humidity, and CO_2 setpoints; all AI teams outperformed a reference human grower in net profit, with some teams applying higher early-season and end-season temperatures to accelerate development and ripening while still achieving better heat-use efficiency (Hemming et al., 2020). Analysis with a virtual greenhouse “digital twin” linked these distinct temperature trajectories to differences in yield and resource use, offering a comparative benchmark for data-driven climate strategies.

Model-based optimal control studies provide an additional perspective on intelligent temperature-yield management. A PSO-based model predictive control framework combined a greenhouse climate model with a biophysical yield model and optimized heating, ventilation, and lighting setpoints to maximize yield while minimizing energy costs, outperforming traditional control and genetic-algorithm-based MPC in both yield and energy efficiency in a tomato case study (Gong et al., 2023). At year-round scale, a rule-based MPC using external weather and month-averaged tomato prices to select temperature setpoints was compared with on/off control and open field; simulations for Beijing showed that only strategies jointly optimizing yield and energy cost achieved satisfactory profit, highlighting how economic and biophysical models must be integrated when evaluating intelligent temperature control options (Xu et al., 2024).

9 Discussion, Applications, and Future Perspectives

Existing temperature-yield models for greenhouse tomato are powerful decision-support tools but still face notable limitations and uncertainties. Process-based models often rely on a relatively small set of experiments for parameterization and may not fully capture the variability in low-technology or highly heterogeneous greenhouses, where temperature extremes and spatial microclimate variation are common. Global sensitivity and uncertainty analyses have shown that yield predictions can be highly sensitive to a few temperature-related parameters, such as thresholds for fruit abortion or growth inhibition, meaning that modest parameter errors can translate into large yield errors when conditions move outside the “ideal” range. Many models assume relatively uniform microclimate and well-controlled systems, so their validity can degrade in real commercial settings with imperfect heating and cooling, where optimality degrees for temperature and VPD fluctuate widely between seasons and locations. Furthermore, hybrid approaches that enhance process-based models with deep learning can boost accuracy, but they introduce their own sources of uncertainty related to training data representativeness, sensor noise, and potential overfitting, making model transfer to new greenhouses or future climates less certain unless explicitly tested.

Despite these limitations, temperature-yield models are increasingly embedded in precision agriculture and smart greenhouse platforms to support real-time management. Decision-support systems using crop water productivity models such as AquaCrop already leverage external temperature and long historical weather records to estimate greenhouse tomato yields and optimize irrigation under future climate scenarios. IoT-based microclimate monitoring frameworks quantify “optimality degrees” or comfort ratios for temperature, humidity and VPD, translating dense sensor data into simple indices that link directly to yield risk and guide heating and cooling strategies. Smart greenhouse platforms go further by combining wireless sensor networks, fuzzy or model-based controllers, and cloud dashboards, enabling automated ventilation, shading and irrigation tuned to maintain temperatures within crop-specific ranges. Integrated digital solutions that add machine learning yield predictors, disease recognition, and even fruit expansion analysis use historical temperature-humidity-yield relationships to recommend set-points and interventions, improving resource efficiency and stabilizing production. As these systems mature, temperature-yield models shift from purely research tools to operational components of climate control, irrigation scheduling, and energy optimization in commercial tomato production.

Future work on modeling temperature-yield relationships will likely be driven by convergence of digital twins, dense IoT sensing, and climate-adaptive algorithms. Greenhouse digital twins are beginning to integrate sensor networks, multivariate yield-forecasting models, and edge computing to provide continuous predictions of final yield based on evolving temperature and other climate variables, allowing growers to test “what-if” scenarios for alternative control strategies before applying them in the real house. Broader reviews of agricultural digital twins and smart farming envision virtual replicas that fuse crop models, weather forecasts, soil sensors, and aerial