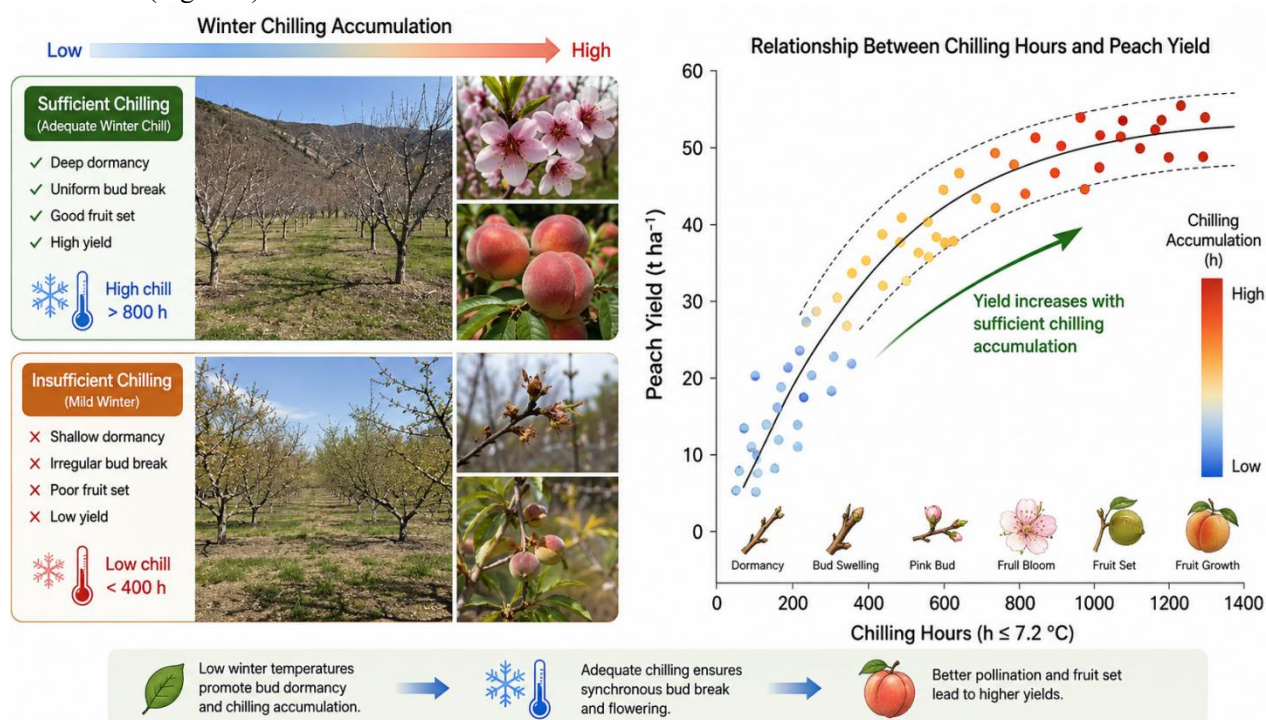


Figure 3 Relationship between winter chilling accumulation and peach yield performance in Brazilian orchards

Complementing these tree-scale models, a regional decision-support tool was developed for the U.S. Midwest and Southeast to anticipate major yield reductions from false springs, using accumulated growing degree days (GDD7.2) and minimum temperatures during freeze events. For each region, an “envelope” curve relating GDD to critical minimum temperature was derived from historical low-yield years; stations falling below this envelope in a given season were classified at risk of major peach yield loss. This approach illustrates how simple temperature-based indicators can be operationalized for risk forecasting at regional scale.

8.3 Validation of predicted yield and quality against observations

Validation of the Brazilian machine learning models used independent data from the same orchards, confirming that Random Forest calibrated with climatic, soil, and foliar variables could reproduce observed yield variation with high accuracy, while simpler linear models underperformed, especially when only a subset of predictors was used. Feature-importance analysis aligned with agronomic expectations-emphasizing chilling hours and mean temperature-supporting both statistical and physiological credibility of the fitted relationships (Moura-Bueno et al., 2026). At the quality level, comparisons among subtropical cultivars showed that modeled GDD-based development patterns were consistent with observed differences in fruit size and mass between low- and high-GDD genotypes, strengthening the case for GDD as a robust explanatory variable for quality-related traits .

For the regional false-spring tool, validation against historical high-yield years demonstrated that the GDD-minimum-temperature envelope correctly identified non-damaging seasons in all sampled years for the Midwest and in 75% of high-yield years for the Southeast, indicating strong but regionally variable skill (Chun and Changnon, 2018). Application to the 2017 false spring showed that the tool successfully anticipated widespread yield reductions in the Southeast while correctly indicating lower risk in much of the Midwest, when observed production data were later examined. Together, these evaluations show that temperature-driven models can achieve useful predictive power for both yield level and catastrophic loss when carefully calibrated to local climate and production systems.

9 Development of Climate-Resilient Peach Production Strategies

Climate-resilient orchard management increasingly focuses on mitigating insufficient winter chill and buffering trees against temperature extremes. In the southeastern United States, anthropogenic warming has already reduced winter chill, increased the probability of low-chill winters, and raised the risk of insufficient chill for moderate- and high-chill cultivars, prompting consideration of adaptive practices such as overhead irrigation for evaporative cooling, vigor control to lower chill needs, and site selection in cooler microclimates. In warm-winter regions like Israel, additional physical strategies-including shading, branch bending, and sprinkling to reduce daytime temperature-are proposed to compensate partially for chill deficits and reduce abnormal bud development and low fruit set under heat spells.

Postharvest temperature management is another critical component of climate-resilient peach systems. Poorly controlled cold chains with repeated temperature spikes to 15°C-20 °C sharply increase ethylene production, accelerate softening, and reduce phenolics, flavonoids, and antioxidant enzyme activities, whereas limiting fluctuations to around 10 °C has little impact on quality, delineating operational thresholds for transport and storage. Reviews of cold-stress physiology emphasize that careful management of storage and transport temperatures, combined with early, preferably non-destructive monitoring tools for chilling injury, is essential to safeguard fruit quality as supply chains lengthen and temperature variability increases.

Climate-resilient production depends strongly on matching cultivar chilling and heat requirements to warming agroclimates. Multi-site analyses across Tunisia and Europe show wide genotypic variation in peach chilling (≈ 20 -63 Chill Portions) and heat requirements (≈ 4381 -6556 GDH), with warm mean temperatures during the chilling period emerging as key drivers of flowering, providing a quantitative basis for selecting cultivars adapted to warm regions. Under mild Moroccan conditions, grouping cultivars by chill/heat needs and flowering time identified low- to medium-chill types as more suitable under climate change, while cultivars like ‘Summer Lady’ showed lower sensitivity to bud and fruit drop during warm autumns and chill deficits, making them strategic genetic resources (Borgini et al., 2024).

Cold-tolerance screening complements agroclimatic matching in regions facing severe winter freezes. In Gansu, China, evaluation of 28 local germplasms identified large variation in semi-lethal temperature (LT₅₀, -28.22 to -17.22 °C), with the highly resistant ‘Dingjiaba Liguang Tao’ showing the lowest LT₅₀ and strong associations between cold hardiness and soluble sugars, proteins, proline, and xylem and cork anatomy. A separate comprehensive evaluation under -5°C to -35 °C stress similarly highlighted cultivars such as ‘Ziyan Ruiyang’ and ‘Ganlu Shumi’ with low LT₅₀, high membership scores, and good field survival, providing robust parents for breeding new cold-resistant varieties and expanding resilient cultivar portfolios.

Intelligent monitoring and control systems offer powerful tools to manage orchard microclimates under increasing thermal stress. An IoT-based “smart orchard” architecture using multi-sensors (air and soil temperature, humidity, light, rainfall, wind) and LoRa transmission demonstrated reliable environmental monitoring in peach orchards with complex terrain, enabling remote supervision and providing the data backbone for temperature-focused decision support. A related multi-parameter orchard system couples sensor data to actuators (fans, pumps, LEDs, alarms) and a cloud platform + mobile interface, allowing threshold-based, remote control of the microclimate that stabilized yields, improved fruit quality, and reduced labor costs through more precise environmental regulation.

Downstream in the supply chain, AI-based decision support can optimize temperature management for quality preservation. An artificial neural network system trained on commercial cold-room data predicts the evolution of hardness, soluble solids, and acidity as functions of storage temperature, relative humidity, and time, thereby estimating optimal commercialization windows and suggesting pre-cooling setpoints that maximize the period of peak consumer-perceived quality. Insights from virtual cold-chain experiments, which identify tolerable versus harmful temperature excursions, can be integrated into such DSS tools to define safe fluctuation ranges and reduce waste while maintaining high-quality fruit delivery.

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