

3.2 Effects on plant morphology and biomass accumulation

Temperature regulation also reshapes tomato morphology during vegetative growth, often by altering elongation patterns, leaf traits, and whole-plant partitioning. Seedlings developed at 28.5°C and 31.5°C showed significant hypocotyl elongation, while stronger heat exposure caused more severe visible injury, including chlorosis, leaf wilting, and stem bending in both seedlings and adult plants (Tokić et al., 2023). Under greenhouse lighting systems with different thermal properties, warmer leaf conditions were associated with thinner and smaller leaves and with a higher fraction of biomass allocated to vegetative tissues, indicating that temperature interacts with canopy energy balance to shape plant form and dry-matter distribution.

Biomass accumulation responds to temperature in a more complex way than morphology because higher temperature can stimulate growth processes while reducing final dry matter if respiratory or assimilate costs become too high. In growth-chamber experiments, a daily mean temperature of 30°C increased relative growth rate, net assimilation rate, and leaf area ratio, and gas-exchange at the later stage was about twice that at 20°C (Yamaura et al., 2021). However, the same study found that total dry matter was lower at 30°C and that non-structural carbohydrate accumulation in leaves and stems decreased, showing that supra-optimal temperature can accelerate carbon use and short-term growth while limiting biomass storage and final vegetative accumulation (Yamaura et al., 2021).

3.3 Effects on root development and nutrient uptake

Root systems are highly temperature-sensitive, and both low and high root-zone temperatures restrict root development and nutrient capture. Under heat stress, tomato seedlings showed inhibited primary root length at both 37°C and 45°C, while lateral root number was significantly suppressed under 37°C, demonstrating that root architecture is modified even before severe aboveground damage becomes apparent (Tokić et al., 2023). Low root-zone temperature had similarly negative effects: at 7°C and 13°C, root development was delayed and the number and diameter of ducts in root and stem were reduced, which limited mineral absorption and transport capacity (Miao et al., 2023).

Temperature effects on roots translate directly into nutrient uptake efficiency and shoot nutrition. Across six root-zone temperature treatments, nutrient uptake for most mineral elements peaked at 26.7°C, and root dry weight, shoot dry weight, shoot growth, plant height, and water use all peaked near 25°C, indicating a clear physiological optimum for root-mediated support of vegetative growth (Tindall et al., 1990). Additional evidence from low-temperature and nutrient-composition studies showed that increasing root temperature increased shoot total N, P, Mg, and K, whereas low root temperature caused nitrate and potassium to accumulate in roots because ion translocation was hindered, helping explain why cool root zones slow tomato growth even when nutrients are supplied adequately.

4 Effects of Temperature Regulation on Photosynthesis and Physiological Processes

4.1 Temperature effects on photosynthetic performance

Temperature regulation directly controls tomato photosynthetic capacity because both chilling and heat stress impair the efficiency of the photosynthetic apparatus. Under sub-optimal temperature, tomato showed reduced chlorophyll content and declines in Y(II), Fv/Fm, qP, and ETR, with larger reductions in the cold-sensitive cultivar than in the tolerant one, indicating that genotype influences the extent of photochemical damage (Gao and Wu, 2024). Heat stress similarly depressed gas exchange and photosynthesis by lowering P_{Nmax} and SPAD values, while increases in internal CO₂ concentration indicated that the limitation was mainly non-stomatal and associated with photosystem and Rubisco impairment (Luo et al., 2023).

Evidence from fluorescence-based studies shows that temperature stress acts strongly on electron transport, especially within PSII. In tomato leaf and fruit, OJIP fluorescence parameters clearly distinguished heat from chilling injury, and heat had a greater effect on the PSII electron transport chain than chilling, with fruit tissues showing stronger changes than leaves. Day/night temperature regime also matters: at the fruiting stage, positive DIF increased chlorophyll content, net photosynthetic rate, stomatal conductance, Fv/Fm, and ϕ PSII, whereas negative DIF reduced these traits and increased non-photochemical quenching.