

CLIMATE RESILIENT TOMATO PRODUCTION USING PROTECTED CULTIVATION AND SMART GREENHOUSE TECHNOLOGIES

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Abstract

Tomato (*Solanum lycopersicum*) production faces escalating threats from climate change rising temperatures, heat waves, erratic rainfall, prolonged droughts, increased pest pressure (notably *Tuta absoluta*), and shifting disease dynamics that compromise yield stability, quality, and economic viability in open-field systems. This review examines climate-resilient tomato cultivation through protected environments (low-cost high tunnels, net houses, polyhouses) and smart greenhouse technologies integrated with IoT sensors, AI-driven decision support, and precision control systems. Protected structures moderate microclimates (temperature 2–8 °C below ambient, relative humidity stabilization, UV filtering), extend growing seasons, reduce pesticide reliance by 40–70%, and achieve yield increases of 50–150% compared with open-field cultivation in heat-prone regions. Advanced smart systems employ real-time monitoring of soil moisture, canopy temperature, VPD, CO₂, and light via wireless sensor networks, coupled with predictive models (hybrid CNN-LSTM, fine-tuned LLMs) for automated irrigation, fertigation, ventilation, shading, and pest early warning. Case studies from tropical/subtropical zones demonstrate water savings of 30–60%, energy-efficient climate control, and enhanced fruit quality (higher TSS, firmness, lycopene). Challenges include high initial capital costs, energy demands in off-grid areas, and farmer training gaps, addressed through low-cost retrofits, solar-powered automation, and public-private extension models. The convergence of protected cultivation with smart technologies offers a scalable pathway to climate-proof tomato production, ensuring food security, income stability, and reduced environmental footprint amid accelerating global warming.

1. INTRODUCTION

The global agricultural landscape is currently undergoing a transformative shift as the cultivation of *Solanum lycopersicum*, or the common tomato, faces unprecedented challenges from anthropogenic climate change (Gupta et al., 2025). As one of the most widely grown and economically significant vegetable crops worldwide, with annual production volumes exceeding 190 million tons, the tomato serves as a vital component of human nutrition and a cornerstone of international agricultural trade (Zhao et al., 2025). However, the biological sensitivity of this species to environmental fluctuations particularly extreme temperatures, erratic precipitation, and the shifting ranges of invasive pests has necessitated a transition toward more resilient production systems (FAO, 2024). The integration of protected cultivation frameworks, ranging from simple unheated high tunnels to fully automated smart greenhouses, coupled with the precision of Internet of Things (IoT) and Artificial Intelligence (AI) technologies, represents the frontier of modern horticulture

(Thompson & Wright, 2025). This technological convergence aims to decouple agricultural output from the increasing volatility of the external environment, ensuring food security in a future marked by climatic uncertainty (IPCC, 2024).

2. The Bioclimatic Imperative for Resilient Tomato Systems

The necessity for climate-resilient tomato production is driven by the multifaceted impact of global warming on the plant's physiological and ecological requirements. Tomatoes are poikilothermic by nature, meaning their metabolic and developmental processes are highly dependent on ambient temperatures (Ngabirano et al., 2023). As global temperatures are predicted to increase by 2 degrees Celsius by the end of the century, the standard open-field cultivation model faces significant risks (Kürklü et al., 2025). Climate change influences tomato production through multiple interconnected stress pathways including thermal stress, water scarcity, and pest proliferation. The major climate-driven pressures affecting tomato cultivation are summarized in Figure 1.

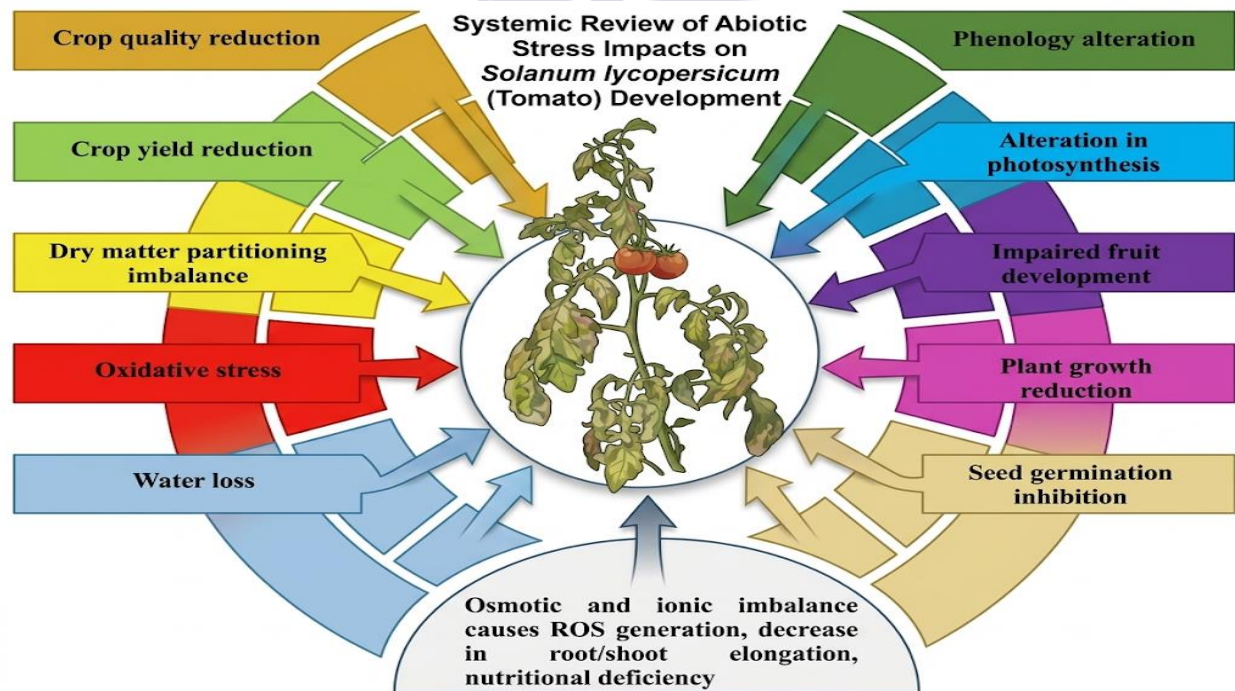


Figure 1: Climate Change Impacts on Tomato Production Systems

2.1 Physiological Stress and Thermal Thresholds

Tomato plants exhibit specific thermal optima for different growth stages, including germination, vegetative growth, flowering, and fruit ripening. Persistently high temperatures, particularly those exceeding the critical threshold of 32 degrees Celsius during the day and 22 degrees Celsius at night, induce severe heat stress (Abbas et al., 2025). This thermal load disrupts pollination; high temperatures can cause pollen desiccation or reduce the viability of the pollen tube, leading to poor fruit set or complete cluster loss (Kaur & Saini, 2024). Furthermore, the synthesis of lycopene the antioxidant pigment responsible for the red color of tomatoes is most efficient within a narrow range of 21 to 24 degrees Celsius. When temperatures deviate significantly from this range, fruit coloration becomes uneven, reducing market value (Hameed et al., 2026).

In regions like Turkey, extreme heatwaves during recent growing seasons have resulted in yield losses ranging from 6% to 53%, with an average decline of 12.5% across the high-tech greenhouse sector (Ozdemir et al., 2025). These losses are often accompanied by a decline in tomato quality, forcing growers to accept lower sales prices even for the fruit harvested. The inability to control internal microclimates during such extreme events highlights a critical vulnerability even in advanced systems, necessitating the adoption of more robust

cooling and climate control strategies (EEA, 2024).

2.2 Climate-Driven Bio-Invasions and Pest Dynamics

Beyond direct physiological stress, climate change acts as a catalyst for the spread of invasive pests and pathogens. The shifting geographical distribution of insect pests is linked to changes in temperature, rainfall, and windspeed (Bibi et al., 2025). In East Africa, rising temperatures and fluctuating humidity levels have been identified as drivers for the proliferation of invasive tomato insect pests (USAID, 2025).

The tomato leaf miner, *Tuta absoluta*, represents a devastating threat. Its lifecycle and spread are significantly influenced by climatic variables, with warmer conditions facilitating faster generation cycles and expanded migration (Mwaura et al., 2026).

The dry periods following humid spells, characteristic of changing rainfall patterns in tropical and subtropical regions, create optimal conditions for bio-invasions (Gakuo et al., 2025). Furthermore, changes in soil moisture and relative humidity alter the interaction between pests, their natural enemies, and the host plant, resulting in higher damage levels (Kamau et al., 2026).

Table 1. Impacts of Climatic Variables on Tomato Production

Climatic Variable	Observed Change Trend	Primary Impact on Tomato Production
Temperature	Annual increase of ~0.04 to 0.05 degrees Celsius	Pollen sterility, reduced fruit set, and lycopene degradation (Kürklü et al., 2025; Ngabirano et al., 2023)
Rainfall	Increased fluctuation/Extreme events	Flooding, soil erosion, and increased fungal pathogen pressure (Ngabirano et al., 2023; Sindhushree et al., 2025)
Humidity	Decreased (e.g., up to 13.3% in some regions)	Increased pest proliferation and physiological drought stress (Ngabirano et al., 2023)
Windspeed	Marginal increases	Structural damage to tunnels and rapid dispersal of winged pests (Ngabirano et al., 2023)
CO2 Levels	Persistent rise	Potential yield increase of ~38% if other factors are managed (Kürklü et al., 2025)

3. Structural Frameworks of Protected Cultivation

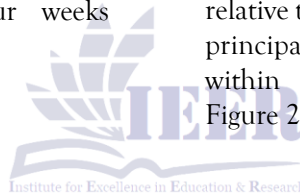
Protected cultivation serves as the first line of defense against climatic stressors. By enclosing the crop, growers can moderate the microclimate and exclude specific pests (Sani et al., 2025).

3.1 Low-Cost Passive Systems: High Tunnels and Hoop Houses

High tunnels are hooped frames of walk-in height covered with polyethylene that lack active environmental control. They rely on passive ventilation, commonly by manually rolling sidewalls up in the morning and down in the evening (Galinato & Miles, 2013). The primary advantage is their ability to exclude rainfall, which drastically reduces the incidence of foliar diseases like early blight (*Alternaria solani*) that rely on rain splash for dispersal (Rogers & Wszelaki, 2012). In states like New York and Kentucky, high tunnels have been shown to advance the harvest of summer tomatoes by three to four weeks (O'Connell et al., 2012).

3.2 Structural Engineering of High-Tech Greenhouses

High-tech greenhouses are designed as permanent industrial facilities capable of year-round production. These structures are built upon concrete foundations and utilize robust frames made of galvanized steel or aluminum (Singh et al., 2021). Glazing materials like glass, polycarbonate, or acrylic are selected for specific light transmission and thermal insulation properties. These greenhouses are engineered to withstand significant snow loads and high wind speeds (Martinez-Vazquez et al., 2025). High-tech systems incorporate mechanical ventilation, high-pressure fogging for evaporative cooling, and automated shading systems. This allows for the production of indeterminate tomato varieties that can achieve heights of several meters, utilizing vertical space to maximize yield per unit area (Njeri et al., 2024). One of the key advantages of protected cultivation is the ability to modify the crop microclimate relative to external environmental conditions. The principal microclimatic modifications achieved within protected structures are illustrated in Figure 2.



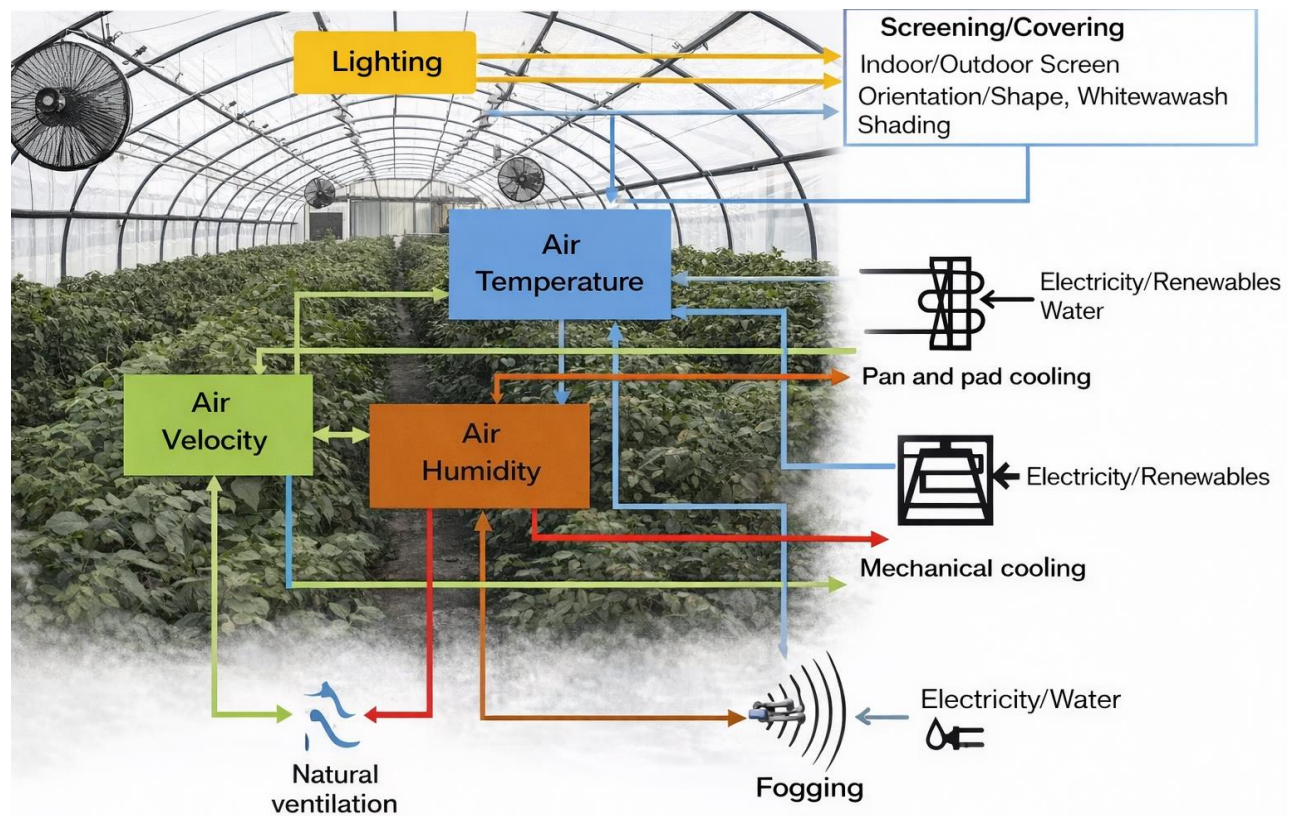


Figure 2: Microclimate Modification Inside Protected Structures

3.3 Comparative Resource Efficiency and Cost-Benefit Analysis

While high-tech systems offer superior resilience and higher yields (averaging 70 kg per square meter), they require significant capital. High

tunnels, costing approximately 1.30 to 1.50 per square foot versus 8 to 30 for greenhouses, provide a more accessible entry point for small-scale growers (Onyango & Hassan, 2025).

Table 2. Resource Efficiency Comparison Across Tomato Production Systems

Production System	Harvest Period	Energy Input (GJ/ha/year)	Yield (Tonnes/ha)	Energy Efficiency (MJ/kg)
Open Field	2 Months	285	40	7.1 (Singh et al., 2021)
High Tunnel	4 Months	452	163	2.8 (Singh et al., 2021)
High-Tech Greenhouse	8 Months	26,000	496	53.0 (Singh et al., 2021)

High tunnels emerge as the most energy-efficient system per kilogram of fruit produced because they leverage natural solar energy without the high embodied energy costs of intensive climate control (Demir & Arslan, 2026).

4. The Digital Architecture of Smart Greenhouses

The transition to "smart" greenhouses is defined by the integration of an IoT ecosystem. This digital layer allows for continuous monitoring and

automated response to environmental shifts (Guo et al., 2026).

4.1 Sensing the Microclimate: Perception and Data Acquisition

The foundation of any smart greenhouse is its sensor network. These devices gather high-resolution data on variables affecting tomato growth. Environmental sensors include temperature and humidity sensors (e.g., DHT11 or SHT series), light intensity (PAR) sensors, and carbon dioxide monitors (Xiao et al., 2025). Soil and substrate sensors measure volumetric water content, electrical conductivity (EC), and pH (Sindhushree et al., 2025). Advanced systems use infrared thermometers to measure leaf temperature and sap flow to determine the actual water needs of the plant (Al-Naemi & Al-Otoom, 2023). These sensors transmit data to microcontrollers like the Arduino Mega, NodeMCU, or Raspberry Pi, which serve as local processing units (Miller et al., 2026).

4.2 Automation and Actuation Systems

The true value of a smart greenhouse lies in translating data into action. Actuation systems manage the mechanical elements of the greenhouse. Automated motors open and close roof vents and activate exhaust fans based on real-time temperature thresholds (Dorji et al., 2024). Solenoid valves and variable-speed pumps deliver precise amounts of water and nutrients directly to plant roots. Smart LED systems adjust their spectrum and intensity throughout the day to supplement natural sunlight (Beyer, 2025).

5. Artificial Intelligence and Control Strategies

Advanced control algorithms and AI models are now employed to manage multi-input/multi-output (MIMO) systems (Su et al., 2025).

5.1 From PID to Deep Reinforcement Learning (DRL)

Greenhouse control has moved from simple logic to sophisticated mathematical models. While Proportional-Integral-Derivative (PID) controllers are the traditional standard, they struggle with the lag in large greenhouse volumes (Kibaki et al., 2024). Deep Reinforcement Learning (DRL) agents learn optimal control policies by interacting with the greenhouse environment. DRL-optimized PID tuning has demonstrated energy savings of 8.81% to 12.99% in tomato greenhouse HVAC operations (Adesanya & Xiao, 2024).

5.2 Machine Learning in Microclimate Management

Machine learning (ML) models are used for predictive tasks like forecasting CO2 demand or soil moisture. Deep learning architectures like CNN-LSTM and Transformers are used for evapotranspiration (ET) estimation, improving predictive accuracy by 10% to 25% over classical physics-based models (Islam et al., 2025). A hybrid approach combining reinforcement learning with a radial basis function neural network (RBFNN) has been shown to enhance energy efficiency by 19.7% (Shawon et al., 2025).

Table 3. Comparison of Greenhouse Control Strategy Performance

Control Strategy	Accuracy/Performance Metric	Key Benefit
Traditional PID	Baseline	Simple to implement (Su et al., 2025)
Fuzzy Logic	+32.04% faster rise time	Robust to non-linear fluctuations (Ibrahim et al., 2024)
DRL-PID	8.81-12.99% energy savings	Adaptive learning of optimal setpoints (Adesanya & Xiao, 2024)
Neuro-Tuner (RL)	19.7% efficiency gain	Superior handling of MIMO dynamics (Xiao et al., 2025)

6. Precision Resource Management: Water, Light, and Nutrients

Climate-resilient production requires optimization of all inputs. In arid regions, desalinated seawater (DSW) provides a sustainable alternative. While high salinity can reduce total yield, it improves tomato quality by increasing the concentration of soluble solids and dry matter (Kürklü et al., 2025). Hydroponic systems further enhance water resilience by recycling nutrient solutions, using up to 90% less water than traditional soil-based farming (Mitchell & Gómez, 2013).

Supplemental lighting using Light-Emitting Diodes (LEDs) has replaced traditional High-Pressure Sodium (HPS) lamps. Intracanalopy lighting allows LEDs to be placed within the plant

canopy to reach lower leaves, increasing photosynthetic efficiency (Lefers et al., 2020).

7. AI-Driven Disease and Pest Management

AI vision systems can identify threats with accuracy surpassing human scouting. Deep Learning models like YOLOv9 (You Only Look Once) can identify up to nine common tomato leaf diseases in real-time with an accuracy of 97% (Ahmad et al., 2024). Vision Transformers (ViTs) are increasingly used for their ability to extract global features, making them robust to variable lighting (Nishankar et al., 2025). Autonomous robots with soft-touch end effectors are now picking cherry and grape tomatoes at the exact point of ripeness, ensuring consistency and reducing labor costs (Fresh Consulting, 2024).

Table 4. AI Model Performance in Tomato Disease and Pest Management

AI Model Architecture	Specific Task	Reported Accuracy	Source
YOLOv9	Real-time disease detection	97.0%	(Ahmad et al., 2024)
ResNet-152	Classification (w/ DCGAN)	99.69%	(Alshammari et al., 2024)
MobileNetV2	Lightweight edge diagnosis	99.9%	(Nishankar et al., 2025)
TLDVLM (Vision-Lang)	Interpretive diagnosis	97.27%	(Zhu et al., 2025)

8. Socio-Economic Feasibility and Operational Challenges

The adoption of smart technologies is not without hurdles. A case study of a medium-tech 18,000-square-foot greenhouse in Florida calculated the production cost at 34.21 per square foot per year. Labor accounted for 59% of the budget, while energy accounted for 18% (Melendez-Vazquez et al., 2025). The break-even price required to cover total costs was 3.42 per pound, which often exceeds current market prices. Furthermore, intensive greenhouse production can emit five times more carbon than open-field farming, necessitating a transition toward renewable energy integration and solar thermal heating (Nadar et al., 2023; GRACE Project, 2024).

The digitalization of agriculture also creates a surge in electronic waste (e-waste) containing hazardous heavy metals. Addressing this requires circular economy principles, such as "design-for-recycling" and take-back schemes, to mitigate environmental risk (Sindhushree et al., 2025).

9. Synthesis of Regional Case Studies

Implementation varies by local pressures. In Bhutan, a low-cost smart greenhouse using solar thermal energy to heat soil via pipes maintained temperatures 7 degrees Celsius higher than the exterior, allowing winter harvests (Dorji et al., 2024). In Almería, Spain, greenhouses have transitioned to desalinated seawater to combat the overexploitation of aquifers (Lefers et al., 2020). In Guangdong, China, an integrated digital framework shortened the tomato growth cycle by 10-15% while increasing yield by 20-30% (Guo et al., 2026).

10. Conclusion

Protected cultivation combined with smart greenhouse technologies represents a paradigm shift from climate-vulnerable open-field tomato production toward resilient, high-efficiency systems capable of buffering against rising temperatures, water scarcity, extreme weather, and intensifying biotic pressures. By decoupling crop

performance from unpredictable outdoor conditions, these approaches deliver consistent yields (often 2–3× higher), superior fruit quality, extended marketing windows, and substantial reductions in water, pesticide, and labor inputs critical advantages in regions facing severe climate stress. Integration of IoT for real-time environmental monitoring and AI/ML for predictive analytics enables proactive management, minimizing yield losses from heat stress, suboptimal humidity, or pest outbreaks while optimizing resource use. Although upfront costs and technical capacity remain barriers, declining sensor prices, solar-powered solutions, modular designs, and targeted subsidies are rapidly improving accessibility for small- and medium-scale growers. As global tomato demand grows and climate projections worsen, prioritizing investment in protected-smart systems supported by farmer training, localized varietal adaptation, and policy incentives will be essential to sustain production, enhance rural livelihoods, and secure nutritional supplies in vulnerable agro-ecologies. Ultimately, this technological convergence positions tomato cultivation as a model of adaptive, climate-smart horticulture, demonstrating how precision innovation can reconcile productivity with environmental stewardship in a warming world.

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