

Article

Study on the Effect of Non-Uniform Ventilation on Energy and Plant Growth in a Greenhouse

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Abstract: The progress of local environmental regulation in protected agriculture is sluggish, particularly concerning the local air supply, which poses a significant obstacle to greenhouse energy-saving research. This study establishes a test platform for local air supply in winter and summer by integrating design principles from human settlements' supply air bag models with crop growth requirements. By utilizing a supply air bag to direct fresh air from the air conditioning system to specific areas within the greenhouse, non-uniform ventilation is created. Research has revealed that varying air supply levels in summer exerts a significant influence on environmental conditions, crop growth, and energy efficiency. Noticeable temperature stratification and cooling effects were observed within the conditioning greenhouse. The growth of lettuce was moderately enhanced, with mid-level local air supply demonstrating superior cooling effectiveness and range compared to the other two levels. Optimal control efficacy and energy conservation were achieved through mid-level local air supply. During daytime experiments in winter, this system did not have a significant impact on the greenhouse environment; however, during nighttime experiments, it consistently provided warming effects to maintain temperatures above the minimum requirement for lettuce growth. Therefore, utilizing air supply bags at secure specific positions and implementing targeted air supply methods within cultivation areas in greenhouses can facilitate the creation of suitable local environments for crop growth while achieving energy savings. Future research in this field could focus on further refining air supply bag models to enhance energy efficiency and local environmental control effects.

Keywords: non-uniform ventilation; air conditioning; air supply bag system; greenhouse; horticulture



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1. Introduction

Greenhouses are now essential for managing the cultivation conditions of crops, ensuring optimal growth and yield. The evolution of greenhouse environmental control systems began in the 19th century, with major strides made by the mid-20th century. A seminal study by Went in 1943 laid the groundwork for systematic research into tomato cultivation under controlled greenhouse environments [1]. This pioneering work paved the way for subsequent studies that explored a range of environmental variables, including air and

soil temperature, humidity [2], light [3], carbon dioxide concentrations [4], crop modeling [5], and the integration of artificial intelligence [6]. Fernandez's research highlighted a crucial principle: the necessity of consistent environmental parameters for peak plant development. However, it is also clear that different stages and parts of crop growth have unique environmental demands. For example, while tomatoes can thrive within a broad temperature range of 15–28 °C [7], the optimal temperature for seed germination is a more specific 25–27 °C [8]. Petrikovszki's observations further refine these parameters, noting that although tomato seedlings thrive at temperatures between 20–30 °C, temperatures above 30 °C can impede their growth [9]. The hierarchy of crop sensitivity to environmental conditions is typically flowers, followed by roots, shoot tips, and then fruits [10]. Consequently, it is imperative to customize environmental control strategies to enhance crop growth and productivity.

Through the recognition of the various temperature demands of different crop parts and stages of growth, uniform environmental control shifts towards localized environmental control in greenhouses. This approach not only benefits crop development but also addresses the significant energy consumption associated with traditional greenhouse regulation methods. Current environmental regulation often results in high energy use, with lighting and HVAC systems being the primary consumers, accounting for 69.9% and 27.9%, respectively [11]. With consideration of the cultivation area within a greenhouse often occupying a small fraction of the total space, by focusing energy inputs on the specific areas where crops require it, together with passive management elsewhere, we can achieve a dual goal of enhancing crop growth and reducing energy consumption. Studies have shown that theoretically, non-uniform environment control can save 69.9% of the energy consumption in greenhouses [12].

Temperature stratification and non-uniform ventilation are common phenomena in greenhouses. When regulating the microenvironment of greenhouses, it is essential to minimize these two phenomena as much as possible. The phenomenon of temperature stratification in a greenhouse refers to the significant temperature differences between air at different heights within the greenhouse, typically characterized by higher temperatures in the upper layers compared to the lower layers. This phenomenon is relatively common in greenhouses, especially at night or when ventilation is poor. The main causes include the rise of hot air, ground radiation cooling, the influence of the greenhouse structure, and poor ventilation [13]. The phenomenon of non-uniform ventilation in greenhouses refers to the significant differences in air flow and exchange among different areas within the greenhouse, resulting in some areas having good air circulation while others experience air stagnation, creating ventilation dead zones. This phenomenon affects the distribution of temperature, humidity, and carbon dioxide within the greenhouse, thereby impacting plant growth and health. The main causes include illogical ventilation port design, greenhouse structure influence, and illogical plant layout [14].

Studies on localized temperature regulation, particularly for the root environment, have yielded promising results. Pramanik's team discovered that higher soil temperatures can suppress the photosynthetic rate of winter wheat, with stomatal conductance decreasing as soil temperature and moisture content rise [15]. In cucumber cultivation, warming the root zone has been shown to significantly benefit seedling growth, preserving the photosynthetic capacity of existing leaves and promoting new leaf expansion [16]. Similarly, Kawasaki demonstrated that root zone heating in hydroponic tomatoes is an effective and cost-efficient method under low-temperature conditions [17]. While root zone control is more manageable than air control, and current methods often involve heat conduction [18] and local heating in hydroponics [19], it is evident that localized regulation of above-ground parts such as fruits, leaves, and flowers is equally crucial. Shamshiri's

review of optimal microclimate requirements for different tomato organs at various stages and the development of evaluation methods for suboptimal temperatures highlight this importance [20]. Targeted heating near tomato fruits and leaves, for instance, can slightly increase temperatures by 1–1.5 °C, leading to improved yields [21]. Kawasaki's research further indicates that local heating can enhance pollen viability, fruit count, and weight in tomatoes and cucumbers, while also reducing fuel consumption by 26.2% compared to control groups [22,23].

Despite the potential benefits of localized control, the field faces several challenges in its infancy. There is a lack of standardized facility equipment and evaluation indicators for creating local environments. Additionally, specific crops have unique air velocity requirements for optimal gas exchange and photosynthesis, with an optimal range of 0.3–0.5 m/s [24]. Excessive velocities can hinder these processes and lead to abnormal growth patterns. Current operational strategies and assessments for local control systems often rely heavily on the expertise of agricultural practitioners.

In contrast, non-uniform conditioning methods in residential and public buildings have been well researched and established, with techniques such as displacement ventilation [25,26], stratum ventilation [27], wall-mounted ventilation [28], personalized ventilation [29], and demand-controlled ventilation systems [30] designed to regulate thermal comfort and indoor air quality. The environmental models, facilities, and evaluation metrics in this context are relatively mature [31]. For greenhouses, local control equipment design and operation must consider crop-specific needs, greenhouse structure, and energy consumption. Evaluation metrics should focus on crop yield, growth status, energy efficiency, and control effectiveness. Since crop yield and growth status are relatively stable under optimal conditions [32,33], research on non-uniform environmental control in greenhouses should prioritize energy efficiency and the creation of locally optimal environments.

Similar studies have been conducted on microenvironmental regulation in greenhouses. Kimura et al. investigated the impact of microclimate on strawberries within greenhouse environments, conducting an analysis on how microclimatic variations induced by roof ventilation affect the growth rate of strawberries. The study concluded that spatial non-uniformity in certain areas, resulting from environmental controls, reached 69% during daytime periods [34]. Ma et al. identified varying microclimates within greenhouses, which significantly affect crop quality. To address this, a computer-controlled conveyor system was implemented to ensure uniform heat and irradiation distribution across plants. Results showed that this system significantly reduced crop variability compared to traditional greenhouses [35]. Spatial temperature distribution in greenhouses is critical but often overlooked in research. Xu et al. developed a computational fluid dynamics model to analyze this, incorporating air (light absorption), crops (light absorption, reflection, transmission, and transpiration), and soil (light absorption and heat radiation) under dynamic solar load, based on energy conservation principles [36]. However, the aforementioned studies are either based on passive regulation significantly influenced by external environmental conditions or rely on high-energy-consumption methods for regulation. Identifying a low-energy, active regulation approach represents an ideal alternative.

In this study, we have adapted a non-uniform ventilation model from human-inhabited environments to suit the characteristics of greenhouse structures. We have identified the optimal positions for air supply, outlet temperature, and air supply velocity, with the aim of implementing non-uniform ventilation in small glass greenhouses through the air conditioning–air supply system. The growth of lettuce under conditions of different air supply heights, the effectiveness of environmental control, and energy efficiency have been assessed. This evaluation contributes to the development of more energy-efficient and crop-optimized greenhouse systems.

2. Materials and Methods

2.1. Experimental Greenhouse

This study was conducted in two glass greenhouses situated in Yangling, Shaanxi Province, China, which is located in a cold climate zone. A schematic representation of the greenhouse setup is illustrated as Figure 1a. Each greenhouse has the same dimensions of 6 m in length, 4 m in width, and 4 m in height, with a ridge 4.5 m in height. The skylight, positioned to allow for optimal natural light, measures 2.4 m by 1.2 m and can open to a maximum angle of approximately 30°. The ridges of the greenhouses are oriented in a north–south direction to facilitate even sunlight exposure. Inside, each greenhouse features two rectangular tidal cultivation beds, each with dimensions of 4.0 m by 1.5 m and raised 0.6 m above the ground level, with each bed's crops cultivated in a 4 × 9 arrangement. These beds are designed to elevate the crops, improving their growing conditions. The greenhouse is fitted with internal insulation, side insulation, and external shading devices to enhance thermal retention, particularly during the colder winter nights. In contrast, during the summer months, the skylight remains fully open to promote ventilation, while in winter, it remains closed to conserve heat. The side insulation is deployed after 18:00 to further insulate the space. The parameters of the flexible air supply pipe are shown in Figure 1b.

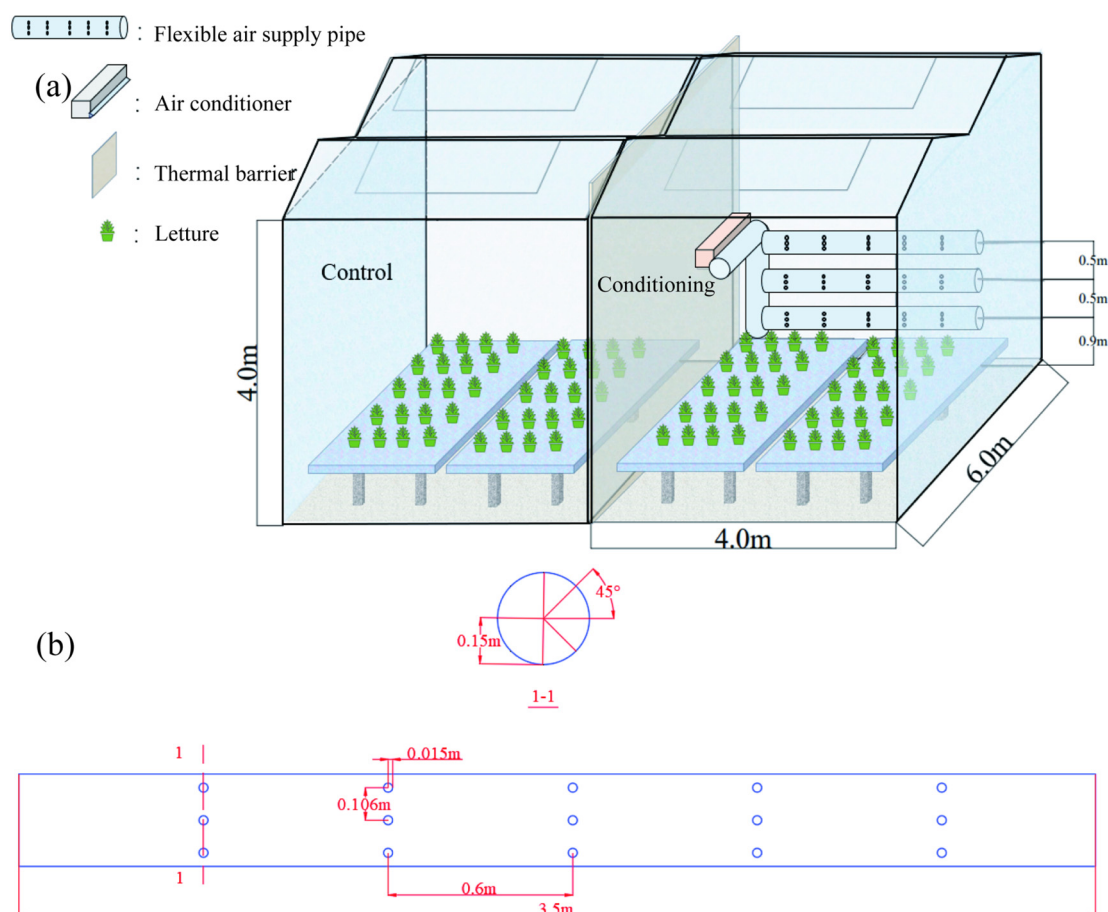


Figure 1. (a) Schematic diagram of the control greenhouse and conditioning greenhouse, (b) the layout of the flexible air supply pipe.

The conditioning greenhouse featured an air conditioning and air supply system that included a flexible ductwork (polypropylene) designed to direct fresh air from the air conditioning unit to specific areas within the greenhouse, facilitating targeted air distribution. Table 1 outlines the key specifications of the air conditioning unit utilized in this study. The

ductwork was strategically suspended at three different elevations—0.9 m, 1.4 m, and 1.9 m above the ground—to accommodate various test scenarios. During the summer months, the average wind speed at the outlets of the air supply pipes was recorded at 11.4 m/s, with a temperature of 16.3 °C. This velocity decreased significantly to an average of 0.22 m/s at the level of the crop canopy. In contrast, during the winter season, the air supply bags registered an average wind speed of 10.1 m/s and a temperature of 29.4 °C at the outlets. At the crop canopy level, the average wind speed was notably lower, at 0.14 m/s. As shown in Figure 2, the air supply bag outlets were evenly distributed along the eastern side of the greenhouse, ensuring a consistent and efficient air distribution pattern.

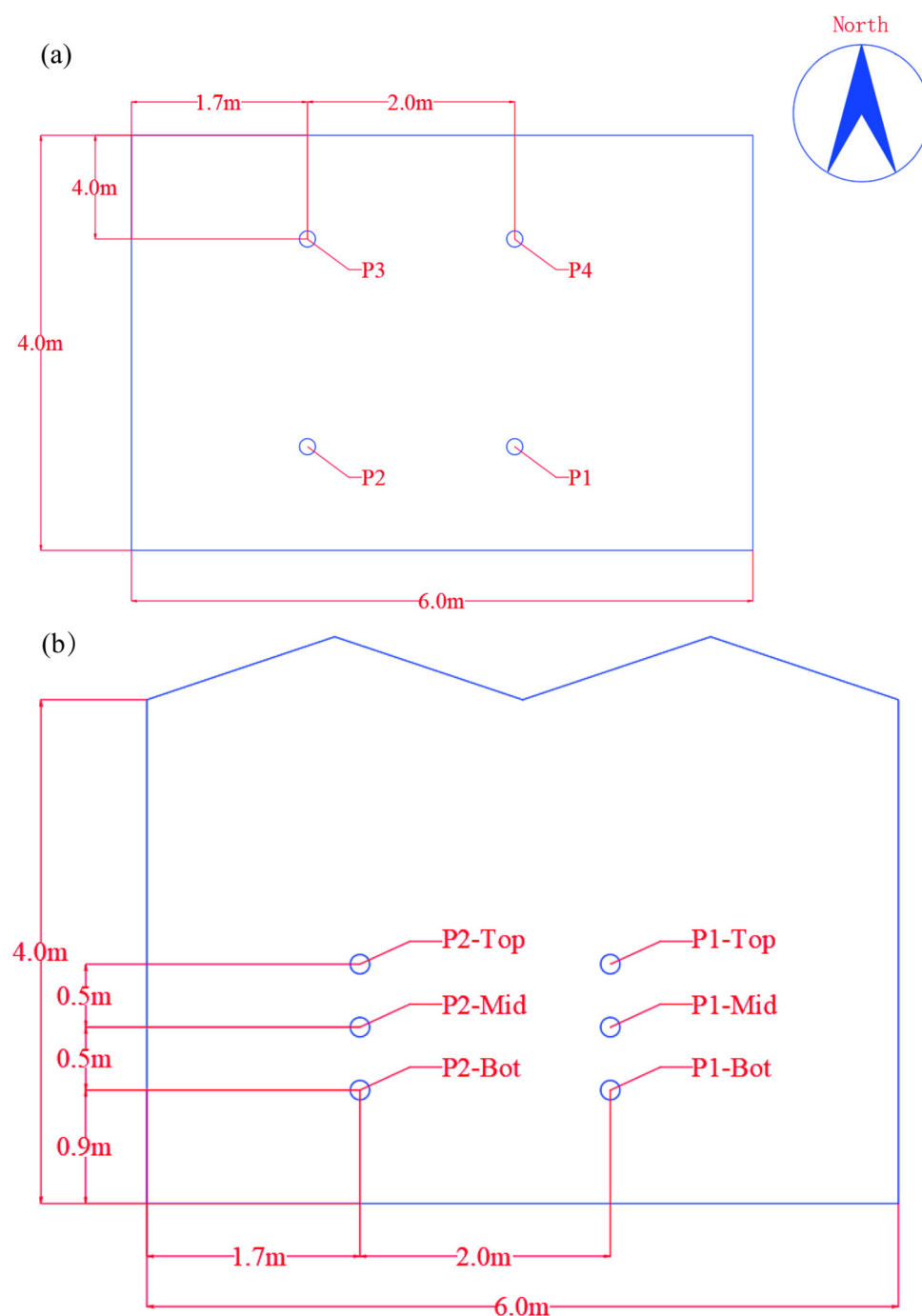


Figure 2. The measurement point arrangement: (a) top view, (b) front view.

Table 1. Parameters of air conditioners.

COP	Air Supply Volume (m ³ /h)	Heating Power (kW)	Cooling Power (kW)
3.82	1000	2100	1480

2.2. Experimental Scheme

The experiments were conducted during both winter and summer seasons. With the implementation of this system, the study focused primarily on the temperature distribution within the greenhouse, crop growth, and energy efficiency.

2.2.1. Settings of Air Conditioning and Air Supply Pipe System

In summer, our experimental focus was on conducting cooling trials at various heights of air delivery, while in winter, we shifted our attention to heating, with a particular emphasis on both daytime and nighttime conditions. The test design for both seasons, informed by preliminary observations, is meticulously outlined in Table 2. In the early stages of our winter experiments, we aimed to determine the optimal timing for activating the air conditioning system. Concurrently, we sought to assess a variety of operational modes to optimize the efficiency of the heating process. This systematic approach allowed us to explore the most effective strategies for maintaining thermal environment throughout the year.

Table 2. Test schedule.

Season	Date	Air Conditioner Opening Time	Air Conditioner Parameter Setting	
Summer	Lower-level air supply: 5 June 2023–15 June 2023	10:00–17:00	Cooling	
	Middle-level air supply: 16 June 2023–25 June 2023		16 °C	
	Upper-level air supply: 26 June 2023–5 July 2023		6.5 m/s	
Winter	Preliminary Experiment: 24 November 2023–15 December 2023	10:00–17:00	Heating	
		18:00–The day after 12:00		
		3:00–9:00		
	Lower-level air supply: 18 December 2023–20 December 2023	3:00–9:00		
	Middle-level air supply: 21 December 2023–23 December 2023			
	Upper-level air supply: 24 December 2023–25 December 2023			
	Lower-level air supply: 26 December 2023–5 January 2024			

2.2.2. Measurement of Indoor Temperature, Humidity, Carbon Dioxide Concentration, and Air Conditioning Electricity Consumption

Throughout the test phase, we implemented a meticulous monitoring system in both the test and control greenhouses to ensure accurate data collection. This system was specifically designed to measure temperature, humidity, and carbon dioxide concentration at four strategically positioned points in the horizontal direction within each greenhouse. To ensure a comprehensive data set, each measurement point was equipped with sensors at three distinct heights: 0.9 m, 1.4 m, and 1.9 m above ground level. These heights were chosen to represent various levels within the greenhouse environment. Utilizing suspension ropes, a single sensor was securely positioned at each height, resulting in a total of 24 sensors deployed across both greenhouses. These sensors were programmed to collect and record data at one-minute intervals, ensuring high-frequency data collection that would provide detailed insights into the greenhouse conditions. The collected data were then uploaded to a cloud-based platform for analysis, allowing for real-time monitoring and easy access to the information. In parallel, the energy consumption of the air conditioning unit was monitored using an in situ smart electricity meter. This meter allowed us to track the efficiency of our heating and cooling systems and to correlate energy usage with the

environmental conditions within the greenhouses. A detailed description of the sensor parameters is provided in Table 3, while Figure 2 offers a visual representation of the sensor placement within the greenhouses. This visual aid helps to contextualize the data and understand the spatial distribution of the measurements, which is crucial for accurate analysis and interpretation of the results.

Table 3. Sensor parameters.

Measured Parameters	Instrument	Measuring Range	Measurement Accuracy
Temperature, humidity and carbon dioxide	4G environmental sensor	−40~+80 °C	±0.3 °C (25 °C)
		0~100% RH	±2% RH (60%, 25 °C)
		400–2000 PPM	±50 PPM (5 °C)
Electricity consumption	WIFI smart meter	Voltage: AC 90–250 V Electric current: 50 mA–63 A	

2.2.3. Measurement of Lettuce Growth Indicators

The lettuce variety cultivated in this test is the butterhead lettuce, known for its optimal growth temperature between 15 to 25 °C and a growth cycle spanning 30 to 45 days. To systematically track its developmental progress, growth data were collected at 10-day intervals, with a primary focus on key metrics such as plant height, canopy width, and leaf area, as well as both dry and fresh weight. The methodologies employed for these measurements are detailed in Table 4.

Table 4. Lettuce growth measurement methods.

Measurement Item	Measurement Method
fresh weight	After removing the roots and controlling the moisture content, the lettuce was weighed using a balance
dry weight	The lettuce was first de-enzymed (or “killed green”) in a drying oven at 105 °C for 30 min and then dried at 65 °C for 1–2 days. After drying, it was weighed using a balance to determine the dry weight.
plant height, canopy width	Using a tape measure, the dimensions were measured twice, and the average value was taken to ensure accuracy.
leaf area	Measurement using the Portable Laser Leaf Area Meter CI-202 from CID, Camas, WA, USA

In our experiments, we cultivated butterhead lettuce, a variety renowned for its optimal growth temperature range of 15 to 25 °C and a growth cycle that typically lasts between 30 and 45 days. To systematically monitor the lettuce’s developmental progress, we established a rigorous data collection protocol. Growth data was meticulously gathered at 10-day intervals, targeting key metrics that are indicative of the plant’s health and maturity. These metrics included plant height, canopy width, leaf area, as well as both dry and fresh weight. The selection of these parameters was driven by their relevance to the overall growth and yield of the lettuce. The methodologies used for these measurements were carefully documented and are detailed in Table 4. This comprehensive approach not only allowed us to track the lettuce’s growth over time but also enabled us to assess the effectiveness of our cultivation strategies and environmental controls. By focusing on these critical metrics, we aimed to gain a deeper understanding of the growth dynamics of butterhead lettuce and to optimize the conditions for its cultivation.

3. Results and Analysis

3.1. Temperature Variation in the Greenhouses

Figure 3a–c present a comprehensive comparative analysis of the mean temperatures at different heights within both the experimental and control greenhouses during the summer

season. A consistent pattern of temperature fluctuations is evident between the two greenhouses, suggesting a baseline similarity in their environmental conditions. Despite the temperature in the crop zone not being ideally suited for optimal growth—potentially due to the air conditioner’s limited cooling capacity—there is a noticeable reduction in the conditioning greenhouse’s average temperature by 1.3 °C. This reduction is particularly pronounced when the air conditioning–flexible air supply pipe system is activated, leading to a distinct temperature stratification. This stratification is characterized by a gradient of temperatures, with progressively lower temperatures as one moves from the bottom to the middle and finally to the top layer of the greenhouse. The temperature gradient between the apex and the base can range from a minimal difference to a maximum of 6 °C. As shown in Figure 3b, the lower stratum experiences a significant temperature reduction, with a mean decrease of 2.76 °C. The middle stratum sees a more moderate decline, averaging a reduction of 1.87 °C. In contrast, the uppermost layer exhibits the least temperature change, with an average reduction of 0.62 °C. Upon deactivation of the air conditioning system, the conditioning greenhouse’s temperature profile closely aligns with that of the control greenhouse. This observation underscores the system’s substantial influence on temperature regulation within the conditioning greenhouse, highlighting its effectiveness in creating a more favorable environment for crop growth.

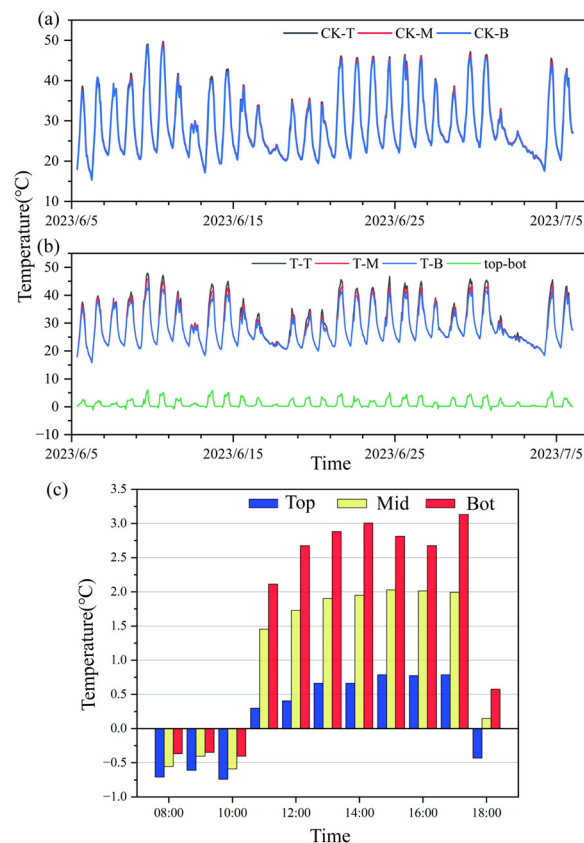


Figure 3. The average temperature reduction variation at different heights: (a) control group, (b) test group, (c) temperature changes in the top, middle, and bottom regions from 8:00 to 18:00.

Figure 4a–c offer a comparative analysis of temperature reductions at various heights within the conditioning greenhouse, corresponding to different air supply heights. The analysis reveals that throughout the system’s operation, all air supply heights result in a temperature decrease of 2–4 °C in the lower layer. However, the impact of the middle- and upper-layer air supplies becomes significantly greater than that of the lower-layer air supply as we move up the greenhouse. Specifically, a middle-level air supply appears

to induce a temperature drop of 1–3 °C in the middle zone and 0–1.5 °C in the upper zone. Among the three air supply configurations, the middle-level supply demonstrates superior environmental regulation efficacy by uniformly affecting all vertical layers of the greenhouse. In contrast, the lower-level supply exerts localized control limited to the lower vegetation zone, while the upper-level supply exhibits hybrid characteristics: its influence on middle-upper layers parallels that of the middle-level system yet mimics the lower-level pattern in the ground vicinity. This hierarchical analysis confirms the middle-level configuration as the optimal strategy for comprehensive thermal management. Upon deactivation of the system, the conditioning greenhouse retains a temperature slightly lower than that of the control greenhouse, indicating a residual cooling effect.

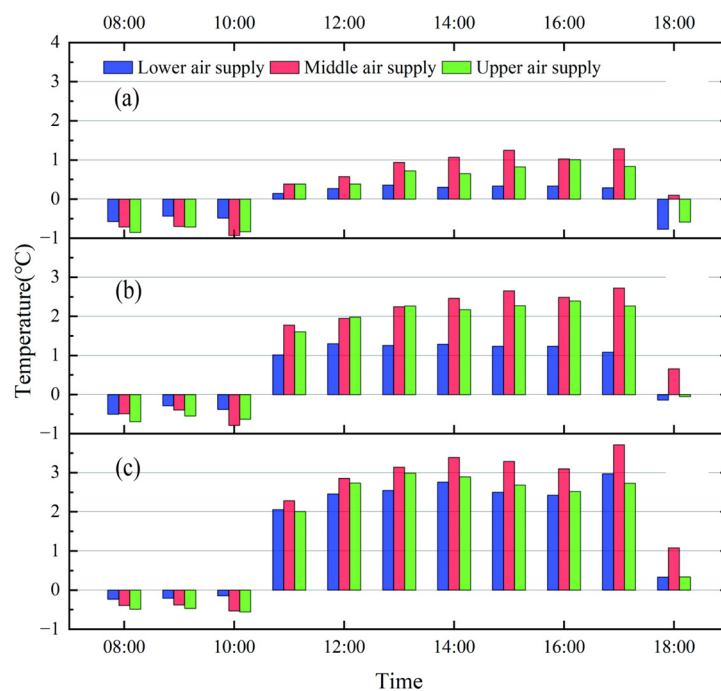


Figure 4. Greenhouse temperature drop with different air supply heights: (a) upper layer, (b) middle layer, (c) lower layer.

The localized air supply from the air conditioning–flexible air supply pipe system leads to an overall temperature reduction and the creation of thermal stratification within the greenhouse, significantly increasing temperature non-uniformity. Hence, when considering the control range, the effectiveness of air supply is ranked as follows: middle-level > upper-level > lower-level. This ranking is crucial for optimizing the environmental conditions within the greenhouse. Taking into account the cultivation methods and growth patterns of crops, for medium-to-high growth postures, such as tomatoes and cherries, middle-level or upper-level air supply should be considered to ensure optimal temperatures in the upper regions of the plants. Conversely, for low-growing crops like lettuce, direct air supply at the level of the crop canopy is recommended to avoid expending extra energy on regulating unnecessary zones. This tailored approach ensures that the air supply system is both energy-efficient and effective in meeting the specific temperature requirements of different crops.

During the winter daytime trials, the system’s lower-level air supply did not significantly increase the temperature within the conditioning greenhouse, likely due to the air conditioning’s insufficient heating capability compared to the heating load required. Consequently, the temperature stratification within the greenhouse was less pronounced than in the summer months, with the temperature difference between the upper and lower layers ranging from 0 to 2 °C. In contrast, during the winter nighttime trials, the activation of the

flexible air conditioning pipe system resulted in a noticeable temperature increase within the conditioning greenhouse, by approximately 2 °C. Interestingly, providing air supply at varying heights did not lead to substantial temperature stratification. The system's effectiveness began to diminish around 9–10 pm. On overcast days, such as 18 December and 22 December, from 10 am to 4 pm, no temperature stratification was observed within the greenhouse. However, on sunny days, the maximum temperature difference peaked at approximately 2 °C. These observations suggest that the system's operation during winter nights can effectively maintain the greenhouse temperature above the critical minimum growth temperature of 0 °C for lettuce. The system's beneficial impact on the greenhouse environment may be attributed to factors such as the natural buoyancy of hot air, the closure of skylights, and the positioning of sensors, which might not be optimally elevated.

Upon comparing Figures 3b, 5b and 6b, it becomes clear that temperature stratification within the conditioning greenhouse is influenced by two primary factors: solar radiation and the operation of the air conditioning–flexible air supply pipe system. In the summer, the combined effects of solar radiation and the air conditioning system contribute to a temperature disparity of 0–6 °C within the greenhouse. In contrast, during the winter, solar radiation is the predominant factor, resulting in a more subdued temperature difference of 0–2 °C. The difference in stratum results between summer and winter days originates from air buoyancy due to air temperature differences. In summer, the cooling air supplied by the flexible air supply pipe tends to settle in the lower layer, while in winter, the heated air tends to rise to the higher layer. This behavior underscores the importance of considering both the system's operation and external factors such as solar radiation when assessing the greenhouse environment.

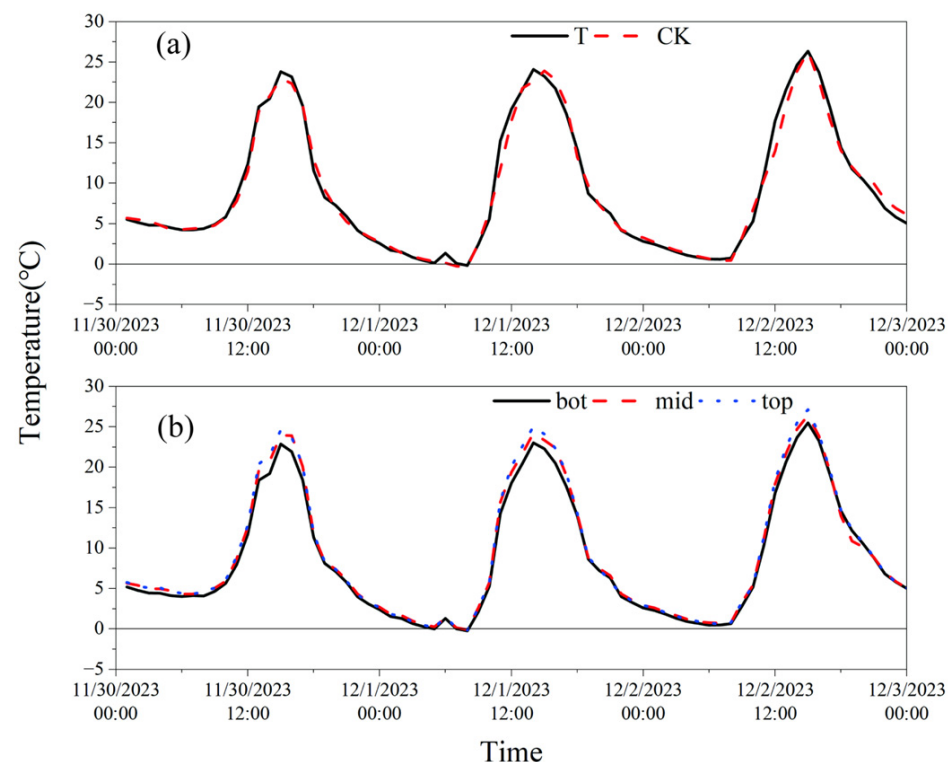


Figure 5. Comparison of daytime temperatures: (a) average temperature comparison between test and control greenhouses during winter test, (b) temperature comparison at different heights in conditioning greenhouse during winter test.

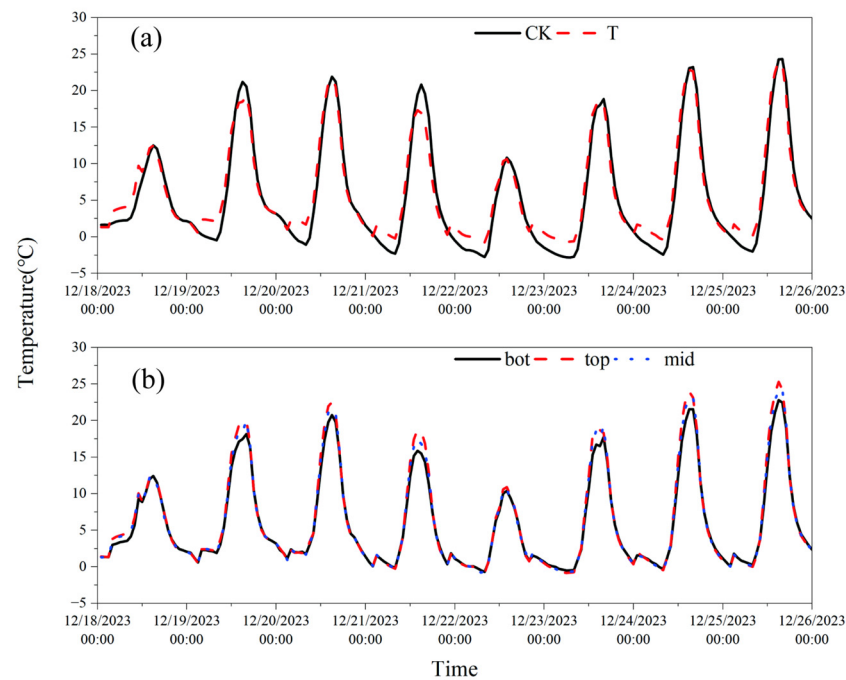


Figure 6. Comparison of nighttime temperatures: (a) average temperature comparison between test and control greenhouses during winter test; (b) temperature comparison at different heights in conditioning greenhouse during winter test.

3.2. Analysis of Lettuce Growth Data

Figure 7 provides a comparative analysis of the growth patterns of lettuce across both winter and summer trial periods. A striking similarity in the growth trajectories of lettuce is observed between the control and test groups. During the summer trials, the lettuce in the test group exhibited enhanced growth, with significant increases in dry weight, fresh weight, and leaf area by 7.28%, 22.06%, and 6.11%, respectively. This suggests that the environmental conditions in the conditioning greenhouse were more conducive to lettuce growth during the summer months. In contrast, during the winter trials, no substantial difference in the growth of lettuce was observed between the test and control groups. This stagnation in growth is primarily attributed to the reduced solar radiation characteristic of the winter months, which leads to a relative decrease in growth compared to the summer season.

In the summer test, the activation of the air conditioning pipe system led to a marked decline in temperature at the lower strata of the greenhouse. Given that lettuce thrives in cooler climates, this temperature adjustment created a more favorable environment for its growth. The system's ability to cool the greenhouse effectively contributed to the observed growth enhancement. However, in the winter test, the operation of the system during daylight hours had a negligible effect on the greenhouse's indoor climate. Interestingly, the nocturnal activation of the system resulted in an approximately 2 °C rise in temperature within the greenhouse. However, it is important to note that at night, the temperature in the control greenhouse consistently remained above the critical threshold of 0 °C for the majority of the time. As a result, the winter test indicated that the system's activation had a minimal impact on the growth of lettuce.

It should be noted that the capability of the air conditioner for cooling and heating appears to be insufficient for the heating and cooling load in the greenhouse, based on the present data. This insufficiency may lead to an underestimation of the cooling and heating effects on lettuce growth. Therefore, while the system shows promise in summer,

its performance in winter requires further optimization to ensure it can effectively support lettuce growth during periods of reduced solar radiation.

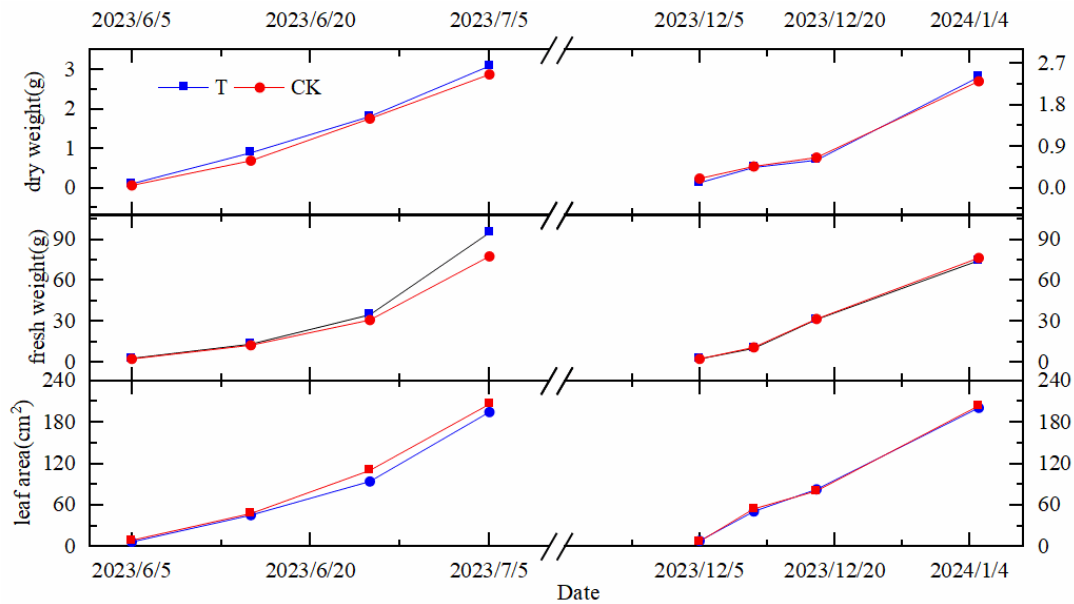


Figure 7. Lettuce growth.

3.3. Estimation the Effect of Non-Uniform Air Supply on Energy-Saving

During the summer test phase, the air conditioning system played a crucial role as a cooling agent within the conditioning greenhouse, providing a stark contrast to the control greenhouse, which remained unmodified to serve as a baseline reference. The system's cooling capacity was precisely quantified by measuring the temperature differential at corresponding heights between the test and control greenhouses. In an ideal scenario, if the control greenhouse were to be adjusted to match the lower-level temperature of the conditioning greenhouse through comprehensive regulation, this would represent the necessary cooling capacity for effective environmental control. The energy consumption was calculated using Equation (1), with the total energy expenditure detailed in Equation (2) and the energy-saving efficiency expressed in Equation (3). A detailed breakdown of the parameters used in these calculations is provided in Table 2. Conversely, during the winter test phase, the lack of significant energy-saving efficiency of non-uniform ventilation was apparent. This limitation highlights the challenges in applying the same energy-saving metrics across different seasons, underscoring the need for season-specific assessments of the system's performance. In summary, the summer test phase allowed for a clear evaluation of the cooling system's impact and energy efficiency, while the winter phase revealed the necessity of a different approach to measure the system's effectiveness in maintaining optimal greenhouse conditions. This contrast underscores the importance of adapting environmental control strategies to the specific demands of each season in the conditioning greenhouse.

$$Q = \rho V c_p \sum_{n=1}^k (T_n^T - T_n^{CK}) \quad (1)$$

$$Q_{total} = Q_{top} + Q_{mid} + Q_{bot} \quad (2)$$

$$a = \frac{Q_{local\ regulation}}{Q_{overall\ regulation}} \quad (3)$$

where Q is energy (kJ); ρ is the density of air, which is 1.29 kg/m^3 ; V is the volume of different zones, specifically the upper, middle, and lower layers; c_p is the specific heat

capacity of air, which is $1.400 \text{ kJ}/(\text{kg}\cdot\text{K})$; T_n^T is the temperature of a specific zone in the conditioning greenhouse; T_n^{CK} is the temperature of a particular zone within the control greenhouse (K); n is the minimum time step recorded by the sensor, which is 1 min, meaning that the energy is calculated every minute; and the calculation duration spans from the time the air conditioning is turned on to when it is turned off: 10:00 to 18:00. a is energy-saving efficiency.

Table 5 and Figure 8 graphically illustrate the energy consumption dynamics observed during the summer air supply experiment. A clear trend emerges: the middle-layer air supply requires the highest energy consumption, while the lower and upper layers demonstrate similar energy usage levels. The energy-saving efficiency of the localized middle-layer air supply is notably lower at 46.35%, compared to the efficiencies of 65.29% for the lower layer and 61.40% for the upper layer. When we compare these data with Figure 3c, it becomes apparent that in the context of summer air supply, the localized supply to the middle layer has a more extensive temperature influence across all three layers than the localized supplies to the lower and upper layers. This broader impact results in a lower energy-saving efficiency for the middle layer, as it requires more energy to achieve the desired temperature distribution. On the other hand, the localized air supply to the upper and lower layers, especially the lower layer, has a more focused impact, requiring less energy expenditure. This targeted approach is more energy-efficient, as it delivers cooling or heating directly where it is most needed. Therefore, for optimal agricultural practices, it is essential to consider both the morphology of the crops and the potential for energy conservation. Positioning the air supply vents near the crop canopy may prove to be a more advantageous strategy, as it targets the area of greatest need while minimizing energy consumption. This approach not only enhances agricultural productivity but also aligns with the broader goals of sustainability and efficiency in agricultural management. By tailoring the air supply to the specific requirements of the crop, we can optimize both energy use and crop growth conditions, leading to a more sustainable and productive agricultural system.

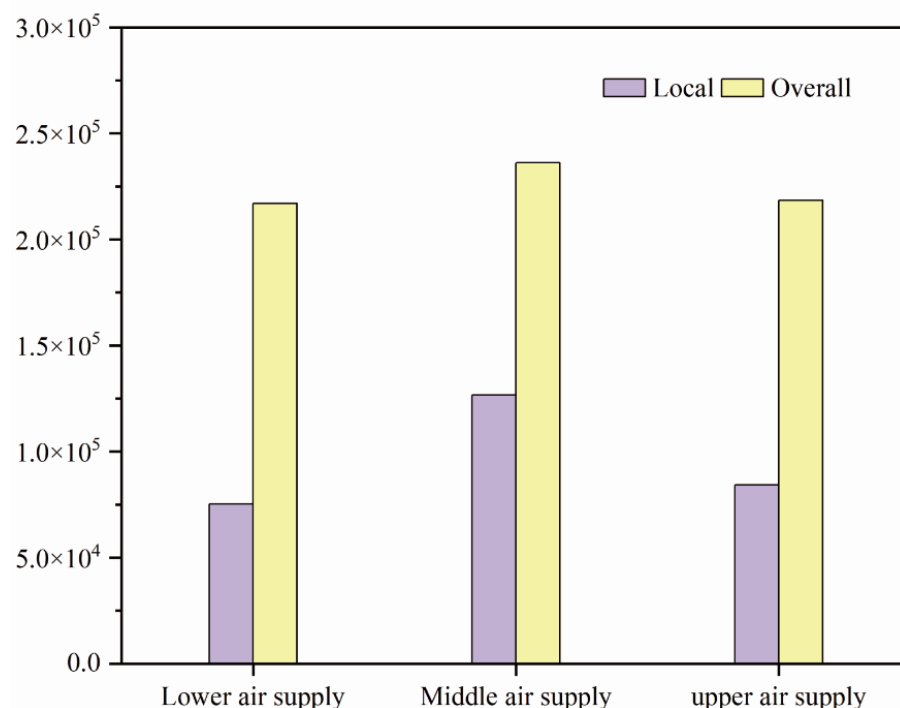


Figure 8. Energy-saving efficiency.

Table 5. Sub-zone division in the greenhouse.

	Length/m	Width/m	Height/m	Volume/m ³
Top layer	6.0	4.0	2.5	60
Lower layer	6.0	4.0	1.0	24
Middle layer	6.0	4.0	0.5	12

4. Conclusions

This study presents an innovative air conditioning–flexible air pipe system, specifically tailored for greenhouse environments, which has demonstrated notable benefits in environmental regulation, crop enhancement, and energy conservation. The system has been shown to be particularly effective in reducing greenhouse temperatures, with an average decrease of 1–2 °C in the lower layer and 3–4 °C in the middle layer during the summer months. Notably, the middle-level ventilation was found to be the most impactful in this regard. In winter, while the system showed minimal impact on daytime temperatures, it successfully increased the overall temperature by 2 °C during the night, effectively preventing freezing conditions. Additionally, the system enhanced lettuce growth in the test group by 7.28–22.06% across various parameters during the summer. However, in winter, the growth differences were not significant, which can be attributed to the reduced solar radiation during this season. The energy-saving efficiency of the system was determined to be 46.35% for middle-level, 65.29% for lower-level, and 61.40% for upper-level ventilation. These findings suggest that middle-level ventilation is well-suited for dense crops that benefit from a broader temperature influence, while upper- and lower-level ventilation are more energy-efficient options for localized temperature regulation. The study underscores the complexity of the greenhouse’s environmental field and sets the stage for future research to refine the system’s design and application. This will further develop the theoretical framework for non-uniform ventilation regulation in greenhouses, leading to more precise and efficient environmental control [37]. In conclusion, the air conditioning–flexible air pipe system offers a promising approach to enhancing greenhouse environmental control and crop productivity. It has the potential for further optimization and broader application, making it a valuable tool in the ongoing quest for sustainable and efficient agricultural practices [38].

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