

increased HSF and HSP expression. Under chilling, tomato appears to use more than the classical CBF route alone: SIGRAS4 promotes chilling tolerance by directly activating many cold-response targets and SICBF promoters, while functioning as a distinct regulon that operates independently of the ICE1-CBF pathway (Liu et al., 2020).

6.3 Molecular regulation of temperature-responsive genes

Temperature-responsive gene regulation in tomato combines conserved stress modules with substantial genotype- and tissue-specific variation. In seedlings, most heat stress transcription factors and HSP genes respond similarly across genotypes, but hormone- and RNA-related regulators such as HsfA6b show differential expression associated with thermotolerance (Hu et al., 2020). In reproductive tissues, heat-stressed microspores upregulate small HSPs, HSP70, HSP90, HSFA2, and HSFA3, while tolerant microspores show higher basal expression of several protective genes before stress, consistent with a primed thermotolerance state (Frank et al., 2009).

Recent genomic studies show that these responses are organized into complex regulatory networks rather than isolated genes. In tomato flower buds, co-expression analysis under heat identified novel HSR-related transcription factors such as SIWRKY75, SIMYB117, and SINAM, and experimentally validated HSF-regulated targets including SIGrpE, SIERDJ3A, SITIL, and SIPOM1 (Li et al., 2023). Genetic mapping and transcriptomics further indicate that heat tolerance is polygenic, with major QTL regions enriched for plant hormone signaling, MAPK signaling, sugar metabolism, and fatty acid metabolism, and with tolerant genotypes showing more gene upregulation than sensitive genotypes under heat stress.

7 Case Study: Effects of Temperature Regulation Strategies on Greenhouse Tomato Production

7.1 Experimental background and temperature management treatments

Recent greenhouse case studies have tested temperature regulation through both structural control and targeted thermal treatments rather than by relying on ambient protection alone. In commercial and research settings, treatments included multi-point canopy monitoring to detect spatial thermal gradients, geothermal pipe heating with water temperatures of 25°C, 35°C, and 45°C against an unheated control, and comparisons between regulated greenhouse environments and more variable open-field conditions (Ouyang et al., 2022; Šalagovič et al., 2024). These designs reflect a common experimental logic: quantify how precisely managed air or root-zone temperature modifies crop performance relative to uncontrolled or weakly controlled systems.

Other studies used dynamic or stage-specific strategies that more closely resemble practical greenhouse decision-making. A low pre-night temperature integration strategy imposed 9.4°C, 11.3°C, 13.3°C, and 15.1°C pulses for the first 3 h of the night while keeping the same 24-h mean temperature, whereas root-zone regulation trials combined daytime air temperatures of 20°C, 25°C, 30°C, and 35°C with root-zone settings of 15°C, 20°C, 25°C, and 30°C to identify efficient combinations for early growth (Ju et al., 2023). Additional greenhouse studies also evaluated heat mitigation through micro-spray plus drip irrigation, and precision control through sensor placement near the ground, canopy, and roof, showing that temperature management treatments increasingly integrate climate control with real-time monitoring and automated adjustment (Figure 2) (Xue et al., 2023; Zhang et al., 2024).

7.2 Effects of temperature regulation on growth and physiological responses

Temperature regulation consistently altered vegetative growth and physiological activity in greenhouse tomatoes. Soil warming significantly affected plant height, leaf area index, assimilation rate, leaf temperature, chlorophyll, and dry matter accumulation, and across two years the strongest treatment ranked T3 > T2 > T1 > control for most growth and physiological indicators (Ouyang et al., 2022). Root-zone regulation produced similarly clear effects during early growth, with 20°C-25°C root-zone settings generally supporting favorable crop growth rate and relative growth rate across several air temperature regimes (Ju et al., 2023).

Heat mitigation strategies also improved physiological resilience when greenhouse temperatures became excessive. Under high-temperature greenhouse conditions, micro-spray reduced average daily air temperature by about 0.76°C-0.8°C and leaf temperature by 4.6°C-4.9°C, while increasing photosynthetic rate, PSII efficiency,