3.2 Interaction between temperature, humidity, CO_2, and radiation

Temperature in greenhouses co-varies tightly with relative humidity and VPD, shaping plant responses more than any single variable alone. Microclimate monitoring in commercial tomato systems showed that zones with slightly higher temperatures tended also to exhibit higher VPD, and these combined conditions influenced local growth and fruit development more strongly than either driver considered independently. A detailed sensor-network study using an IoT-based “optimality degree” index quantified how diurnal swings in temperature of nearly 15 °C between day and night were accompanied by large changes in RH and VPD, often driving the climate outside tomato comfort ranges for substantial portions of the day (Rezvani et al., 2020). In warm seasons, natural ventilation alone was insufficient to prevent thermal inversion, leading to high humidity and sub-optimal VPD at night even as daytime conditions became too hot and dry, underscoring the need to manage temperature and humidity jointly rather than in isolation.

Radiation and CO_2 further modulate how temperature and humidity translate into crop performance. Reviews of greenhouse horticulture under climate change in the Mediterranean emphasize that rising temperature, declining RH, increasing VPD and modified solar radiation typically act together, often pushing microclimates beyond optimal thresholds for photosynthesis, transpiration, and reproductive development (Fanourakis et al., 2025). In such conditions, high radiation loads during heat events can exacerbate canopy temperature and water demand, while CO_2 enrichment or shading and cooling strategies may partially offset stress but also alter energy and water use. Process-based and data-driven crop models increasingly incorporate temperature, humidity (via stomatal conductance or VPD), CO_2 and shortwave radiation as coupled drivers, demonstrating that realistic prediction of biomass or yield requires capturing interactions among all four rather than simple temperature sums alone (Sun et al., 2025).

3.3 Seasonal and regional variations in greenhouse temperature regimes

Seasonal shifts in outside climate strongly reshape greenhouse temperature regimes and their suitability for tomato production. Long-term microclimate monitoring in tomato greenhouses has shown distinct spring-summer-autumn patterns, with larger intra-house gradients and more frequent exceedance of high-temperature thresholds during summer, even when the annual mean appears acceptable. An IoT-based assessment in Iran quantified “optimality degrees” for temperature, RH and VPD and found that winter months achieved higher overall optimality, largely because heating systems maintained conditions near target ranges, whereas in summer the lack of automated cooling produced long periods with daytime temperatures above 34 °C and night temperatures below 17 °C, unsuitable for tomato growth (Figure 2) (Rezvani et al., 2020). Numerical analyses of soilless glasshouses in North Africa similarly demonstrated strong seasonal effects on indoor profiles, with differences in roof-level temperatures between crop and no-crop scenarios narrowing but not eliminating the impact of external seasonal forcing (Abid et al., 2024).

Regional climate also determines baseline greenhouse temperature challenges and thus the design of appropriate control strategies. A systematic review across climatic zones reported that optimal tomato production in Mediterranean and arid regions typically requires carefully controlled ranges around 18-25 °C, with rising ambient temperatures reducing yields by more than half in some simulations when air temperatures approach 35 °C (Nițu et al., 2025). Survey-based evidence from high-tech soilless tomato greenhouses in Türkiye showed that extreme heat events during one season led to yield losses averaging 12.5%, alongside substantial increases in water, fogging, fertilizer and electricity use, and widespread reports of difficulty in climate control (Kürklü et al., 2025). In colder regions, solar or soft-shell greenhouses can increase average indoor temperatures by 10 °C-15 °C above outdoors during winter, greatly reducing low-temperature stress but at the cost of pronounced diurnal swings that must be managed to avoid humidity problems and localized stress hotspots. Across structures, seasons and regions, greenhouse temperature dynamics emerge from interacting structural, radiative and airflow processes, tightly coupled with humidity, CO_2 and radiation. Spatial heterogeneity and seasonal-regional contrasts are large enough to influence tomato growth and yield, indicating that both empirical analysis and modeling of temperature-yield relationships must explicitly represent microclimate patterns rather than rely on single-point or season-average conditions.