Analysis of the Impact of Greenhouse Environmental Variability on Growth Uniformity in Melons

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***Abstract*— Greenhouse environments show considerable temporal variability, yet climate control often focuses on maintaining average set-points rather than managing instability. This study investigates how variability in temperature, relative humidity, CO_2 concentration, and radiation influences growth uniformity in greenhouse-grown melons (Cucumis melo L.). Environmental variability was quantified using daily, rolling, and lagged coefficients of variation, while growth uniformity was assessed through plant-to-plant variation in vegetative traits. Results reveal stage-dependent responses, with temperature and humidity variability exerting the strongest effects during early and mid growth stages. These findings emphasize the importance of variability-aware climate management for improving growth uniformity and production predictability.**

***Keywords*— Melon, Environmental variability, Growth uniformity, Microclimate stability, Smart greenhouse.**

I. INTRODUCTION

Greenhouse-based horticulture has become an essential component of modern agriculture by enabling stable crop production under increasingly unpredictable climate conditions. Recent advances in smart greenhouse systems—such as multi-sensor monitoring networks, automated climate control, and data-driven decision-support tools—have significantly improved growers' ability to regulate temperature, humidity, CO_2 concentration, and radiation in real time [1-3]. Despite these technological developments, greenhouse environments still exhibit substantial temporal variability, driven by external weather fluctuations, ventilation events, heating cycles, and crop transpiration processes. Such variability can create microclimate instability within the canopy, ultimately influencing crop growth and uniformity.

Traditionally, greenhouse climate management has focused primarily on maintaining average set-points, while the role of environmental variability itself has received relatively little attention. However, emerging perspectives in crop science suggest that plants respond not only to absolute environmental conditions but also to their fluctuations over time. Prior studies have demonstrated that abrupt temperature shifts can alter fruit development in horticultural crops such as kumquat [4], and that microclimate stabilization through shading or ventilation management improves melon quality and sweetness [5-6]. In addition, research on muskmelon has shown that spatial heterogeneity caused by planting density can affect yield distribution and uniformity [7]. These findings underscore the importance of both spatial and temporal stability in greenhouse environments.

At the same time, plant-to-plant growth variation, often treated as experimental noise, has recently been recognized as a biologically meaningful signal that reflects the interaction between plants and their micro-environment. Precision agriculture studies have highlighted the value of quantifying variability to improve sampling accuracy and understand crop–environment interactions more effectively [8]. Growth uniformity is particularly important in commercial melon production, where variability in shoot length, stem diameter, and leaf development can influence labor efficiency, harvest scheduling, grading costs, and marketability.

Despite its importance, few studies have quantitatively examined how time-series environmental variability—measured using statistical metrics such as the coefficient of variation (CV)—directly influences plant-level growth uniformity in greenhouse-grown melons. Moreover, the stage-specific sensitivity of melon plants to microclimate instability remains poorly understood. Since melons undergo distinct physiological transitions across early, mid, and late vegetative stages, their responses to environmental fluctuation may differ substantially over time.

To address these gaps, this study analyzes a multi-sensor environmental dataset and detailed plant growth measurements collected from a commercial smart greenhouse operated by the Jeollanam-do Agricultural Research and Extension Services (Naju, Republic of Korea). Environmental variability was quantified using daily CV, 7-day rolling CV, and lagged CV metrics, while growth uniformity was evaluated through plant-to-plant CV of shoot length, stem diameter, and leaf morphological traits. Stage-specific regression, correlation, and time-series analyses were conducted to identify how microclimate instability influences growth uniformity at each developmental phase.

The objectives of this study are as follows:

1. To quantify temporal environmental variability in temperature, humidity, CO_2 concentration, and radiation throughout the melon growth cycle.
2. To evaluate plant growth uniformity using daily and stage-wise CV metrics for major vegetative traits.
3. To assess relationships between environmental variability and growth uniformity across early, mid, and late developmental stages.
4. To provide insights that support the development of next-generation smart greenhouse control strategies incorporating environmental stability metrics.

The findings of this study contribute to the emerging understanding that environmental variability—not only average climate conditions—plays a crucial role in determining plant growth uniformity. This research also provides empirical evidence for integrating variability-based monitoring into AI-driven climate control algorithms to improve productivity and predictability in melon cultivation.

II. Materials and Methods

A. Experimental Site and Plant Materials

The experiment was performed in a commercial smart greenhouse located in Naju, Republic of Korea, operated by the Jeollanam-do Agricultural Research and Extension Services. The greenhouse is equipped with automated ventilation, heating, and fertigation systems and contains a multi-sensor network for continuous climate monitoring. An overview of the greenhouse interior is provided in Figure 1(a).

Figure 1. Overview of the experimental greenhouse and melon cultivars used in this study.

Two melon cultivars, ‘Damas’ and ‘Supia’, were cultivated on substrate beds under standard commercial management practices. Representative images of the cultivars used in this study are shown in Fig. 1(b–c).

B. Environmental data acquisition

Environmental variables were recorded every hour using calibrated sensors positioned at canopy height.

The variables and their definitions are listed in Table 1.

TABLE I. Environmental variables measured in the greenhouse and their definitions.

Variable	Symbol	Unit	Description
Internal air temperature	T_in	°C	Hourly temperature inside the greenhouse
External air temperature	T_out	°C	Outdoor reference temperature
Internal relative humidity	RH_in	%	Hourly relative humidity inside the greenhouse
Internal CO_2 concentration	CO_2_in	ppm	Hourly CO_2 concentration
External solar radiation	Rad_out	$W \cdot m^{-2}$	Outdoor radiation measured by pyranometer
Cumulative solar radiation	RadCum_out	$MJ \cdot m^{-2}$	Daily accumulated radiation

C. Plant Growth Measurements

Growth data were collected periodically from tagged representative plants.

Measured traits and definitions are summarized in Table 2.

TABLE II. Growth traits measured in representative melon plants and their definitions.

Trait	Unit	Definition
Shoot length	cm	Main vine length measured periodically
Stem diameter	mm	Measured 10 cm above the grafting point
Leaf number	count	Number of fully expanded leaves
Leaf length	cm	Longest lamina length
Leaf width	cm	Lamina width at its widest point

D. Data Cleaning and Preprocessing

To ensure data quality, the following preprocessing procedures were performed:

1) Missing-value imputation

Hourly environmental missing data were filled using linear interpolation.

Missing growth data between measurement days were interpolated using cubic interpolation to daily resolution.

2) Outlier removal

Environmental measurements outside the IQR ± 1.5·IQR range were considered sensor errors and removed.

Plant growth measurements exceeding ±3 SD within each sampling day were excluded.

3) Daily aggregation

Hourly environmental measurements were aggregated to daily statistics:

- Mean
- Standard deviation

- Minimum / maximum
- Daily range
- Daily coefficient of variation (CV = σ / μ)

E. Environmental Variability Metrics

Environmental instability was quantified using:

Daily CV:

$$CV = \frac{\sigma}{\mu} \quad (1)$$

7-day rolling CV:

$$CV = \frac{\sigma(t-6:t)}{\mu(t-6:t)} \quad (2)$$

Lag-3 CV (physiological delay effect):

$$CV_{lag3}(t) = CV(t-3) \quad (3)$$

This metric was used to test the hypothesis that environmental fluctuations influence growth with temporal delay.

F. Growth Uniformity and Daily Growth Increment

Plant-to-plant uniformity (CV):

$$CV_{growth} = \frac{\sigma_{plants}}{\mu_{plants}} \quad (4)$$

In addition, daily growth increments were computed:

$$d1 = v_t - v_{t-1} \quad (5)$$

where vt is the interpolated trait value.

This metric enabled correlation analysis between environment CV_lag3 and growth response.

G. Growth stage classification

Growth stages were determined by inflection points in shoot elongation patterns.

Definitions are summarized in Table 3.

TABLE III. DEFINITION OF MELON GROWTH STAGES AND THEIR BIOLOGICAL INTERPRETATIONS

Stage	**Biological meaning**
Early	Rapid vine elongation and early leaf development
Mid	Vigorous vegetative growth and thickening
Late	Growth stabilization prior to fruit maturity

H. Data Alignment

Environmental and growth datasets had different granularities (hourly vs. sampling-day).

To synchronize environmental data (hourly → daily) and growth data (periodic → daily):

- Growth data interpolated to daily resolution
- Daily growth increments calculated
- Environmental CV, rolling CV, and lagged CV aligned to matching dates
- A unified analysis dataset constructed for regression and correlation modeling

I. Statistical analysis

1) Regression analysis

Linear regression models were used to evaluate effects of environmental variability on growth uniformity:

$$Y = \beta_0 + \beta_1 X + \epsilon \quad (6)$$

- X: environmental variability (CV)
- Y: growth uniformity (CV)
- $\beta 1$ effect of environmental variability on growth uniformity

2) Correlation analysis

Lag-3 environmental CV values were correlated with daily growth increments (d1) to assess short-term physiological responses of melon plants to recent environmental fluctuations.

3) Visualization

Time-series plots were used to illustrate environmental variability and growth trajectories, while growth uniformity was visualized using plant-to-plant CV curves.

Correlation heatmaps were generated to summarize the relationships between environmental variability and growth responses, and stage-wise scatterplots with regression lines were used to compare sensitivity across growth stages.

All analyses were performed in Python using pandas, NumPy, seaborn, and statsmodels.

III. RESULTS

A. Environmental variability across the cultivation period

Environmental conditions displayed clear stage-dependent instability, particularly in internal temperature.

Phase-wise temperature variability (daily CV) differed significantly between stages (Figure 2).

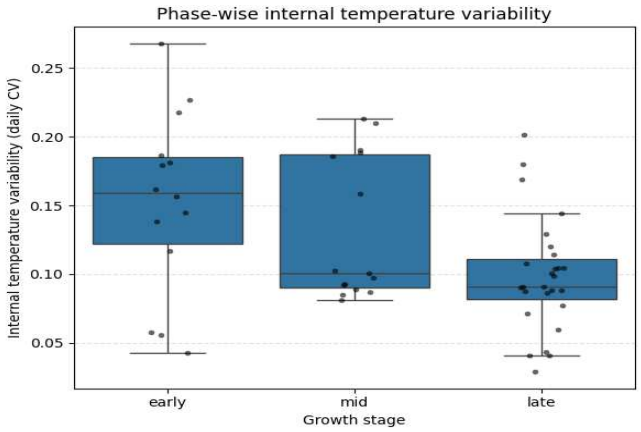

Figure 2. Phase-wise internal temperature variability expressed as daily coefficient of variation (CV) across the early, mid, and late growth stages.

The early stage exhibited the highest variability, reflecting unstable microclimate conditions during early growth.

Variability declined during the mid stage and was lowest in the late stage.

Daily environmental CV time-series (Figure 3) confirmed these patterns.

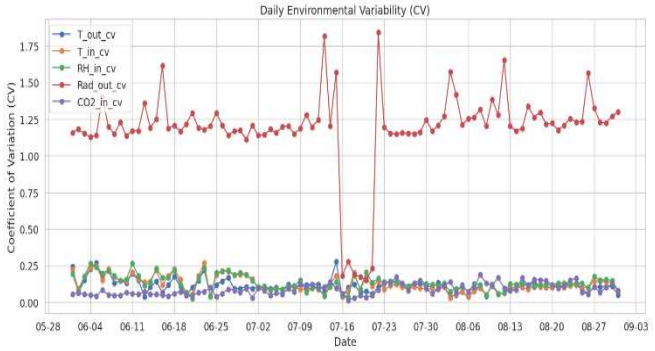

Figure 3. Daily coefficient of variation (CV) of environmental variables, including internal temperature, relative humidity, CO_2 concentration, and external radiation, throughout the cultivation period.

Temperature and humidity variability fluctuated markedly during early development, while CO_2 variability remained moderate.

Radiation variability followed external weather patterns and exerted limited influence on internal instability.

These results indicate that melon plants experienced substantial environmental fluctuations, especially during the early and mid growth stages.

B. Growth uniformity characteristics

Growth uniformity expressed as plant-to-plant CV also differed across developmental stages.

Stem diameter CV showed the widest dispersion during the early stage and reached the highest median values during the mid stage (Figure 4), indicating amplified inter-plant divergence during active stem thickening.

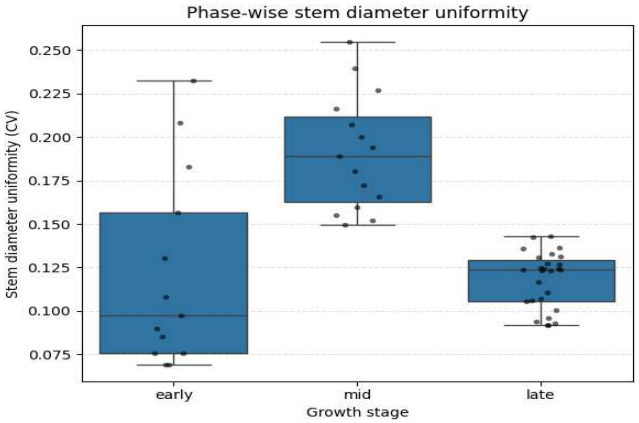

Figure 4. Phase-wise stem diameter uniformity expressed as plant-to-plant coefficient of variation (CV) across the early, mid, and late growth stages.

Uniformity improved during the late stage as growth slowed and structural development stabilized.

Daily growth CV trajectories (Figure 5) further illustrated these trends.

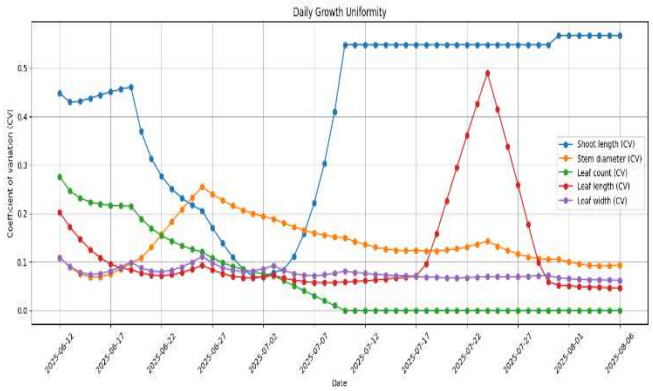

Figure 5. Daily growth uniformity expressed as plant-to-plant coefficient of variation (CV) for major growth traits (stem diameter, leaf number·length·width).

Stem diameter CV increased sharply during the mid stage, while leaf number CV remained elevated during early and mid developmental phases.

Leaf morphological traits showed moderate fluctuations that aligned with environmental variability.

These patterns demonstrate that growth uniformity is dynamic and strongly influenced by physiological stage.

C. Effect of internal temperature variability on stem diameter uniformity

Regression analysis revealed a strong positive relationship between internal temperature variability (7-day CV) and stem diameter CV during the mid stage (Figure 6).

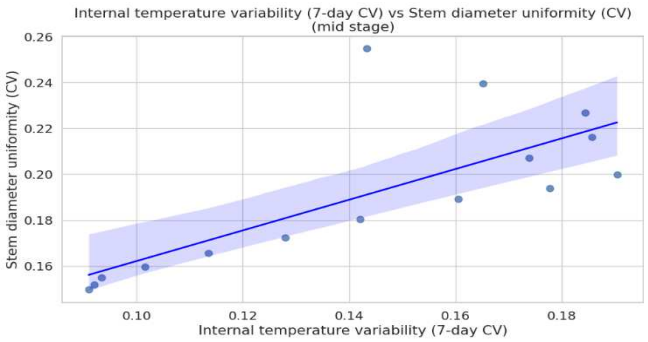

Figure 6. Relationship between internal temperature variability (7-day CV) and stem diameter uniformity (CV) during the mid-growth stage.

Stage-wise regression results showed:

- Mid stage: slope = 0.668, p = 0.0013, R^2 = 0.562
  → indicating that increased temperature variability substantially reduced uniformity during this period.
- Early stage: slope = –3.09, p = 0.013
  → suggesting that seedlings were highly sensitive to unstable temperatures, responding with reduced and inconsistent structural growth.
- Late stage: positive but weaker association (R^2 = 0.376)
  →indicating a diminished influence once growth stabilized.

Overall, the mid stage exhibited the strongest and most consistent sensitivity to temperature instability.

D. Effect of internal humidity variability on leaf count uniformity

Humidity variability (7-day CV) significantly influenced leaf count uniformity in the early and mid stages (Figure 7).

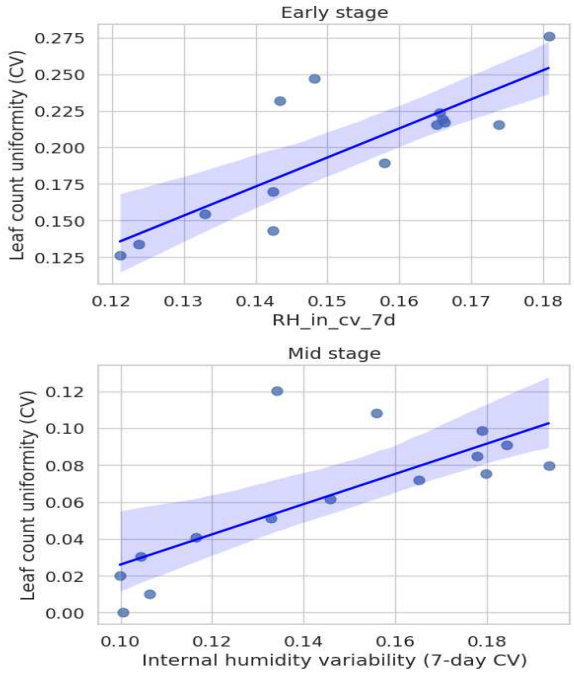

Figure 7. Effect of internal humidity variability (7-day CV) on leaf count uniformity (CV) during the early and mid growth stages.

Stage-wise regression results are summarized in Table IV.

TABLE IV. STAGE-WISE REGRESSION RESULTS EVALUATING THE EFFECT OF INTERNAL HUMIDITY VARIABILITY (7-DAY CV) ON LEAF COUNT UNIFORMITY (CV).

Stage	Slope	p-value	R^2
Early	1.986	0.00049	0.659
Mid	0.818	0.00101	0.577
Late	~0	Not significant	-

The early stage displayed the greatest sensitivity (slope = 1.986, p = 4.9×10^{-5}, R^2 = 0.659), indicating that unstable humidity conditions strongly disrupted leaf development.

The mid stage also showed a significant effect (slope = 0.818, p = 0.00101, R^2 = 0.577).

In contrast, the late stage exhibited no meaningful relationship, consistent with reduced leaf initiation during this period.

These results confirm that humidity stability is critical during early canopy expansion.

E. Short-term physiological responses to environmental instability

Lag-3 environmental CV values were examined to evaluate short-term physiological sensitivity (Figure 8).

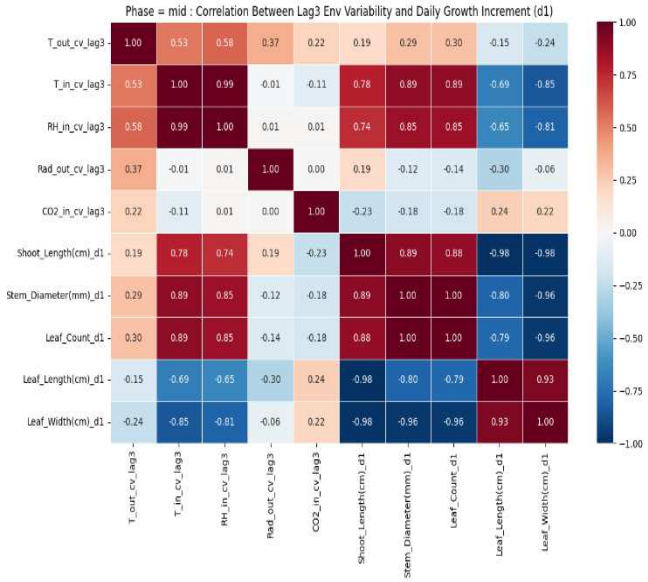

Figure 8. Correlation matrix between lag-3 environmental variability (CV) and daily growth increments (d1) across major growth traits.

Temperature and humidity variability from the preceding three days showed strong positive correlations ($|r| > 0.85$) with daily stem diameter and leaf number increments, indicating delayed but substantial effects of environmental instability on growth.

Leaf morphological traits exhibited negative correlations with temperature variability, suggesting that excessive instability inhibited leaf expansion.

These findings highlight that melon plants respond to both concurrent and recent environmental fluctuations, with growth sensitivity differing by trait and stage.

F. Summary of stage-dependent responses

Across all analyses—including variability patterns, growth uniformity changes, regression results, and lagged correlations—the mid growth stage consistently demonstrated the highest sensitivity to environmental instability.

The early stage was also vulnerable, particularly in leaf development, whereas the late stage exhibited reduced responsiveness.

Collectively, the results indicate that temperature and humidity stability are essential for ensuring uniform structural and morphological development in greenhouse-grown melons.

IV. DISCUSSION

This study investigated how greenhouse environmental variability affects spatial growth uniformity in melon cultivation. The findings demonstrate that both the magnitude and timing of environmental instability strongly influence plant-to-plant variation, with distinct sensitivity patterns across growth stages.

First, internal temperature and humidity exhibited notably high variability during the early and mid growth stages. These fluctuations coincided with critical physiological periods—initial canopy establishment and active stem thickening—during which plants rely heavily on stable microclimate conditions. The observed increase in temperature and humidity variability during these periods is consistent with previous greenhouse studies reporting that early canopy expansion amplifies microclimate heterogeneity and increases plant-level exposure differences (e.g., airflow gradients, radiation interception). As a result, melon plants in this study experienced substantial environmental instability during the developmental windows in which they were most vulnerable.

Growth uniformity followed a similar stage-dependent pattern. Stem diameter CV was highest during the mid stage, reflecting rapid structural differentiation, while leaf count variability peaked during early development when leaf initiation rates are most sensitive to moisture and temperature stress. These observations support prior findings that morphological divergence among plants becomes pronounced when vegetative organs expand at different rates under unstable environmental conditions.

Regression analyses further clarified the causal influence of environmental variability. Internal temperature variability (7-day CV) showed the strongest positive association with stem diameter CV during the mid stage, indicating that even moderate temperature instability can intensify structural divergence during active stem thickening. The significant negative association observed in the early stage suggests that temperature fluctuations at the seedling phase suppress uniform elongation, leading to growth disparities that persist into later stages. Meanwhile, humidity variability significantly affected leaf count uniformity during both early and mid stages, highlighting the importance of stable moisture conditions for promoting consistent leaf initiation.

The lag analysis (lag-3 CV) revealed that short-term environmental instability exerts delayed effects on daily growth increments, particularly for stem diameter and leaf number. Strong correlations between lagged temperature and humidity variability and growth increments indicate that melon plants respond not only to real-time conditions but also to cumulative stress or instability over preceding days. This finding aligns with plant physiological research emphasizing that water balance, carbon allocation, and cell expansion exhibit delayed responses to stress signals.

Overall, the results illustrate that growth uniformity in melons is governed by both the magnitude and the timing of environmental variability. The mid stage emerged as the most sensitive period, during which structural growth processes amplify the effects of unstable microclimate conditions. Meanwhile, early-stage sensitivity underscores the role of stable environmental management during seedling establishment, as early divergence can propagate throughout the cultivation period.

These insights have practical implications for greenhouse management. Interventions such as improved air circulation, optimized humidity control, and predictive climate regulation could help minimize microclimate instability during critical growth stages. The integration of environmental variability metrics (CV) into decision-support systems may also enhance growers' ability to maintain uniform growth, which is essential for standardized fruit quality and commercial grading.

Future studies should validate these findings across additional cultivars and greenhouse configurations, and explore the physiological mechanisms underlying stage-specific sensitivity—particularly the interactions between temperature variability, transpiration dynamics, and assimilate allocation.

V. CONCLUSION

This study quantified the effects of greenhouse environmental variability on growth uniformity in melon cultivation by integrating stage-wise analyses, regression modeling, and short-term lag correlations. The results demonstrated that instability in internal temperature and humidity significantly contributes to plant-to-plant variation, with distinct sensitivity patterns across developmental stages.

Temperature variability exerted the strongest influence during the mid growth stage, where stem diameter uniformity was highly responsive to fluctuations. Humidity variability predominantly affected leaf count uniformity during the early and mid stages, emphasizing the importance of moisture stability during canopy establishment and expansion. Lag-3 analyses further revealed that short-term environmental instability has delayed but substantial effects on daily growth increments, particularly for structural traits such as stem diameter and leaf number.

Overall, the findings highlight that both the magnitude and timing of environmental variability are critical determinants of growth uniformity in greenhouse-grown melons. Maintaining stable microclimate conditions during early and mid growth stages is essential to minimize structural divergence and improve crop uniformity—an important factor for fruit quality, marketability, and precision management.

Future work should extend this approach to multiple cultivars and greenhouse types, incorporate physiological modeling to explain stage-specific sensitivity, and integrate environmental variability metrics into intelligent control systems to enhance predictive and real-time climate regulation

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