On the modeling side, several frameworks explicitly integrate temperature into greenhouse tomato yield prediction. Dynamic crop models such as TOMGRO represent organ initiation and growth via temperature-responsive source-sink processes, calibrated under controlled temperature, $CO_2$ and light conditions, and have been proposed as tools for environment control decisions (Higashide, 2022). Yield models developed for model-based greenhouse design implement literature-based temperature effects on yield and reproduce responses under both near-optimal and sub-optimal regimes, including extreme diurnal oscillations in contrasting climates. Spatially explicit approaches combining geostatistics with crop growth models show that ignoring intra-greenhouse temperature heterogeneity can bias simulated development rates and yield, particularly between central zones and sidewalls. More recently, integrated climate-and-yield models for specific greenhouse types, such as Chinese solar greenhouses, have been validated against multi-site experiments and used to explore design and operational scenarios, again emphasizing indoor air temperature as a key determinant of predicted yield (Zhou et al., 2025).

Against this background, the present study focuses on modeling the relationship between temperature and tomato yield in greenhouse systems. The first objective is to quantify how different descriptors of temperature regimes-such as daily mean, diurnal amplitude, spatial gradients, and the frequency and duration of supra-optimal events-affect yield and its components under realistic microclimate variability. The second objective is to incorporate these relationships into a modeling framework suitable for coupling with greenhouse climate models and control strategies, building on existing dynamic and design-oriented yield models while simplifying where necessary for operational use. The central hypotheses are that: (i) tomato yield in greenhouses is a non-linear function of both average temperature and exposure to critical heat or cold thresholds at sensitive stages; (ii) explicit representation of intra-greenhouse temperature variation improves yield prediction compared with models using only bulk climate; and (iii) a temperature-focused yield model can support evaluation of design options and climate-control strategies under current and future climate conditions.

## 2 Physiological Basis of Temperature Effects on Tomato Growth and Yield

### 2.1 Temperature regulation of photosynthesis and respiration

Tomato photosynthesis operates optimally within a moderate temperature range; deviations in either direction impair carbon gain and growth. Greenhouse and field studies show that high air temperatures, especially above about 38-40 °C, reduce net photosynthetic rate, stomatal conductance and ultimately fruit yield, reflecting damage to both $CO_2$ assimilation and water relations over time (Figure 1) (Liu et al., 2023). Sub-high temperature combined with high light (35 °C, 1000 $\mu mol \cdot m^{-2} \cdot s^{-1}$) sharply decreased net photosynthetic rate, Rubisco activity, PSII and PSI quantum yields, while increasing non-regulated energy dissipation and ROS accumulation, indicating irreversible photoinhibition of both photosystems when thermal and light loads coincide (Talukder et al., 2025).

Lower temperatures also limit photosynthesis by depressing chlorophyll content, electron transport and chlorophyll fluorescence parameters, resulting in reduced dry matter accumulation and yield (Zhang et al., 2023). Under sub-optimal day/night regimes around 15/10 °C, sensitive cultivars show greater reductions in fresh weight, chlorophyll content, Fv/Fm and electron transport rate than tolerant ones, whereas tolerant genotypes maintain higher soluble sugars and proline, supporting photochemistry and osmotic balance. Soil temperature interacts with shoot processes: moderate soil warming to about 26 °C increased leaf assimilation rate, chlorophyll, dry matter and yield in greenhouses, while also stimulating soil respiration and microbial biomass, suggesting coordinated temperature effects on root function and canopy photosynthesis.

Respiration is likewise temperature sensitive, affecting carbon use efficiency and growth. Analyses of tomato under high temperature indicate that respiration rates and growth rates shift together, with elevated temperatures increasing metabolic rates but also reducing metabolic efficiency and substrate carbon use (Alsamir et al., 2020). Nighttime respiratory costs interact with daytime photosynthesis to determine net biomass gain, and high night temperatures have been highlighted as critical constraints in warm greenhouse climates (Sato et al., 2006). Evaluations in solar greenhouses show that water-use efficiency at the leaf level is highest at 20-30 °C, beyond