control greenhouses show decreased stem diameter, plant height and fresh weight, elevated electrolyte leakage, lower relative water content, reduced photosynthetic efficiency and increased malondialdehyde, together with accumulation of phenolics, flavonoids and lycopene, consistent with membrane damage and activation of antioxidant defenses under chronic heat (Sellami and Kooli, 2026).

At the reproductive level, moderate but sustained temperature elevation during a critical pre-anthesis window disrupts specific metabolic processes in the androecium. Under 32 °C/26 °C, androecial glucose and fructose decline while sucrose increases, coinciding with reduced acid invertase transcript abundance, altered sugar metabolism and sharply reduced fruit set despite unchanged pollen production. Proline transporter expression on the microspore surface also falls under these conditions, suggesting impaired osmoprotection and turgor regulation in developing pollen. Conversely, screening of contrasting genotypes under high temperature in greenhouses reveals that tolerant cultivars can maintain fruit weight or even improve fruit hardness, whereas susceptible ones show large decreases in fruit size components, highlighting genotypic differences in maintaining reproductive function and fruit quality under heat (Rajametov et al., 2021).

Low temperature stress in greenhouse tomatoes also induces multi-level responses affecting both vegetative and reproductive stages. Reviews of cold responses report delayed flowering, enhanced pollen sterility and strong reductions in fruit set and yield, alongside decreased photosynthetic capacity due to impaired gas exchange, pigment content and chloroplast function (Yadav et al., 2021). Detailed analyses of sub-optimal day/night temperatures show that sensitive cultivars display greater declines in Fv/Fm, photochemical quenching and biomass than tolerant ones, while tolerant genotypes maintain higher levels of osmolytes such as soluble sugars and proline that support ROS scavenging and membrane stability. At the root level, exposure to low root-zone temperature (around 10 °C) reduces root activity, water and nutrient supply to shoots, lowers photosynthesis and chlorophyll fluorescence, and triggers accumulation of hydrogen peroxide, malondialdehyde and proline; only partial recovery occurs after re-warming, indicating lasting damage to the photosynthetic apparatus and growth potential (Zhang et al., 2023). Collectively, these mechanisms explain why both heat and cold episodes in greenhouses can depress tomato yield and underscore the importance of modelling temperature effects across this full stress spectrum.

3 Greenhouse Environmental Characteristics and Temperature Dynamics

3.1 Temperature distribution and microclimate formation in facilities

Air temperature in greenhouses is far from uniform, even when a single central sensor suggests a stable “bulk” climate. Multi-year monitoring in commercial tomato greenhouses has revealed horizontal gradients of up to about 3 °C in daily average temperature and 0.6 kPa in vapour pressure deficit (VPD), driven by structure, airflow patterns, and crop canopy (Šalagovič et al., 2024). These small but persistent differences translated into measurable variability in stem growth, fruit growth rate, and truss mass between locations, indicating that microclimate heterogeneity can meaningfully affect yield. Similar work in single- and multi-span houses reported horizontal temperature differences on the order of 1 °C between center and sides, confirming that assumptions of homogeneous air conditions are unrealistic for modern structures and should be revisited in energy and climate calculations (Ogunlowo et al., 2021).

Vertical stratification further complicates the thermal environment, particularly in tall or large-span facilities. A combined experimental-numerical study in a plastic greenhouse found that air near the roof could be more than 13 °C warmer than air lower in the crop zone at midday, with much smaller differences in the morning (Li et al., 2024). Computational fluid dynamics simulations that explicitly account for crop transpiration and optical effects show that plant canopies can increase temperature standard deviation by more than 30% compared with bare-structure assumptions, and that the hottest air often resides just below the roof where solar gains concentrate (Xu et al., 2022). Field studies in low-automation Mediterranean tomato houses report horizontal differences up to 7 °C-10 °C at certain times, highlighting how limited ventilation and solar load interact to create spatially complex microclimates that challenge single-point monitoring strategies.