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Stress-Aware Greenhouse Climate Control: Integrating Plant Physiology, Intelligent Environmental Control, and Energy Management for Sustainable Protected Horticulture

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Review Article

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ABSTRACT

Greenhouse climate management is undergoing a paradigm shift from maintaining fixed environmental setpoints toward dynamic, plant-centered control strategies that optimize crop physiological performance while minimizing energy and water consumption. Despite remarkable advances in greenhouse technologies, most existing climate-control approaches remain environment-driven and frequently overlook the dynamic interactions among temperature, vapor pressure deficit (VPD), radiation, carbon dioxide concentration, and plant physiological responses. This review synthesizes recent advances in stress-aware greenhouse climate control by integrating plant physiology, environmental sensing, intelligent control algorithms, and energy-efficient engineering solutions into a unified conceptual framework. The analysis demonstrates that plant stress is more accurately characterized by physiological indicators including canopy temperature, stomatal conductance, transpiration, chlorophyll fluorescence, daily light integral, and VPD than by conventional environmental thresholds alone. Comparative synthesis further reveals that individual climate-control technologies effectively mitigate specific stress factors but inevitably introduce trade-offs among energy demand, water consumption, carbon retention, and disease risk. Emerging technologies, including artificial intelligence, digital twins, wireless sensor networks, and multi-objective predictive control, provide new opportunities to optimize greenhouse climate simultaneously for crop productivity, resource-use efficiency, and environmental sustainability. Based on this synthesis, we propose a stress-aware greenhouse climate-control framework in which environmental regulation is guided by real-time plant physiological status rather than fixed climatic setpoints. The framework supports adaptive decision-making across diverse greenhouse systems and provides a foundation for the next generation of intelligent, resilient, and low-carbon protected horticulture.

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1. Introduction

Global horticultural production is facing unprecedented challenges arising from climate change, increasing energy prices, freshwater scarcity, and the growing demand for year-round production of high-quality fruits, vegetables, and ornamental crops (Lakhiar *et al*., 2025). Rising temperatures, more frequent heat waves, irregular precipitation patterns, and increasing atmospheric CO_2 concentrations are altering the environmental conditions under which protected cultivation systems operate (Yuan *et al*., 2024). Simultaneously, the expansion of urban agriculture and the necessity to improve resource-use efficiency have accelerated the adoption of greenhouse production systems worldwide (Fei *et al*., 2025). Consequently, greenhouse cultivation has become one of the most important technological approaches for ensuring sustainable horticultural production while minimizing the environmental footprint of intensive agriculture (Farvardin *et al*., 2024). Greenhouses provide a semi-controlled or fully controlled environment that enables growers to manipulate key climatic variables, including air temperature, relative humidity (RH), vapor pressure deficit (VPD), solar radiation, CO_2 concentration, and root-zone conditions, thereby maintaining favorable conditions for plant growth throughout the year (Vatistas *et al*., 2022). Compared with open-field cultivation, protected horticulture substantially increases crop productivity, improves water and fertilizer use efficiency, reduces pesticide application, and enhances product quality and uniformity (Banjare *et al*., 2024). Nevertheless, these benefits are achieved at the expense of increased dependence on climate-control technologies that require considerable energy and water inputs. In many commercial greenhouse systems, heating, cooling, ventilation, and dehumidification account for the majority of operational energy consumption, making climate regulation one of the principal economic and environmental challenges facing modern protected horticulture (Ghani *et al*., 2019). Historically, greenhouse climate management has relied on maintaining predetermined environmental setpoints for air temperature, RH, and, in more advanced systems, CO_2 concentration (Chen *et al*., 2024). Conventional control strategies generally operate by comparing measured environmental conditions with predefined thresholds and activating heating, ventilation, cooling, shading, or humidification systems whenever deviations occur. Although this approach has been successfully implemented for decades, it assumes that maintaining constant environmental conditions automatically ensures optimal plant performance (Kaya, 2025).

However, numerous physiological studies have demonstrated that plant responses are governed not by individual environmental variables alone, but by their dynamic interactions and by the physiological status of the crop (Suzuki *et al*., 2014). Consequently, identical environmental setpoints may produce markedly different growth responses depending on species, cultivar, developmental stage, canopy architecture, water availability, radiation intensity, and external climatic conditions (Sadras *et al*., 2024). Among the interacting environmental variables, VPD has emerged as one of the most influential determinants of plant performance because it integrates the combined effects of temperature and atmospheric moisture on transpiration and stomatal behavior (Grossiord *et al*., 2020). Likewise, canopy temperature, daily light integral (DLI), stomatal conductance, chlorophyll fluorescence, transpiration rate, and photosynthetic carbon assimilation provide direct information regarding plant physiological status that cannot be inferred solely from air temperature or RH measurements (Marie, 2024). Excessive VPD may induce hydraulic stress even under adequate irrigation, whereas excessively low VPD suppresses transpiration, reduces nutrient transport, and increases susceptibility to fungal diseases (Zhang *et al*., 2018). Similarly, excessive solar radiation may increase leaf temperature beyond the optimum for photosynthesis despite apparently acceptable greenhouse air temperatures (Perez *et al*., 2020). These observations demonstrate that plant stress results from the interaction of multiple environmental drivers rather than from isolated climatic variables. Recent advances in sensor technologies, wireless communication, machine vision, thermal imaging, Internet of Things (IoT) platforms, and artificial intelligence have fundamentally transformed the ability to monitor greenhouse environments and crop responses in real time (Bicamumakuba *et al*., 2025). Modern greenhouse systems are capable of continuously measuring environmental conditions while simultaneously estimating plant physiological status through infrared thermography, hyperspectral imaging, sap-flow sensors, chlorophyll fluorescence measurements, and machine-learning-based image analysis (Akbar *et al*., 2024). Despite these technological advances, most commercial greenhouse control systems remain predominantly environment-centered, responding primarily to deviations in temperature or humidity rather than directly regulating plant stress. As a result, substantial opportunities remain to improve crop productivity, resource-use efficiency, and environmental sustainability by integrating physiological information into greenhouse climate-control strategies (Villagran *et al*., 2024). The concept of stress-aware greenhouse climate control has recently emerged as a promising framework for addressing these limitations. Rather than maintaining rigid environmental setpoints, stress-aware control prioritizes the continuous assessment and mitigation of plant physiological stress through adaptive regulation of interacting climatic variables. Within this framework, greenhouse operation is guided by measurable indicators of crop physiological status including canopy temperature, VPD, stomatal conductance, chlorophyll fluorescence, transpiration rate, and carbon assimilation allowing environmental conditions to vary within acceptable ranges provided that plant stress remains below critical thresholds (Li *et al*., 2025). This plant-centered approach represents a fundamental shift from controlling the greenhouse environment itself to controlling the physiological consequences of that environment on crop performance (Shamshiri *et al*., 2018). Unlike conventional climate-control strategies, stress-aware greenhouse management recognizes that different climate-control technologies mitigate different forms of stress while simultaneously generating secondary physiological and energetic consequences (Nitu *et al*., 2025). For example, natural ventilation effectively reduces thermal stress but often dilutes CO_2 concentrations, potentially limiting photosynthesis during periods of high carbon demand. Evaporative cooling alleviates heat stress in arid environments but may increase RH sufficiently to suppress transpiration and promote disease development under humid conditions (Sharaf-Eldin *et al*., 2023). Similarly, photovoltaic installations reduce solar heat gain while simultaneously decreasing photosynthetically active radiation reaching the crop canopy. Heat pumps, geothermal cooling systems, thermal energy storage, and desiccant-based dehumidification each improve particular aspects of greenhouse climate but differ substantially in their energy consumption, water requirements, investment costs, and applicability under different climatic conditions (Soussi *et al*., 2022). Consequently, greenhouse climate management should be viewed as a multi-objective optimization problem rather than a collection of independent engineering solutions. Although numerous review articles have examined greenhouse cooling technologies, renewable energy integration, environmental control systems, or artificial intelligence individually (Maraveas *et al*., 2023; Villagran *et al*., 2025), relatively few studies have synthesized these topics within a unified physiological framework that explicitly considers plant stress as the primary decision variable. Existing reviews frequently classify technologies according to engineering principles or energy performance, while giving comparatively limited attention to the physiological mechanisms through which these technologies influence plant growth and productivity. Moreover, the inevitable trade-offs among energy consumption, water use, carbon retention, disease risk, and crop physiological performance remain insufficiently integrated into current greenhouse climate-control frameworks. This fragmented perspective limits the development of intelligent decision-support systems capable of simultaneously optimizing productivity, sustainability, and economic performance. The transition toward digital agriculture provides an unprecedented opportunity to overcome these limitations. Emerging technologies such as digital twins, machine learning, reinforcement learning, model predictive control (MPC), wireless sensor networks, and cloud-based decision-support platforms increasingly enable greenhouse climate to be regulated using predictive, plant-responsive algorithms rather than static environmental thresholds (Ke *et al*., 2026). Integrating these technologies with real-time physiological monitoring creates the possibility of adaptive climate-control systems capable of anticipating plant stress before irreversible damage occurs while simultaneously minimizing energy and water consumption. Such developments are expected to play a central role in achieving climate-resilient and carbon-efficient greenhouse production under future environmental conditions. Against this background, the present review proposes a comprehensive stress-aware framework for greenhouse climate management that integrates plant physiology, environmental sensing, intelligent control systems, and energy-efficient engineering technologies. First, we describe the physiological basis of plant responses to thermal, hydraulic, radiative, and carbon-related stresses and identify measurable indicators suitable for real-time greenhouse monitoring. Second, we critically evaluate passive and active climate-control technologies according to their effectiveness in alleviating specific stress factors while highlighting the trade-offs associated with energy consumption, water use, CO_2 retention, and crop performance. Third, we examine the role of renewable energy systems, thermal energy storage, artificial intelligence, and predictive control in enabling next-generation greenhouse operation. Finally, we identify key research gaps and propose future directions for developing intelligent, plant-centered greenhouse systems that simultaneously optimize crop productivity, resource-use efficiency, and environmental sustainability. By shifting the focus from environmental setpoint regulation to dynamic management of plant physiological stress, this review provides a conceptual foundation for the next generation of resilient, energy-efficient, and climate-smart protected horticulture.

2. Review Methodology

This review was conducted as a structured narrative review supported by a systematic literature search to synthesize recent advances in stress-aware greenhouse climate control. Peer-reviewed publications were retrieved from the Web of Science, Scopus, ScienceDirect, and Google Scholar databases, with emphasis on studies published between 2015 and 2025. Additional relevant articles were identified through backward and forward citation tracking. The review focused on greenhouse climate-control technologies, plant physiological responses, renewable energy systems, environmental sensing, and intelligent control strategies. Only studies presenting experimentally validated or quantitative results in greenhouse or controlled-environment horticulture were included, whereas studies unrelated to horticultural greenhouse systems or lacking sufficient methodological rigor were excluded. Information extracted from each study included greenhouse type, crop species, climatic conditions, climate-control technology, physiological indicators, energy and water use, and operational performance. Unlike conventional technology-based reviews, the selected literature was classified according to the primary physiological stress addressed, including thermal, hydraulic, radiative, humidity-related, and carbon-assimilation stresses. Greenhouse technologies were evaluated based on their physiological effectiveness, resource-use efficiency, operational feasibility, and compatibility with advanced sensing and intelligent control systems. In this review, stress-aware greenhouse climate control is defined as a plant-centered approach that dynamically regulates environmental conditions using physiological indicators such as canopy temperature, vapor pressure deficit (VPD), stomatal conductance, transpiration, chlorophyll fluorescence, and daily light integral (DLI), with the objective of simultaneously improving crop productivity, resource-use efficiency, and environmental sustainability.

3. From Conventional Climate Control to Stress-Aware Greenhouse Management

3.1. Limitations of conventional greenhouse climate control

Greenhouse climate management has traditionally relied on maintaining predefined environmental setpoints for variables such as air temperature, relative humidity (RH), carbon dioxide (CO_2) concentration, and solar radiation (Chen *et al*., 2025). These setpoint-based control strategies have been widely adopted because they are simple to implement and provide acceptable environmental stability for many commercial production systems. Heating, cooling, ventilation, shading, and humidification systems are typically activated whenever environmental variables deviate from predetermined thresholds, with the primary objective of maintaining relatively constant greenhouse conditions. Although conventional control strategies have contributed substantially to improvements in crop productivity and resource management, they exhibit several important limitations (Stagnari *et al*., 2009). Most notably, they assume that maintaining fixed environmental conditions automatically ensures optimal plant growth. However, plant physiological responses are highly dynamic and depend not only on individual environmental variables but also on their complex interactions (Singh *et al*., 2020). Crop responses vary according to species, cultivar, developmental stage, canopy architecture, irrigation status, radiation intensity, and external weather conditions. Consequently, identical environmental setpoints may produce markedly different physiological responses under different production scenarios (Asane *et al*., 2025). Furthermore, conventional greenhouse control systems generally respond to changes in environmental conditions only after predefined thresholds have been exceeded. Such reactive approaches frequently fail to detect early physiological stress, resulting in temporary reductions in photosynthesis, stomatal conductance, transpiration, nutrient uptake, and biomass accumulation before corrective actions are implemented (Kaur *et al*., 2021). As greenhouse production systems become increasingly sophisticated and energy costs continue to rise, maintaining fixed environmental conditions is no longer sufficient to maximize productivity while minimizing resource consumption (Figure 1).

3.2. Plant physiological responses as the basis of climate management

Plants continuously perceive and respond to fluctuations in their surrounding environment. Temperature, radiation, humidity, CO_2 concentration, and root-zone conditions collectively regulate photosynthesis, respiration, transpiration, nutrient transport, and carbon allocation (Li *et al*., 2024). Rather than responding independently to each climatic variable, plants integrate multiple environmental signals through coordinated physiological processes. Among these processes, stomatal regulation represents one of the primary mechanisms governing plant adaptation to environmental stress (Zhang *et al*., 2024). Stomata dynamically balance carbon assimilation with water conservation by regulating gas exchange between leaves and the surrounding atmosphere. Under favorable environmental conditions, stomata remain sufficiently open to maximize photosynthesis while maintaining adequate transpiration for evaporative cooling and nutrient transport (Zhang *et al*., 2024). Conversely, excessive evaporative demand, heat stress, or water deficits induce partial stomatal closure, reducing transpiration and limiting CO_2 uptake. Although this response protects plants against excessive water loss, prolonged stomatal closure inevitably decreases photosynthetic carbon assimilation and crop productivity (Peláez-Vico *et al*., 2024). Similarly, canopy temperature provides an integrated indicator of plant water status and stomatal activity. Under optimal conditions, transpiration cools leaf surfaces, maintaining canopy temperatures close to or slightly below air temperature. When transpiration declines due to hydraulic stress or stomatal closure, canopy temperature rises rapidly, often before visible symptoms of stress become apparent (Ranawana *et al*., 2023). Consequently, canopy temperature has become one of the most reliable non-destructive indicators for real-time greenhouse monitoring (Tan *et al*., 2018).

3.3. Physiological indicators supporting stress-aware climate control

Recent advances in environmental sensing have enabled continuous monitoring of crop physiological status. Unlike conventional environmental variables, physiological indicators directly reflect the interaction between plants and their environment and therefore provide more meaningful information for climate management. Among these indicators, vapor pressure deficit (VPD) has emerged as one of the most important variables because it integrates air temperature and humidity into a single measure of atmospheric evaporative demand (Averbuch and Moshelion, 2026). Maintaining crop-specific VPD ranges improves transpiration, nutrient transport, and stomatal regulation, whereas excessively high or low VPD induces hydraulic stress, calcium deficiency, reduced photosynthesis, or increased disease susceptibility (López *et al*., 2021). Other important physiological indicators include canopy temperature, stomatal conductance, transpiration rate, chlorophyll fluorescence, photosynthetic carbon assimilation, leaf-to-air temperature difference, daily light integral (DLI), and water-use efficiency. Chlorophyll fluorescence provides rapid information regarding photosystem II efficiency and early stress detection (Moustaka and Moustakas, 2023), while DLI integrates light intensity and photoperiod to evaluate the cumulative radiation available for photosynthesis (Szabó *et al*., 2025). Collectively, these indicators provide a comprehensive assessment of crop physiological performance that cannot be achieved through temperature or RH measurements alone.

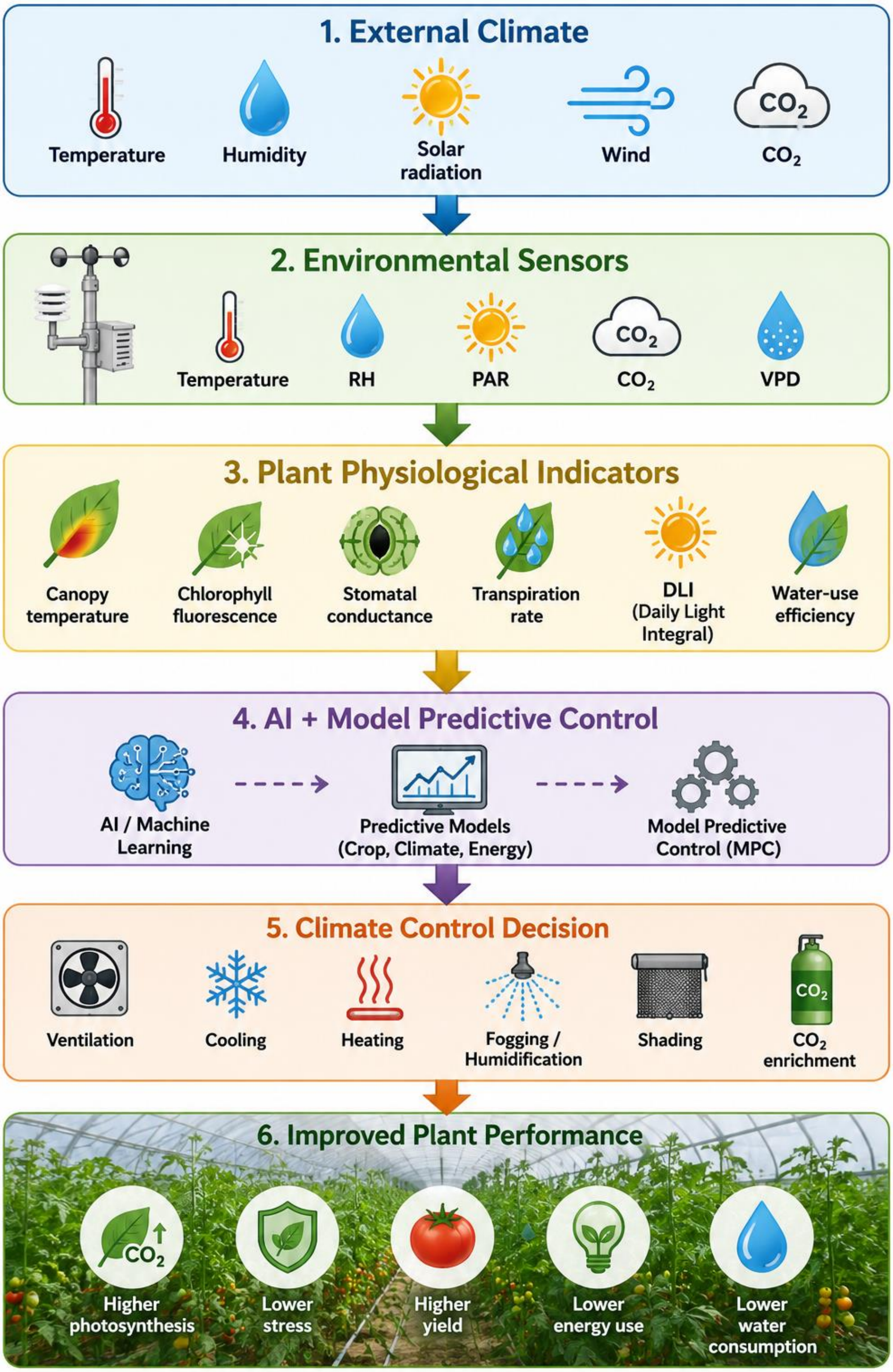

Figure 1. Conceptual Framework of Stress-Aware Greenhouse Climate Control

3.4. Definition and principles of stress-aware greenhouse climate control

Stress-aware greenhouse climate control represents a plant-centered paradigm in which environmental regulation is guided by real-time crop physiological status rather than by maintaining rigid environmental setpoints

(Li *et al*., 2024). The primary objective is not to maintain constant temperature or humidity but to minimize physiological stress while optimizing crop productivity, resource-use efficiency, and environmental sustainability (Shah and Wu, 2019). Within this framework, environmental variables become control inputs rather than final objectives. Climate-control technologies including ventilation, evaporative cooling, shading, thermal energy storage, dehumidification, geothermal systems, and renewable energy integration are dynamically coordinated to maintain favorable physiological conditions throughout the crop production cycle (Ghiasi *et al*., 2023). Because plant stress is influenced simultaneously by multiple environmental factors, stress-aware control requires integrated rather than independent regulation of temperature, RH, VPD, CO_2 concentration, and radiation (Zandalinas and Mittler, 2022). Advances in wireless sensor networks, thermal imaging, chlorophyll fluorescence sensing, IoT platforms, and artificial intelligence increasingly enable real-time estimation of plant physiological status. Combined with predictive algorithms and model predictive control (MPC), these technologies support proactive rather than reactive greenhouse operation by anticipating stress before irreversible reductions in crop performance occur (Biswal *et al*., 2026).

3.5. Conceptual framework for next-generation greenhouse management

The transition from conventional climate control to stress-aware greenhouse management represents a fundamental evolution in protected horticulture. Instead of optimizing individual environmental variables independently, future greenhouse systems should simultaneously optimize plant physiological performance, energy efficiency, water productivity, and carbon-use efficiency through multi-objective decision making (Lu *et al*., 2025). Accordingly, greenhouse climate management should be viewed as a dynamic feedback system in which environmental sensors, plant physiological indicators, intelligent control algorithms, and climate-control technologies operate as interconnected components. Physiological signals provide continuous information regarding crop status, intelligent algorithms translate these signals into optimized control decisions, and environmental technologies implement the required actions while minimizing energy and water consumption (Yang *et al*., 2025). This integrated framework forms the scientific basis for evaluating the climate-control technologies discussed in the following sections and provides the foundation for the development of resilient, low-carbon, and intelligent greenhouse production systems.

4. Physiological Basis of Environmental Stress in Greenhouse Crops

4.1. Plant responses to greenhouse environmental conditions

Plant growth and productivity in greenhouse production systems are governed by the continuous interaction between environmental conditions and physiological processes. Air temperature, solar radiation, relative humidity (RH), vapor pressure deficit (VPD), carbon dioxide (CO_2) concentration, and root-zone conditions collectively regulate photosynthesis, respiration, transpiration, nutrient uptake, and biomass accumulation. Because these environmental factors fluctuate throughout the day and across seasons, plants constantly adjust their physiological activities to maintain cellular homeostasis and optimize resource utilization. Unlike open-field crops, greenhouse plants are cultivated in environments where climatic conditions can be actively manipulated. Nevertheless, even under protected cultivation, temporary imbalances among temperature, humidity, radiation, and CO_2 frequently induce physiological stress before visible symptoms appear. Such stress responses reduce photosynthetic efficiency, alter water relations, impair nutrient transport, and ultimately decrease crop yield and quality. Consequently, greenhouse climate management should prioritize maintaining favorable physiological conditions rather than simply controlling environmental variables.

4.2. Thermal stress

Temperature is one of the primary determinants of plant metabolic activity. Photosynthesis, respiration, enzyme kinetics, membrane stability, and reproductive development are all strongly influenced by air and leaf temperature. Moderate increases in temperature generally accelerate metabolic processes; however, temperatures exceeding the optimum range rapidly disrupt physiological function. Heat stress reduces photosynthetic carbon assimilation by decreasing Rubisco activity, destabilizing thylakoid membranes, and impairing photosystem II (PSII). Elevated temperatures also increase photorespiration, accelerate respiration losses, and enhance reactive oxygen species (ROS) production, resulting in oxidative damage to proteins, lipids, and nucleic acids. As thermal stress intensifies, stomata partially close to reduce transpirational water loss, further restricting CO_2 uptake and photosynthetic efficiency. Conversely, suboptimal temperatures reduce membrane fluidity, inhibit enzyme activity, and limit root water uptake, thereby slowing plant growth and delaying crop development. Because the optimal temperature range varies among crop species and developmental stages, greenhouse climate management should maintain dynamic thermal conditions that maximize physiological performance rather than fixed temperature setpoints.

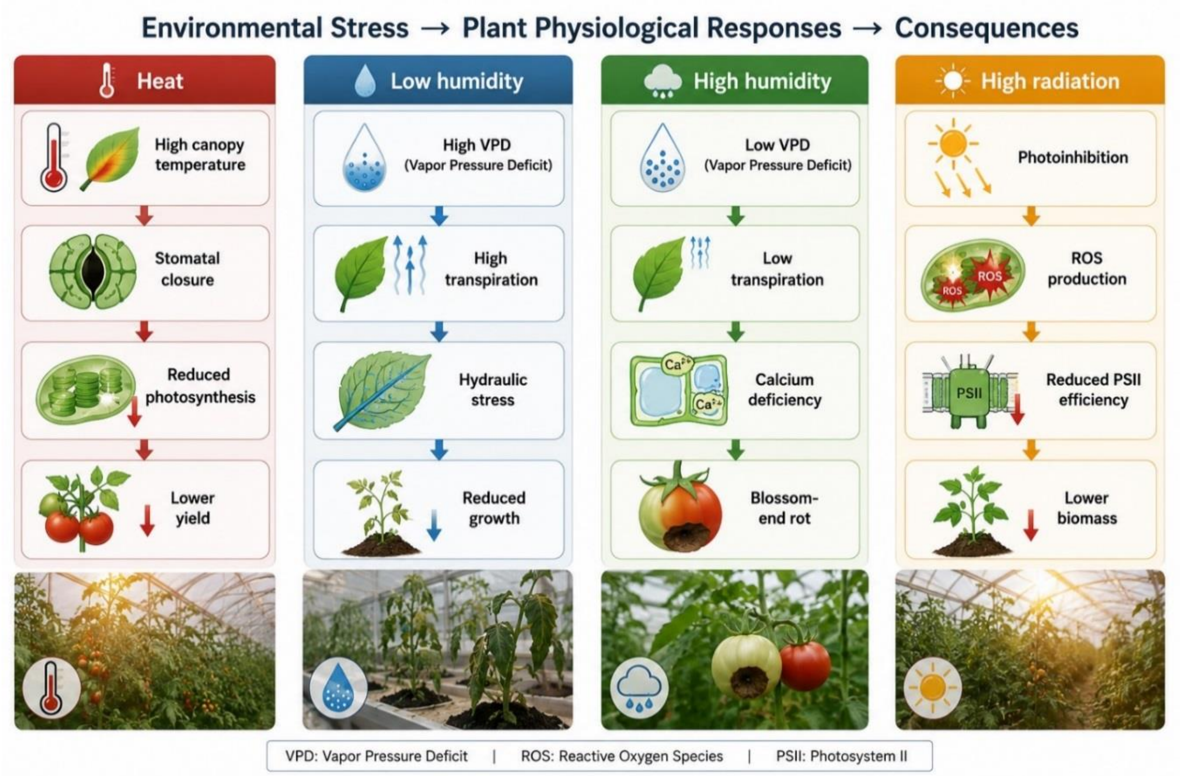

Figure 2. Environmental Stress–Plant Response Relationships

4.3. Hydraulic stress and vapor pressure deficit

Among environmental variables, VPD has emerged as one of the most informative indicators of plant water relations because it integrates the combined effects of air temperature and RH on atmospheric evaporative demand. VPD directly influences transpiration, stomatal conductance, leaf temperature, nutrient transport, and water-use efficiency. Excessively high VPD increases transpiration beyond the capacity of root water uptake, inducing hydraulic stress and partial stomatal closure. As stomata close, transpiration decreases, canopy temperature rises, and photosynthetic carbon assimilation declines despite adequate soil or substrate moisture availability. Prolonged exposure to high VPD therefore reduces biomass accumulation, fruit size, and crop quality. In contrast, excessively low VPD suppresses transpiration and limits xylem transport of relatively immobile nutrients such as calcium, increasing the incidence of physiological disorders including blossom-end rot in tomato and tip burn in leafy vegetables. High humidity associated with low VPD also promotes prolonged leaf wetness and increases disease pressure caused by fungal and bacterial pathogens. Consequently, maintaining crop-specific optimum VPD ranges has become a central objective of modern greenhouse climate management.

4.4. Radiative stress and light management

Solar radiation provides the energy required for photosynthesis but simultaneously represents one of the principal sources of greenhouse heat gain. Under excessive radiation, leaf temperatures frequently exceed air temperature, resulting in photoinhibition, increased photorespiration, and oxidative stress. Excessive radiation also accelerates transpiration, particularly when combined with elevated VPD, thereby increasing hydraulic stress. Conversely, insufficient radiation limits photosynthetic carbon fixation and biomass production. Daily light integral (DLI), which integrates photosynthetically active radiation (PAR) over the photoperiod, has therefore become a more biologically meaningful indicator than instantaneous light intensity alone. Crop-specific DLI management through supplemental lighting, spectral modification, or dynamic shading enables optimization of photosynthesis while minimizing thermal stress and unnecessary energy consumption. The increasing availability of light-emitting diode (LED) technology has further improved greenhouse light management by allowing independent regulation of light intensity, photoperiod, and spectral composition. Dynamic lighting strategies integrated with real-time climate control provide new opportunities to coordinate radiation management with temperature and VPD regulation.

4.5. Carbon limitation and CO_2 dynamics

Carbon dioxide is the substrate for photosynthesis and therefore directly influences crop productivity. In densely planted greenhouses, photosynthetic activity frequently reduces internal CO_2 concentration below ambient levels during daylight hours, particularly under limited ventilation. Conversely, excessive ventilation intended to reduce temperature or humidity may rapidly dilute enriched CO_2, decreasing carbon-use efficiency while increasing heating or cooling demand. Maintaining appropriate CO_2 concentrations enhances photosynthesis, biomass accumulation, and water-use efficiency by increasing the rate of carbon assimilation per unit of transpired water. However, the physiological benefits of CO_2 enrichment depend strongly on simultaneous optimization of temperature, VPD, radiation, and nutrient availability. Consequently, CO_2 management should be considered an integral component of stress-aware climate control rather than an independent environmental variable.

4.6. Physiological indicators for real-time stress detection

The transition toward intelligent greenhouse management has increased interest in physiological indicators capable of detecting plant stress before visible symptoms develop. Among these, canopy temperature measured by infrared thermography provides a rapid indicator of stomatal closure and hydraulic stress. Chlorophyll fluorescence analysis enables early assessment of photosystem II efficiency and photochemical damage under thermal, drought, or radiation stress. Additional physiological indicators include stomatal conductance, transpiration rate, leaf-to-air temperature difference, sap flow, photosynthetic rate, and water-use efficiency. When integrated with environmental measurements, these indicators provide comprehensive information regarding crop physiological status and substantially improve decision-making compared with conventional environmental monitoring alone. Recent advances in multispectral imaging, hyperspectral sensing, machine vision, and wireless sensor networks further enable continuous, non-destructive monitoring of plant responses throughout the production cycle. These technologies form the foundation of next-generation greenhouse climate-control systems driven by real-time crop physiology.

4.7. Implications for stress-aware greenhouse climate management

Plant physiological responses demonstrate that environmental variables cannot be managed independently because changes in one climatic factor inevitably influence multiple physiological processes. For example, ventilation simultaneously modifies temperature, RH, VPD, and CO_2 concentration, whereas evaporative cooling decreases temperature but increases humidity. Similarly, shading reduces thermal stress while altering the light available for photosynthesis. These interactions illustrate that greenhouse climate management represents a multi-objective optimization problem requiring continuous balancing of crop physiology, resource-use efficiency, and environmental sustainability. Accordingly, effective greenhouse climate control should be based on integrated physiological monitoring rather than fixed environmental thresholds. A stress-aware management framework utilizes physiological indicators as feedback signals for intelligent decision-making, enabling dynamic adjustment of climate-control technologies according to crop requirements, developmental stage, and external weather conditions. This physiological perspective provides the scientific basis for evaluating greenhouse climate-control technologies discussed in the following sections.

5. Technologies for Stress-Aware Greenhouse Climate Control

Modern greenhouse climate management requires the coordinated application of multiple technologies to regulate the environmental conditions that determine plant physiological performance. Within a stress-aware framework, climate-control technologies are not evaluated solely according to their engineering efficiency or energy consumption, but according to their ability to alleviate specific physiological stresses while minimizing adverse effects on crop productivity, resource-use efficiency, and environmental sustainability. Because temperature, humidity, radiation, and carbon dioxide interact continuously, no single technology can simultaneously eliminate all forms of stress. Consequently, greenhouse climate control should be considered an integrated, multi-objective process in which complementary technologies operate synergistically to maintain optimal plant physiological status.

5.1. Passive climate-control technologies

Passive climate-control strategies constitute the first line of defense against environmental stress because they reduce thermal load before active energy-consuming systems become necessary (Jørgensen and Ma, 2025). These technologies primarily include greenhouse orientation, structural design, covering materials, external and internal shading, reflective coatings, natural ventilation openings, and near-infrared (NIR)-selective greenhouse films. From a physiological perspective, passive systems reduce excessive canopy temperature and radiative stress by limiting solar heat gain while maintaining adequate light availability for photosynthesis (Gridtayawong *et al.*, 2026). Appropriate greenhouse orientation improves solar distribution throughout the day, whereas spectrally selective glazing materials reduce infrared radiation without substantially decreasing photosynthetically active radiation (PAR). Dynamic shading systems further mitigate photoinhibition, excessive transpiration, and leaf overheating during periods of intense solar radiation (Gomez-Casanovas *et al.*, 2023). The principal advantage of passive technologies is their negligible operational energy requirement and relatively low maintenance cost. However, their cooling capacity depends entirely on prevailing weather conditions and greenhouse design (Soussi *et al*., 2022). Excessive shading may reduce the daily light integral (DLI), thereby limiting photosynthesis and fruit yield, while permanently reflective materials may increase winter heating demand (Jayalath *et al*., 2024). Consequently, adaptive shading systems and seasonally adjustable covering materials are generally preferred over static solutions. Within stress-aware greenhouse management, passive technologies should serve as preventive measures that reduce the occurrence of thermal and radiative stress before active cooling systems are activated (Tian *et al*., 2025).

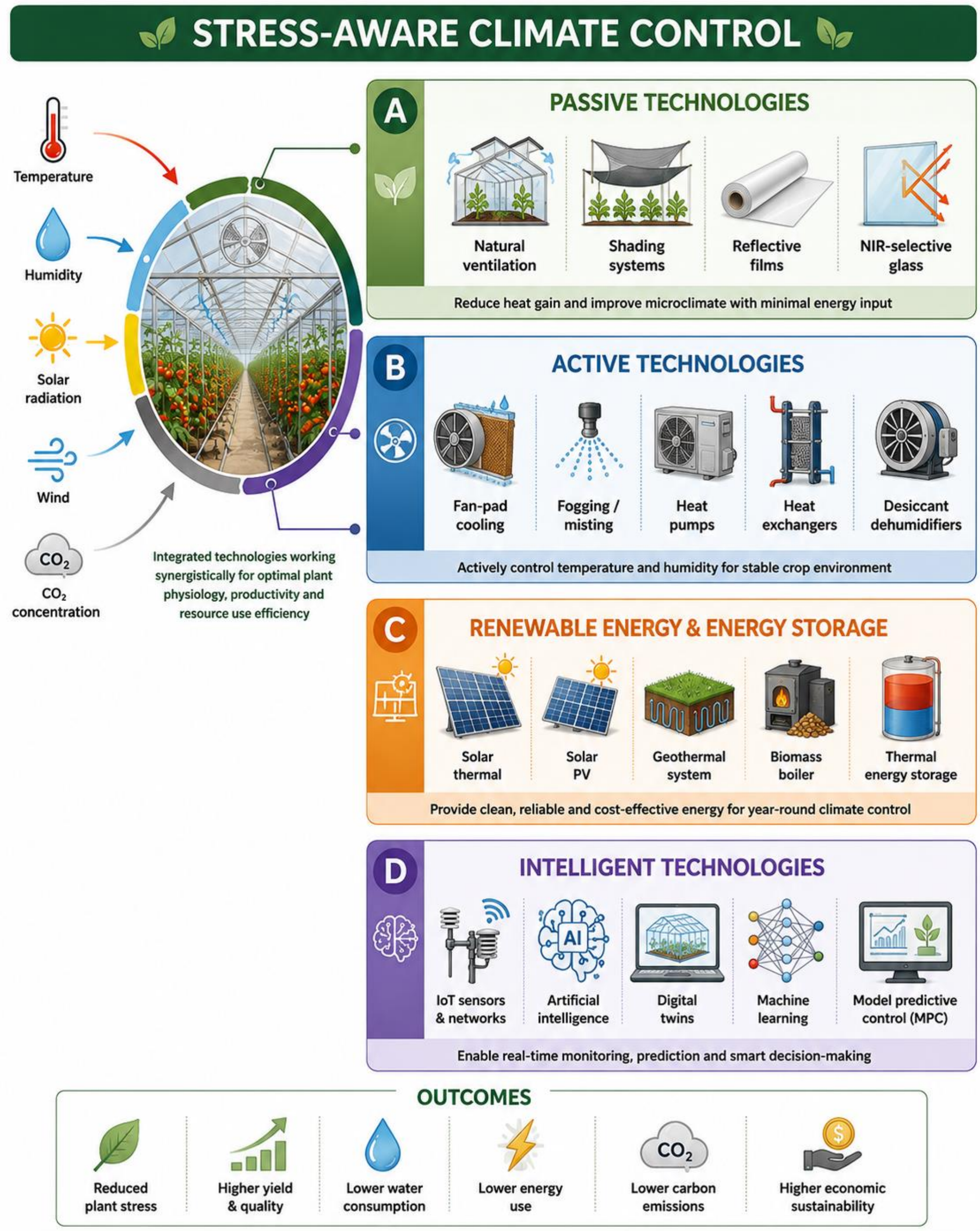

Figure 3. Classification of Greenhouse Climate-Control Technologies

5.2. Ventilation-based climate control

Ventilation remains one of the most widely implemented greenhouse climate-control strategies because it simultaneously regulates temperature, humidity, and internal air composition. Natural ventilation utilizes wind pressure and buoyancy forces to exchange greenhouse air with the external environment, whereas forced ventilation employs mechanical fans to ensure adequate air movement under unfavorable climatic conditions (Zhang *et al*., 2022). From a physiological perspective, ventilation primarily mitigates thermal stress by removing sensible heat while simultaneously reducing humidity and increasing vapor pressure deficit (Zhang *et al*., 2022). Under favorable climatic conditions, improved air circulation enhances transpiration, leaf cooling, gas exchange, and nutrient transport. However, ventilation also introduces important physiological trade-offs. Excessive air exchange may reduce internal CO_2 concentrations, limiting photosynthetic carbon assimilation despite improved temperature control (Al-Helal *et al*., 2025). Furthermore, under cool weather conditions, ventilation-driven dehumidification frequently results in significant heat losses, thereby increasing energy consumption. The effectiveness of ventilation strongly depends on external weather conditions, greenhouse geometry, roof-vent configuration, and crop canopy characteristics (Akrami *et al*., 2020). Consequently, ventilation should not operate as an independent control strategy but rather as one component of an integrated climate-management system coordinated with shading, evaporative cooling, CO_2 enrichment, and humidity control.

5.3. Evaporative cooling technologies

Evaporative cooling is among the most effective approaches for reducing greenhouse temperature in hot and arid climates. The technology exploits the latent heat of water evaporation to decrease air temperature and improve plant water relations (Ghani *et al*., 2019). Commercial greenhouse systems commonly employ fan-and-pad cooling, roof evaporative cooling, misting, and high-pressure fogging systems. Within a stress-aware framework, evaporative cooling effectively reduces thermal stress by lowering canopy temperature and decreasing transpirational demand (Luan and Vico, 2021). Under dry climatic conditions, simultaneous reductions in temperature and VPD improve stomatal conductance, maintain leaf water status, and enhance photosynthetic efficiency (Zhang *et al*., 2021). Nevertheless, evaporative cooling inherently increases relative humidity, which may suppress transpiration, reduce calcium transport, prolong leaf wetness, and increase disease incidence under humid conditions (Ranawana *et al*., 2023). Therefore, its effectiveness depends strongly on ambient humidity, crop species, and seasonal weather conditions. Recent developments in variable-rate fogging, pulse-width modulation control, and sensor-based misting systems have substantially improved water-use efficiency while reducing unnecessary humidity accumulation (Margareta *et al*., 2025). Integrating evaporative cooling with real-time VPD monitoring enables dynamic regulation according to crop physiological requirements rather than fixed temperature thresholds, thereby improving both water productivity and climate stability (Villagran *et al*., 2024).

5.4. Heat-based cooling and dehumidification systems

Unlike ventilation and evaporative cooling, heat-based technologies enable independent regulation of temperature and humidity, making them particularly suitable for semi-closed and closed greenhouse systems (Kucukerdem and Ozturk, 2025). These technologies include air-to-air heat exchangers, air-to-water heat exchangers, mechanical heat pumps, condensation-based dehumidification systems, and liquid or solid desiccant technologies. Their principal physiological advantage is the ability to maintain favorable VPD while minimizing CO_2 losses associated with conventional ventilation. Heat exchangers recover sensible and latent heat from greenhouse exhaust air, thereby improving energy efficiency during dehumidification (Zhu *et al*., 2026). Mechanical heat pumps simultaneously remove sensible and latent heat, providing highly precise climate regulation despite relatively high electricity demand (Kou *et al*., 2024). Desiccant systems remove atmospheric moisture without excessive cooling, making them especially valuable in humid climates where conventional evaporative cooling becomes ineffective (Abbas *et al*., 2025). Although these technologies require higher capital investment and greater operational complexity than conventional systems, their compatibility with renewable energy sources, thermal storage, and intelligent climate-control algorithms makes them increasingly attractive for high-value horticultural production.

5.5. Renewable energy and thermal energy storage

Improving greenhouse sustainability requires not only efficient climate-control technologies but also sustainable energy sources. Renewable energy systems including photovoltaic panels, solar thermal collectors, geothermal heat exchangers, and biomass heating are increasingly integrated into greenhouse production to reduce fossil-fuel dependence and greenhouse gas emissions (Maraveas *et al*., 2023). Thermal energy storage further enhances system efficiency by decoupling energy generation from energy demand. Water tanks, underground storage, rock beds, and phase-change materials (PCMs) store excess thermal energy during periods of surplus availability and release it when climatic conditions require heating or cooling (Eze *et al*., 2024). This temporal flexibility reduces peak energy demand, stabilizes greenhouse temperature, and improves overall system resilience. From a physiological perspective, renewable energy technologies indirectly contribute to stress mitigation by enabling more stable environmental conditions while reducing operational costs and environmental impacts (Panda *et al*., 2025). Their integration with advanced climate-control technologies forms an essential component of future low-carbon greenhouse production systems.

5.6. Intelligent climate-control technologies

Rapid advances in digital agriculture have transformed greenhouse climate management from reactive environmental regulation toward predictive, plant-centered decision making (Dineshkumar, 2025). Wireless sensor networks, Internet of Things (IoT) platforms, machine vision, thermal imaging, artificial intelligence (AI), and model predictive control (MPC) increasingly enable continuous monitoring of both environmental variables and plant physiological status. Artificial intelligence algorithms can analyze large datasets describing temperature, radiation, humidity, VPD, CO_2 concentration, canopy temperature, and crop development to predict stress before irreversible physiological damage occurs (Vennam *et al*., 2026). Machine learning models continuously improve prediction accuracy by learning from previous greenhouse operation, whereas digital twins provide virtual representations of greenhouse systems capable of evaluating multiple control strategies before implementation (Zhang *et al*., 2026). Model predictive control represents one of the most promising approaches for stress-aware greenhouse management because it simultaneously optimizes multiple objectives, including crop productivity, energy consumption, water use, and carbon efficiency (Xiao *et al*., 2024). Instead of reacting to instantaneous environmental conditions, MPC predicts future climate dynamics using weather forecasts, crop models, and greenhouse energy balances, enabling proactive rather than reactive climate regulation (Benzzine *et al*., 2025).

5.7. Comparative evaluation and technology integration

No individual climate-control technology can simultaneously optimize all aspects of greenhouse performance. Passive systems provide low-cost prevention of thermal stress but have limited adaptability under extreme climatic conditions. Ventilation effectively removes sensible heat but often compromises CO_2 enrichment and energy efficiency. Evaporative cooling performs exceptionally well in arid climates but becomes less effective under humid conditions. Heat-based systems provide precise regulation of temperature and humidity but require substantial capital investment. Renewable energy technologies reduce environmental impacts but require intelligent integration with storage systems and climate-control infrastructure. Consequently, future greenhouse climate management should rely on integrated hybrid systems in which multiple technologies operate cooperatively according to crop physiological requirements, climatic conditions, and available energy resources (Bicamumakuba *et al*., 2025). Such systems should continuously balance the competing objectives of maximizing crop productivity while minimizing energy consumption, water use, carbon emissions, and disease risk. Within this framework, stress-aware greenhouse climate control evolves from a collection of independent engineering technologies into an intelligent, adaptive decision-support system centered on maintaining optimal plant physiological performance.

6. Technology Trade-Offs and Multi-Objective Optimization in Stress-Aware Greenhouse Climate Control

6.1. The need for multi-objective climate management

Greenhouse climate control has traditionally been designed to optimize individual environmental variables, such as air temperature, relative humidity (RH), or carbon dioxide (CO_2) concentration (Chen *et al*., 2025). However, these variables are highly interconnected, and improving one aspect of the greenhouse environment frequently results in undesirable changes in another. Consequently, greenhouse climate management should be regarded as a multi-objective optimization problem, where the simultaneous objectives include maximizing crop productivity and quality while minimizing energy consumption, water use, carbon emissions, operational costs, and disease risk (Getahun *et al*., 2024). From a stress-aware perspective, the primary objective is not to maintain fixed environmental conditions but to maintain optimal plant physiological status under continuously changing environmental conditions (Scheibe *et al*., 2019). This requires balancing the interactions among temperature, radiation, VPD, CO_2 concentration, transpiration, and crop developmental stage. The optimal climate therefore becomes dynamic rather than static, varying according to crop species, growth stage, external weather, and production objectives.

6.2. Physiological trade-offs among climate-control technologies

Each greenhouse climate-control technology effectively alleviates specific forms of environmental stress while simultaneously introducing secondary physiological consequences (Fanourakis *et al*., 2025). Understanding these interactions is essential for selecting appropriate technologies under different production scenarios. Passive shading effectively reduces canopy temperature and photoinhibition while decreasing cooling demand. However, excessive shading lowers the daily light integral (DLI), potentially reducing photosynthesis, biomass accumulation, and fruit yield (Zamani *et al*., 2025). Therefore, dynamic or movable shading systems are generally preferable to permanent shading materials because they allow light transmission to be adjusted according to crop requirements and seasonal conditions (Zamani *et al*., 2025). Ventilation efficiently removes sensible heat and excess humidity but inevitably exchanges greenhouse air with the external environment (Li *et al*., 2023). While this process improves transpiration and reduces thermal stress, it frequently dilutes CO_2 concentrations, thereby reducing photosynthetic carbon assimilation. In cool climates, excessive ventilation also increases heating demand by removing warm internal air, highlighting the conflict between dehumidification and energy conservation (Zhu *et al*., 2026). Evaporative cooling is particularly effective under hot and arid conditions, where simultaneous reductions in air temperature and VPD improve leaf water status and delay stomatal closure (Gauthey *et al*., 2024). Nevertheless, increasing RH may suppress transpiration under humid conditions, reduce calcium transport, and increase the incidence of diseases such as Botrytis cinerea and powdery mildew (Fanourakis *et al*., 2026).

Consequently, evaporative cooling should be dynamically controlled using physiological indicators rather than fixed temperature thresholds. Heat pumps, heat exchangers, and desiccant-based dehumidification systems provide precise regulation of temperature and humidity while minimizing CO_2 losses (Xia *et al*., 2026). However, their higher installation costs and energy requirements may limit adoption in low-value production systems. Their economic viability improves substantially when integrated with renewable energy sources or thermal energy storage systems. These examples illustrate that no individual technology can eliminate all forms of plant stress without creating secondary limitations (Liu *et al*., 2022). Effective greenhouse climate management therefore depends on coordinated combinations of complementary technologies.

6.3. Balancing energy efficiency and crop physiological performance

Improving greenhouse energy efficiency should not compromise plant physiological performance. Strategies designed solely to reduce energy consumption may inadvertently expose crops to thermal, hydraulic, or carbon-assimilation stress, ultimately decreasing productivity and product quality (Paul and Machavaram, 2026). For example, reducing ventilation to conserve heat may increase RH and lower VPD, suppressing transpiration and increasing disease risk. Conversely, excessive ventilation improves humidity control but increases heating demand and decreases CO_2-use efficiency (Chen *et al*., 2026). Similarly, maximizing shading reduces cooling requirements but may lower photosynthetic activity through reduced light availability (Campany *et al*., 2016). Stress-aware greenhouse management addresses these conflicts by evaluating climate-control decisions according to their combined effects on crop physiology and resource consumption. This integrated perspective enables greenhouse operators to identify operating conditions that maximize productivity per unit of energy and water rather than minimizing energy consumption alone (Ghiasi *et al*., 2023).

6.4. Integration of renewable energy and climate-control technologies

Renewable energy technologies are increasingly recognized as essential components of sustainable greenhouse production. Photovoltaic systems, solar thermal collectors, geothermal heat exchangers, biomass heating, and thermal energy storage can substantially reduce greenhouse dependence on fossil fuels while improving long-term economic sustainability (Hasan *et al*., 2023). However, renewable energy systems should not be considered independent technologies but rather enabling components of integrated greenhouse climate management. Thermal energy storage, for example, allows surplus solar energy collected during the day to be utilized for nighttime heating or cooling, reducing peak electricity demand and stabilizing greenhouse temperature (Elkhatat and Al-Muhtaseb, 2023). Ground-source heat pumps maintain high coefficients of performance throughout the year because of relatively stable underground temperatures, making them particularly suitable for high-technology greenhouse systems (Benli, 2013). Integrating renewable energy with intelligent climate-control algorithms further improves system performance by allowing energy-intensive operations to be scheduled during periods of maximum renewable energy availability or lower electricity prices (Ukoba *et al*., 2024). Such coordinated management simultaneously enhances energy efficiency, crop productivity, and environmental sustainability.

6.5. Artificial intelligence and predictive optimization

The rapid development of artificial intelligence (AI) has fundamentally changed greenhouse climate management by enabling predictive rather than reactive control strategies (Adegbite *et al*., 2024). Machine learning algorithms can identify complex nonlinear relationships among environmental variables, crop physiology, and greenhouse energy consumption that are difficult to capture using conventional control methods (Li *et al*., 2025). Model Predictive Control (MPC) has emerged as one of the most promising approaches for stress-aware greenhouse operation. MPC combines crop growth models, greenhouse energy balance equations, and short-term weather forecasts to predict future greenhouse conditions and optimize control actions before plant stress develops (Nagarsheth *et al*., 2025). Instead of responding to current environmental measurements alone, predictive algorithms continuously calculate optimal strategies that simultaneously minimize energy use, water consumption, and physiological stress. Digital twins further enhance predictive optimization by creating virtual representations of greenhouse systems capable of simulating alternative climate-control strategies under different weather scenarios (Chaux *et al*., 2021). Combined with wireless sensor networks, thermal imaging, chlorophyll fluorescence monitoring, and IoT platforms, these technologies provide the foundation for autonomous greenhouse management capable of continuously adapting to changing crop and environmental conditions (Zhang *et al*., 2025).

6.6. Future directions in multi-objective greenhouse optimization

Future greenhouse climate management will increasingly rely on integrated optimization frameworks that simultaneously consider crop physiology, resource efficiency, economic profitability, and environmental sustainability. Instead of optimizing temperature, humidity, or CO_2 independently, next-generation decision-support systems will regulate multiple interacting variables using real-time physiological feedback and predictive modeling (Biswal *et al*., 2026). Emerging research should focus on developing crop-specific physiological thresholds for stress detection, integrating multisensor data with machine learning algorithms, improving digital twin accuracy, and establishing standardized evaluation frameworks for intelligent greenhouse technologies (Sharma *et al*., 2025). Greater attention should also be given to the water–energy–carbon nexus, ensuring that improvements in one sustainability indicator do not inadvertently compromise another. Ultimately, the transition toward stress-aware greenhouse climate control represents a shift from technology-centered management to physiology-driven, data-informed, and sustainability-oriented decision making. Such an approach will enable resilient greenhouse production systems capable of maintaining high crop productivity while reducing environmental impacts under increasingly variable climatic conditions (Gerampinis *et al*., 2026).

7. Future Research Directions for Stress-Aware Greenhouse Climate Control

7.1. Transition toward plant-centered greenhouse management

Greenhouse climate management is undergoing a fundamental transformation from maintaining fixed environmental conditions to dynamically regulating crop physiological status (Chen *et al*., 2025). Future greenhouse systems will increasingly prioritize plant responses rather than environmental setpoints, enabling climate control strategies that adapt continuously to crop developmental stage, genotype, environmental variability, and production objectives. This transition requires a deeper understanding of the interactions among environmental variables, plant physiology, and crop productivity, as well as the development of robust physiological thresholds for different horticultural species. Future research should focus on identifying crop-specific stress indicators that accurately reflect the onset of physiological limitations before visible symptoms occur. Establishing dynamic thresholds for canopy temperature, vapor pressure deficit (VPD), stomatal conductance, chlorophyll fluorescence, and transpiration under different environmental conditions will improve the precision of intelligent climate-control systems and facilitate their application across diverse greenhouse crops (Chen *et al*., 2025).

7.2. Artificial intelligence and autonomous greenhouse operation

Artificial intelligence (AI) is expected to become the central component of future greenhouse climate management (Adegbite *et al*., 2021). While current greenhouse control systems primarily react to measured environmental conditions, AI-based approaches can predict future plant responses using historical climate records, crop growth models, weather forecasts, and real-time sensor data (Pimenow *et al*., 2024). Machine learning, deep learning, and reinforcement learning algorithms have the potential to continuously optimize greenhouse operation by learning from previous production cycles and adapting control strategies to changing environmental conditions (Platero-Horcajadas *et al*., 2024). Autonomous decision-support systems capable of integrating physiological monitoring with environmental control may substantially reduce human intervention while improving productivity and resource-use efficiency (Hindi *et al*., 2026). Future research should therefore prioritize the development of interpretable AI models, standardized training datasets, and hybrid modeling approaches that combine physiological knowledge with data-driven algorithms. Such systems should not only predict environmental conditions but also estimate future crop performance and stress risk under alternative management scenarios.

7.3. Digital twins and predictive greenhouse management

Digital twin technology represents one of the most promising innovations for intelligent greenhouse production. A digital twin is a dynamic virtual representation of a greenhouse that continuously receives information from environmental sensors, crop monitoring systems, and operational equipment (Ariesen-Verschuur *et al*., 2022). By integrating real-time data with process-based crop models and engineering simulations, digital twins enable growers to evaluate alternative climate-control strategies before implementation (Rahman *et al*., 2024). Future digital twin platforms should integrate greenhouse energy balance models, plant physiological processes, crop growth simulations, renewable energy systems, and economic analyses within a unified decision-support framework. Such integration would enable continuous optimization of productivity, energy consumption, water use, and operational costs under changing climatic conditions (Howard *et al*., 2020). Further research is needed to improve model calibration, data assimilation techniques, and computational efficiency to facilitate the commercial adoption of digital twin technologies in protected horticulture.

7.4. Multi-sensor physiological monitoring

Recent advances in sensing technologies have created new opportunities for real-time assessment of crop physiological status (Sharma and Shivandu, 2024). Future greenhouse monitoring systems will likely combine environmental sensors with infrared thermography, hyperspectral and multispectral imaging, chlorophyll fluorescence measurements, sap-flow sensors, gas-exchange systems, and machine vision to generate comprehensive assessments of plant health. Sensor fusion approaches that integrate multiple physiological indicators are expected to improve the accuracy of stress detection compared with single-sensor systems (Kim *et al*., 2026). For example, combining canopy temperature with chlorophyll fluorescence and VPD measurements may enable earlier identification of heat and water stress before reductions in photosynthesis become irreversible. Future research should focus on developing low-cost, reliable, and automated sensing platforms suitable for commercial greenhouse production while establishing standardized protocols for physiological stress assessment across different crop species.

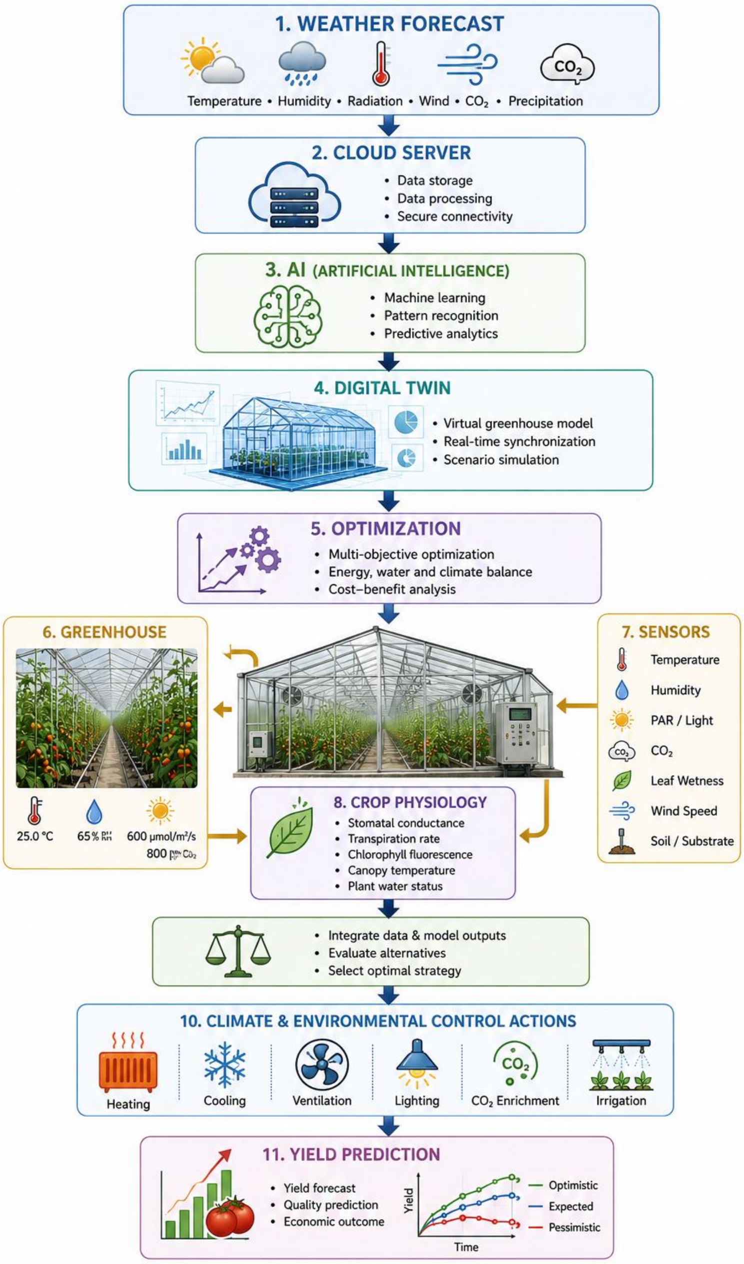

Figure 4. Future Intelligent Greenhouse

7.5. Renewable energy integration and carbon-neutral greenhouses

Improving greenhouse sustainability requires simultaneous optimization of crop productivity and energy efficiency. Renewable energy technologies, including photovoltaic systems, solar thermal collectors, geothermal heat pumps, biomass heating, and thermal energy storage, will play increasingly important roles in reducing greenhouse dependence on fossil fuels (Kalair *et al*., 2021). Future greenhouse energy systems should be designed as integrated energy-management networks rather than isolated technologies. Combining renewable energy generation with intelligent scheduling algorithms, thermal storage systems, and predictive climate-control models can substantially reduce energy costs while maintaining stable crop-growing conditions (Soussi *et al*., 2025). Additional research is needed to evaluate the long-term economic feasibility, life-cycle environmental impacts, and operational reliability of renewable energy systems under different climatic regions and greenhouse production systems.

7.6. Multi-objective optimization and the water-energy-carbon nexus

Future greenhouse climate management must address the complex interactions among water use, energy consumption, carbon emissions, and crop productivity. Optimizing a single performance indicator often produces unintended consequences in other components of the production system. Consequently, future decision-support systems should adopt multi-objective optimization frameworks capable of simultaneously balancing environmental, economic, and physiological objectives. Integrating crop growth models with energy balance simulations, economic analyses, and environmental impact assessments will enable greenhouse operators to identify management strategies that maximize overall system sustainability rather than individual performance indicators. Such approaches are particularly important under climate change, where increasing environmental variability will require more flexible and adaptive greenhouse operation.

7.7. Remaining research gaps

Despite rapid technological advances, several critical knowledge gaps continue to limit the implementation of stress-aware greenhouse climate control. Most published studies evaluate individual technologies under controlled experimental conditions, whereas relatively few investigate integrated climate-control strategies under commercial production environments. Similarly, standardized physiological stress thresholds remain unavailable for many economically important horticultural crops, limiting the transferability of intelligent control algorithms. Additional challenges include limited interoperability among greenhouse sensors, insufficient integration of physiological and engineering datasets, lack of standardized performance metrics for AI-based climate-control systems, and inadequate economic evaluation of emerging technologies. Addressing these limitations will require stronger collaboration among horticulturists, plant physiologists, greenhouse engineers, computer scientists, and data analysts.

7.8. Outlook

The future of greenhouse climate management lies in the convergence of plant physiology, advanced sensing technologies, artificial intelligence, renewable energy, and predictive decision-support systems. Greenhouse control strategies will progressively evolve from maintaining static environmental conditions toward continuously optimizing crop physiological performance under dynamic environmental conditions. This transformation will enable greenhouse production systems that are more productive, resource-efficient, resilient to climate change, and environmentally sustainable. The stress-aware framework presented in this review provides a conceptual pathway for this transition by integrating physiological indicators, intelligent climate-control technologies, and multi-objective optimization into a unified strategy for next-generation protected horticulture. Continued interdisciplinary research and technological innovation will be essential to translate this framework into practical greenhouse management systems capable of meeting future demands for sustainable food production.

Conclusions

Greenhouse climate management is evolving from conventional environmental regulation toward intelligent, plant-centered systems that prioritize crop physiological performance alongside resource-use efficiency and environmental sustainability. This review demonstrates that maintaining fixed environmental setpoints alone is insufficient to optimize greenhouse production because plant responses are governed by the complex interactions among temperature, vapor pressure deficit (VPD), radiation, carbon dioxide concentration, humidity, and crop developmental stage. Consequently, effective greenhouse climate control requires continuous assessment of plant physiological status rather than reliance on static environmental thresholds. A major contribution of this review is the development of a stress-aware greenhouse climate control framework, in which climate-control decisions are guided by real-time physiological indicators such as canopy temperature, stomatal conductance, chlorophyll fluorescence, transpiration rate, daily light integral (DLI), and VPD. By integrating these indicators with environmental sensing, intelligent control algorithms, and advanced climate-control technologies, greenhouse management can shift from reactive environmental regulation to predictive and adaptive decision-making. This plant-centered approach enables earlier stress detection, improves photosynthetic performance, enhances water- and energy-use efficiency, and increases crop resilience under increasingly variable climatic conditions. The synthesis presented in this review further demonstrates that no single climate-control technology can simultaneously eliminate all environmental stresses while maximizing crop productivity and sustainability. Passive cooling, ventilation, evaporative cooling, dehumidification, thermal energy storage, renewable energy systems, and intelligent environmental control each provide distinct advantages but also introduce physiological, energetic, and economic trade-offs. Their effectiveness depends on greenhouse design, climatic conditions, crop species, and production objectives. Therefore, future greenhouse systems should rely on integrated hybrid strategies that dynamically coordinate multiple technologies rather than implementing isolated engineering solutions. Artificial intelligence, Internet of Things (IoT) platforms, digital twins, wireless sensor networks, and Model Predictive Control (MPC) are expected to become key enabling technologies for next-generation greenhouse management. These innovations will facilitate predictive climate regulation by combining real-time physiological monitoring with weather forecasting, crop growth models, and energy management algorithms. Such integrated decision-support systems have the potential to simultaneously optimize crop productivity, energy consumption, water use, carbon-use efficiency, and economic performance while reducing greenhouse gas emissions and operational costs. Despite substantial technological progress, important research challenges remain. Crop-specific physiological stress thresholds, standardized protocols for stress detection, multisensor data integration, interoperability among greenhouse monitoring systems, and long-term validation of AI-driven control strategies require further investigation. Moreover, future studies should increasingly adopt multidisciplinary approaches that integrate horticultural science, plant physiology, greenhouse engineering, renewable energy, computer science, and data analytics to develop robust and commercially applicable climate-control systems. Overall, this review proposes a conceptual transition from environment-centered climate regulation to stress-aware, physiology-driven greenhouse management. This framework provides a comprehensive foundation for evaluating greenhouse climate-control technologies according to their physiological effectiveness, resource-use efficiency, and operational feasibility rather than engineering performance alone. By integrating plant physiology with intelligent sensing, predictive control, and sustainable energy management, stress-aware greenhouse climate control represents a promising pathway toward resilient, low-carbon, and highly productive protected horticulture. The concepts and perspectives presented in this review are expected to support future research, guide technology development, and facilitate the implementation of next-generation greenhouse production systems capable of meeting the growing global demand for sustainable horticultural crops under changing climatic conditions.

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