ASLI QoL 2025
Annual Serial Landmark International Conference on QoL 2025
Indexed in Clarivate Analytics WoS

E-B
Environment - Behaviour
Proceedings Journal

***A**QoL2025Cherating*

e-IPH
e-International Publishing House Ltd., United Kingdom

https://www.amerabra.org/
09th Asia-Pacific International Conference on Quality of Life
Holiday Villa Beach Resort & Spa, Cherating, Malaysia, 18-19 Oct 2025

Effect of height on cooling of single-span and multi-span greenhouses in summer in the YRD Region

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Abstract
Extreme summer heat in the Yangtze River Delta (YRD) drives greenhouse air temperatures above crop tolerance, threatening yield stability. Natural ventilation offers a low-energy alternative to mechanical cooling, but its dependence on structural height remains poorly quantified. This study applies validated CFD simulations—benchmarking turbulence models, with the SST model achieving the highest accuracy (RMSE = 1.77; MAE = 1.64)—to assess single-span and multi-span greenhouses at varying heights. Results demonstrate contrasting mechanisms: taller single-span structures accumulate heat, whereas taller multi-span structures enhance buoyancy-driven ventilation and cooling. The findings establish a CFD-based framework for height optimization, delivering actionable guidelines for climate-adaptive greenhouse design.

Keywords: Greenhouse geometry; Structural height; Natural ventilation; SST turbulence model.

1.0 Introduction

Protected agriculture in the Yangtze River Delta (YRD) region plays a vital role in China's food security, supporting large-scale cultivation of vegetables, flowers, and fruits. However, the subtropical monsoon climate of this region, characterized by high summer temperatures often exceeding 35 °C, high humidity, and weak wind conditions, always poses severe challenges for greenhouse climate regulation. Excessive heat accumulation during the hot season reduces crop yield and quality and increases reliance on mechanical cooling systems, raising operational costs and carbon emissions. Designing energy-efficient greenhouses with adequate natural ventilation has become an urgent priority for sustainable agricultural production in the region.

Greenhouse cooling methods include natural and mechanical ventilation, with natural ventilation being particularly prevalent in the Yangtze River Delta due to its low operating costs and simple design. However, its effectiveness depends on external weather conditions and greenhouse structure. Greenhouse height is a key factor that influences internal airflow and ventilation capacity, impacting cooling efficiency. There are two primary types of greenhouses: single-span and multi-span. Studies have shown notable differences in their cooling performance under the same weather conditions, and variations in height can lead to different cooling mechanisms. Single-span greenhouses are cost-effective and easy to construct, suitable for small to medium operations, but their ventilation is heavily affected by external factors like wind. Multi-span greenhouses, with their interconnected spaces, reduce uneven wind impact and enhance ventilation stability. Changes in height in these structures can alter overall ventilation volume and airflow patterns. Thus, examining the effects of height adjustments in both greenhouse types is essential, although this aspect is often overlooked in research. This knowledge gap limits the development of design guidelines for optimizing greenhouse height under subtropical climate conditions.

In parallel, computational fluid dynamics (CFD) has emerged as a reliable tool to study greenhouse microclimates, offering the ability to visualize airflow and temperature fields that are difficult to measure experimentally. Previous research has applied different turbulence and wall models, yet inconsistencies in model selection have hindered the comparability of results. Therefore, systematically evaluating turbulence models and height-based analyses across greenhouse types is necessary to establish a validated CFD framework for greenhouse cooling optimization.

Against this background, the present study aims to:

1) To identify the most suitable turbulence and wall models for simulating greenhouse airflow and thermal environments under YRD summer conditions.
2) To quantify the influence of structural height on the cooling and ventilation performance of single-span and multi-span greenhouses through CFD simulations.

This research establishes the first CFD-based quantitative framework for evaluating the cooling effects of height in various greenhouse configurations. By addressing these objectives, the outcomes aim to support sustainable design strategies that improve the efficiency of natural ventilation, decrease the dependence on mechanical cooling, and enhance the resilience of protected agriculture to climate change.

2.0 Literature Review

2.1 Single-span vs. Multi-span Greenhouse

Single-span and multi-span greenhouses are the two most common structural configurations, each with advantages and challenges. Single-span greenhouses are cost-effective and easier to construct, making them suitable for small-scale cultivation. However, they are susceptible to external weather conditions, as airflow patterns are significantly influenced by wind speed and direction. Research indicates that the number of spans dramatically impacts indoor airflow distribution, temperature stratification, and crop growth (Kruger, 2008; Ogunlowo, 2021). For instance, temperature differences between the center and sides of single-span greenhouses are minor (ranging from 0.88 to 1.0 °C) compared to multi-span structures, which average around 1.03 °C.

On the other hand, multi-span greenhouses, characterized by their interconnected structures, provide more stable ventilation by minimizing the effects of uneven wind conditions. However, the complexity of their airflow can lead to decreased ventilation efficiency as the number of spans increases (Chu, 2017; He, 2015). Several CFD-based studies (Kruger, 2020) have confirmed that increasing the number of spans can reduce ventilation rates and create challenges such as decreased air exchange and localized hot zones.

These findings highlight that while span type clearly affects microclimate regulation, previous studies have rarely considered height variation in these comparisons, leaving its role in determining cooling performance insufficiently addressed.

2.2 Influence of Greenhouse Height

Greenhouse height is a crucial design element that has long captured the attention of researchers. Edwin Villagrán (2021) found that increasing the height of a multi-span greenhouse can reduce temperatures by between 0.1 °C and 11.7 °C, according to CFD simulations. H. Fatnassi (2017) demonstrated that height and the number of spans significantly impact climate performance in single-span greenhouses, though there are limits to how much height can be increased. Demin Xu (2020) investigated a Liaoshen-type Chinese solar greenhouse (CSG-LS) and validated his CFD model using data collected on a sunny day. His findings indicated that ridge height plays a significant role in enhancing solar energy capture. Overall, greenhouse height is closely linked to cooling regulation and can significantly improve the internal climate, promoting better plant growth.

2.3 CFD Modeling and Turbulence Models

Computational fluid dynamics (CFD) has become an indispensable tool for greenhouse climate studies, allowing detailed visualization of airflow and thermal fields that are difficult to capture experimentally. Different turbulence models have been employed with varying success. For instance, Angeliki Kavga (2023) effectively utilized the Realizable k-epsilon model for computational fluid dynamics (CFD) modeling in greenhouses, integrating it with the LABVIEW environment to achieve noteworthy results. Meanwhile, Rack-Woo Kim (2021) conducted a comprehensive analysis using four different models for greenhouse CFD modeling: the Standard k-epsilon model, the Re-Normalization Group (RNG) k-epsilon model, the Realizable k-epsilon model, and the Standard k-omega model. His findings revealed that the Realizable k-epsilon model offered the best performance, followed closely by the RNG k-epsilon model, and he successfully implemented the Enhanced Wall Treatment (EWT) in his simulations.

D. Piscia (2015) made a valuable contribution by selecting the Standard k-epsilon model for greenhouse modeling. His validation efforts against experimental data confirmed its accuracy, reinforcing its reliability for such applications. Md. Nadim Heyat Jilani (2024) further expanded the field by employing the Shear Stress Transport (SST) k-omega model to assess heat exchange in greenhouses through CFD simulation. His work demonstrated that this model is particularly well-suited for greenhouse environments. Additionally, Xin Zhang (2016) contributed to the discourse by applying the Standard k-epsilon turbulence model for greenhouse simulations, which he validated against experimental data, achieving satisfactory accuracy. The Standard Wall Function (SWF) served as the wall treatment in this study.

However, inconsistencies across studies regarding turbulence model selection, boundary conditions, and wall treatment make it difficult to generalize conclusions. Very few studies benchmark multiple turbulence models against experimental data for greenhouse applications in subtropical climates, limiting the reliability of CFD-based design recommendations.

2.4 Research Gap

From the above review, three critical gaps emerge:

1) Height–Span Interaction: Although span configuration and height both influence greenhouse microclimates, there is a scarcity of studies that systematically compare their combined effects under identical climatic conditions.
2) Limited Validation: Numerous CFD studies fail to rigorously benchmark turbulence and wall models against experimental data, undermining their findings' credibility.
3) Practical Relevance: The reported temperature differences are often minimal and lack sufficient context regarding energy savings, plant health, or design implications.

2.5 Contribution of the Present Study

To address these gaps, this study:

1) Benchmark turbulence and wall models against measured data to find the most reliable CFD approach. Identify the most reliable CFD approach.
2) Evaluate the cooling performance of single-span and multi-span greenhouses at various heights under typical YRD summer conditions.
3) Provides practical, data-driven guidelines for climate-adaptive greenhouse design, emphasizing the role of height in reducing energy consumption and ensuring crop resilience.

3.0 Methodology

3.1 Experimental Data collection and analysis

Field data were collected in the Yangtze River Delta (YRD) to establish boundary conditions and validate the CFD model. A weather station, located 15 meters from the greenhouse in an open field, recorded ambient meteorological variables at one-minute intervals, including temperature, humidity, wind speed, and direction. Internal air temperatures were monitored using ZDR-3W1S temperature loggers (with an accuracy of ±0.1 °C), which were strategically positioned at various heights and locations to capture spatial variations. Surface temperatures of both the greenhouse cover and the ground were measured with a calibrated Fluke 568/566 infrared thermometer. All sensors were factory-calibrated and validated against thermocouples prior to deployment.

3.2 CFD Model Development

A three-dimensional computational domain was developed to simulate both single-span and multi-span greenhouses at 3.8 m and 4.8 m. To reduce boundary effects, the external flow field was extended five times the height of the greenhouse upstream and ten times downstream. The governing equations for mass, momentum, and energy conservation were discretized using the finite-volume method. The SIMPLE algorithm was utilized for pressure-velocity coupling, while second-order upwind schemes were employed for the convective terms.

3.3 Turbulence and Wall Treatment Models

A total of seven turbulence-wall model combinations were evaluated, including Standard k-ε, RNG k-ε, Realizable k-ε, and Shear Stress Transport (SST), each paired with either Standard Wall Function (SWF) or Enhanced Wall Treatment (EWT), as appropriate. The performance of each model was assessed against measured data using mean absolute error (MAE) and root mean square error (RMSE). The SST model exhibited the highest accuracy, with an MAE of 1.64 and an RMSE of 1.77, and was consequently selected for the subsequent simulations.

Table 1. Simulations for Optimal Model

Number	Turbulence model	Wall model
1	$k-\varepsilon$: Standard	SWF
2	$k-\varepsilon$: Standard	EWT
3	$k-\varepsilon$: Realizable	SWF
4	$k-\varepsilon$: Realizable	EWT
5	$k-\varepsilon$: RNG	SWF
6	$k-\varepsilon$: RNG	EWT
7	$k-w$: SST	/

3.4 Boundary Conditions

Meteorological inputs were derived from field measurements taken under typical summer conditions, which included an inflow wind speed of 0.9 m/s at an angle of 150°, an inlet air temperature of 36 °C, and a turbulent intensity of 10%. The material properties, specifically density, thermal conductivity, and specific heat for air, glass, and concrete, were sourced from literature and are summarized in Table 2. The greenhouse roof vents were modelled as pressure outlets, while the ground surface was treated as an isothermal wall boundary.

Table 2. Material Properties

Material type	Density /kg.m^{-3}	Specific heat capacity /Jkg^{-1}.K^{-1}	Thermal conductivity /Wm.K^{-1}	Absorption coefficient /m^{-1}	Refraction Rate
Concrete	2100	880	1.4	0.6	1.6
Glass	2500	700	0.7	0.1	1.7
Air	1.17	1 025.5	0.03	0	1.0

3.4 Mesh and Convergence

A polyhedral mesh with local refinement around vents and crop zones was created to capture intricate airflow structures. Grid independence was confirmed by comparing three mesh densities (coarse, medium, fine), showing less than a 2% variation in average temperature, ensuring efficiency and accuracy. Convergence occurred when the residuals for continuity, momentum, and energy fell below 10^{-5}, with stable outlet temperatures. CFD steady-state simulation is conducive to completing efficient calculations. Moreover, steady-state calculations can fully meet simulation requirements for simulation scenarios with small instantaneous changes, such as greenhouse flow field calculations. All CFD simulations in the research were steady-state, utilizing the SIMPLE algorithm due to the extensive mesh sizes. The SST model converged in 652 steps, as shown in Fig. 1.

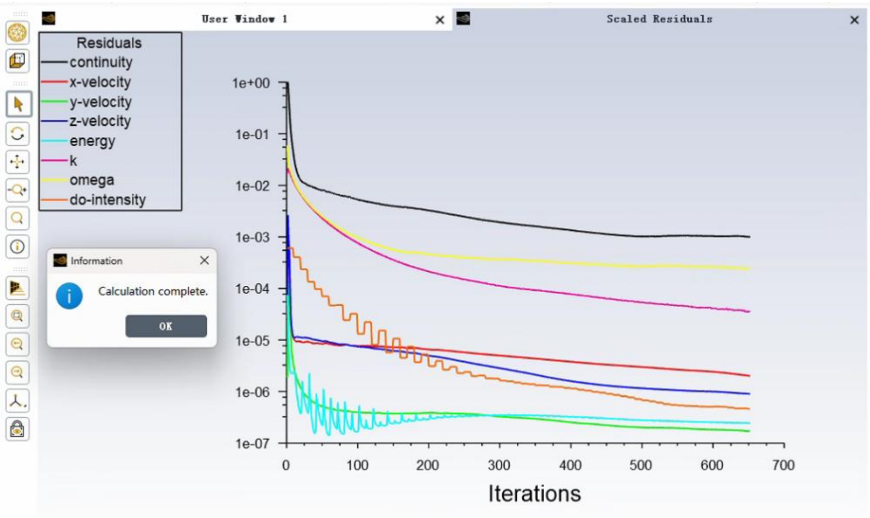


Fig. 1. The iteration curve of the greenhouse simulation

3.5 Model Validation

The simulated air temperature and velocity fields were validated against experimental measurements inside the greenhouse. The maximum deviation was 2.9 °C (7.2%), with an average relative error below 5%, confirming the model's accuracy in replicating greenhouse microclimate dynamics during YRD summer conditions.

4.0 Findings

4.1 Model Performance and Validation

Seven turbulence–wall model combinations were benchmarked against measured data (Table 3). The Shear Stress Transport (SST) model provided the best agreement, with MAE = 1.64 °C and RMSE = 1.77 °C, outperforming other k-ε-based models. Validation against independent experimental data confirmed reliability: the maximum deviation between simulated and observed temperatures was 2.9 °C (7.2%), with average errors below 5%. These results demonstrate that the SST model can accurately reproduce the microclimate of both single-span and multi-span greenhouses under YRD summer conditions. The serial numbers representing the models are the same as in Table 1.

Table 3: Numerical comparison of seven calculation methods

	1	2	3	4	5	6	7
MAE	1.69	1.68	1.68	1.67	1.72	1.79	1.64
RMSE	1.84	1.82	1.82	1.81	1.88	1.97	1.77

After verification, simulation experiments were conducted using the greenhouse model. Each simulation experiment only changed one condition. The conditions and codes for the changed conditions are as follows in Tables 4 and 5.

Table 4. Simulation code for a single-span greenhouse

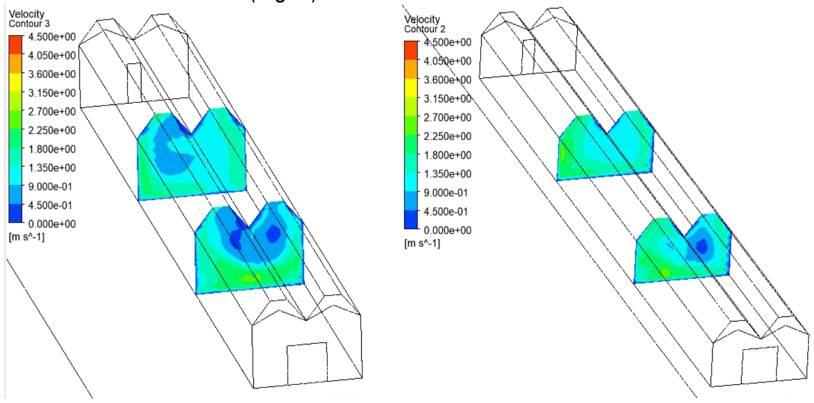
3.8m Height	SA
4.8m Height	SB

Table 5. Simulation code for Multi-span greenhouse

3.8m Height	MA
4.8m Height	MB

4.2 Single-span Greenhouse

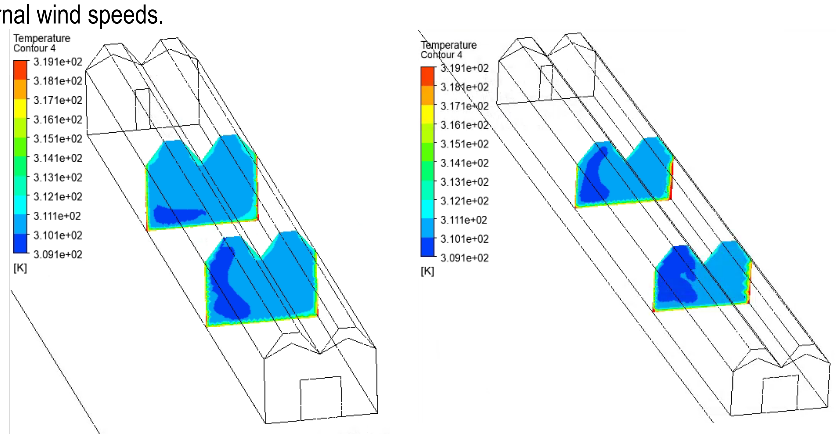
Comparative simulations at 3.8 m (SA) and 4.8 m (SB) revealed that increased height reduced ventilation efficiency. At 3.8 m, stronger airflow developed near the skylight, improving convective heat removal. By contrast, the 4.8 m greenhouse exhibited stagnant zones, particularly near the roof, where hot air accumulated (Fig. 2).



(a). Case of SA (b). Case of SB

Fig 2. Velocity of greenhouses of different heights greenhouses

Temperature distribution confirmed this trend (Fig. 3). The average air temperature was 37.3 °C for 3.8 m and 37.5 °C for 4.8 m, a -0.2 °C difference. Although numerically small, this result reflects a loss of airflow effectiveness at greater height, leading to “heat-cap” formation under low external wind speeds.

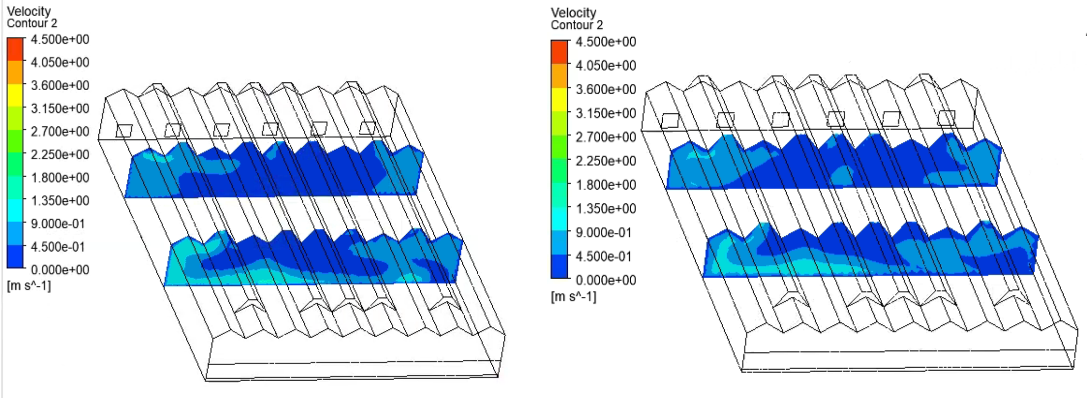


(a). Case of SA (b). Case of SB

Fig 3. Temperature of greenhouses at different heights greenhouses

4.3 Multi-span Greenhouse

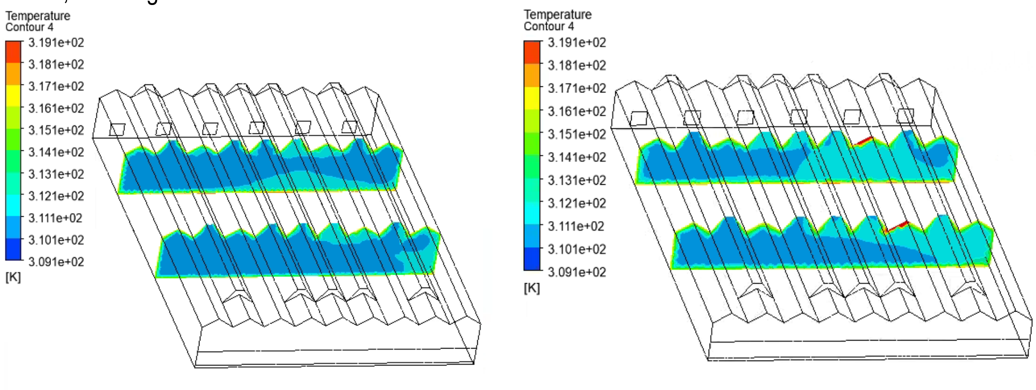
For multi-span configurations, the opposite pattern was observed. At 4.8 m height (MB), airflow was more vertically connected (Fig. 4), enhancing buoyancy-driven circulation compared to the 3.8 m case (MA). This produced more uniform and efficient ventilation, with reduced reliance on external wind.



(a). Case of MA (b). Case of MB

Fig. 4. Velocity of greenhouses of different heights greenhouses

Temperature fields (Fig. 5) further highlighted the cooling advantage of the taller structure. The average indoor temperature was 37.8 °C at 4.8 m compared to 37.9 °C at 3.8 m. Despite the modest numerical difference (−0.1 °C), the taller greenhouse's distribution was notably more uniform, reducing localized heat stress zones.

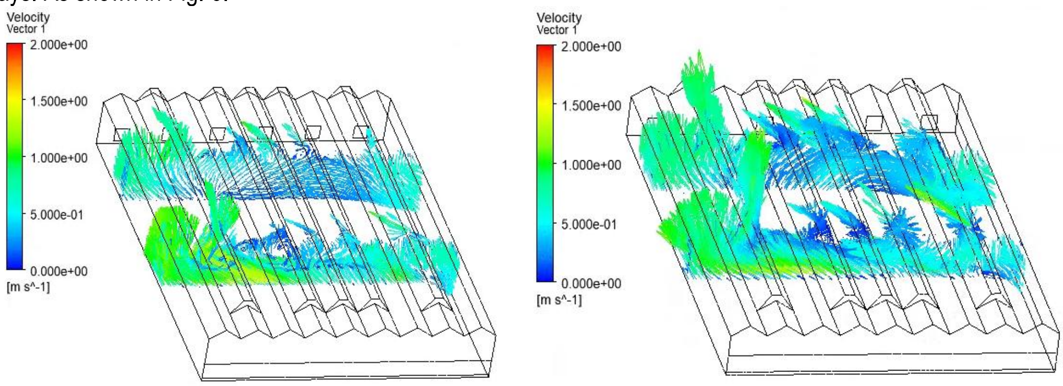


(a). Case of MA (b). Case of MB

Fig. 5. Temperature of greenhouses at different heights greenhouses

4.4 Comparative Analysis

A key finding is the contrasting role of height, where single-span greenhouses - taller structures trap heat and reduce airflow, worsening thermal conditions, while multi-span greenhouses - taller structures enhance buoyancy-driven ventilation and improve uniformity. This demonstrates that structural height cannot be generalized across greenhouse types; its effect depends strongly on internal volume and airflow pathways. As shown in Fig. 6.



(a). Case of MA (b). Case of MB

Fig. 6 Vector diagrams of different heights of greenhouses

4.5 Energy Conservation Potential

$$Q_{air} = \rho c_p V \Delta T \tag{1}$$

$$\Delta T_{out} = T_{in} - T_{out} \tag{2}$$

$$V_{need} = V \times \frac{\Delta T}{\Delta T_{out}} \tag{3}$$

According to Equations (1), (2), and (3), the energy savings from avoiding the use of mechanical ventilation due to temperature changes caused by changes in greenhouse height were calculated. Air density $\rho \approx 1.15$ kg/m³ (around 38°C); constant-pressure specific heat $cp \approx 1.005$ J/(kg·K); V is the greenhouse area, in m³; ΔT is the temperature drop, in K; T_{in} is the indoor greenhouse temperature, in K; T_{out} is the outdoor greenhouse temperature, in K; V_{need} is the fan ventilation volume, in m³.

For a typical fan, SFP = 0.106 kW/(m³ /s) ($\approx$ 20 cfm/W). Based on 1,000 multi-span greenhouses, 90 cooling days per year, and one hour of cooling per day, increasing the greenhouse height reduces energy consumption by approximately 1,400 kilowatt-hours. Reducing the greenhouse height under the same conditions can save approximately 1,200 kilowatt-hours for single greenhouses. This is a perfected calculation that does not take into account real-world losses. In reality, the potential energy savings can be even greater.

5.0 Discussion

5.1 Mechanisms of Height Effects in Single-span Greenhouses

In single-span greenhouses, increased structural height led to unexpected thermal issues. While a taller design offers more air volume, our simulations indicated that weak YRD summer winds (0.9–1.1 m/s) generated insufficient pressure differences across roof vents, creating stagnant zones that resulted in a “heat cap” effect. This aligns with Fatnassi's (2017) findings that excessive ridge height reduces ventilation efficiency in low wind conditions. Thus, single-span structures should avoid significant height increases in hot, low-wind areas, as even small volume gains can hinder airflow.

5.2 Mechanisms of Height Effects in Multi-span Greenhouses

Multi-span greenhouses benefit from increased height, which enhances buoyancy-driven ventilation and facilitates vertical airflow, thereby reducing temperature stratification. Villagrán (2021) noted that taller designs could lower average temperatures between 0.1 °C and 11.7 °C. While our study revealed a modest temperature reduction of 0.1 °C, the resulting improvements in airflow uniformity and fewer hotspots are crucial for preventing localized plant stress. These findings suggest that greater structural height bolsters resilience against low external wind speeds by reinforcing buoyancy as a key factor in ventilation.

5.3 Comparative Perspective and Design Implications

The findings highlight that greenhouse height is not a universal design parameter; its impact varies by greenhouse type:

1) For single-span greenhouses, a height of around 3.8 m optimizes ventilation through wind-driven air exchange.
2) In multi-span greenhouses, a height of approximately 4.8 m enhances buoyancy and stabilizes microclimates.

These insights build on earlier studies (Kruger, 2008; Chu, 2017) that focused primarily on span numbers, rather than the interaction of span and height. Our research introduces a CFD-based framework to assess how greenhouse height affects cooling performance across structural types in subtropical climates.

5.4 Energy and Sustainability Relevance

Although the temperature differences between cases are minor (0.1–0.2 °C), their cumulative impact is significant across regional greenhouse networks. Optimizing structural height could reduce annual cooling energy demand by approximately 1,200 to 1,400 kWh per 1,000 greenhouses. Furthermore, improved natural ventilation decreases reliance on mechanical systems, lowering operational costs and greenhouse gas emissions. These findings highlight the potential of passive design optimization as a climate adaptation strategy for protected agriculture in humid subtropical regions.

5.5 Limitations and Future Work

This study is based on steady-state CFD simulations validated under controlled conditions. However, real-world performance may vary due to transient weather changes, crop canopy effects, and management practices like shading and vent control. Future work should focus on:

1) Long-term field validation in diverse weather conditions.
2) Dynamic crop canopy modelling for evapotranspiration and shading.
3) Evaluating economic trade-offs in construction and operational costs.
4) Testing climate transferability in tropical and arid zones.

6.0 Conclusion& Recommendations

This study introduces a CFD-based framework for evaluating how greenhouse height impacts natural ventilation and cooling in humid subtropical climates. The Shear Stress Transport (SST) model was identified as the most reliable for greenhouse applications. Key findings show that increased height affects greenhouses differently. In single-span greenhouses, more height reduces convective heat removal and creates stagnant zones in low wind. In multi-span greenhouses, greater height enhances buoyancy-driven ventilation, leading to uniform temperatures and better cooling stability. Therefore, height optimization should differ by greenhouse type.
Optimizing greenhouse heights could cut cooling energy demand by 1,200 to 1,400 kWh annually for every 1,000 greenhouses and improve crop resilience to heat stress. This reinforces height optimization as a low-cost, energy-efficient strategy. However, the study has limitations, as simulations did not consider crop canopy effects or varying weather conditions. Future research should focus on long-term field validation and the economic impacts of height adjustments. In summary, this study enhances understanding of the height-ventilation-cooling relationship in greenhouse design and offers practical guidelines for engineers, farmers, and policymakers in subtropical regions.

Acknowledgement
The authors express their deepest gratitude to Universiti Teknologi Mara (UiTM) for providing the resources and support necessary to conduct this research. Thanks to the academic supervisors for invaluable guidance, technical expertise, and encouragement throughout this study.

Paper Contribution to the Related Field of Study
This discovery establishes a theoretical basis for optimizing the height of greenhouses in the Yangtze River Delta, enhancing natural ventilation and cooling. It also supports energy-efficient and cost-effective greenhouse cultivation.