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IMPROVING PLANT CANOPY MICROENVIRONMENT CONDITIONS BY USING DOUBLE CHANNEL AERATION CULTIVATION SYSTEM IN A PLANT FACTORY: SIMULATION ANALYSIS AND EXPERIMENTAL STUDY

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Abstract

To address the current issues in plant factories including stagnant airflow in plant canopies, uneven distribution of environmental factors, and high complexity of environmental control systems, this study developed an integrated double-channel aeration cultivation system (DCAS) combining ventilation ducts with cultivation tanks. A three-dimensional computer fluid dynamic model was developed and validated through simulating the airflow distribution within the plant canopy under different ventilation parameters. According to the simulated results, a ventilation angle of 45° with an intake air velocity of 8 m s^{-1} showed the best airflow uniformity and highest proportion of suitable zone. Based on the optimized parameters, a lettuce cultivation experiment was conducted in a plant factory. The experiments investigated the effects of traditional ventilation mode and DCAS ventilation on lettuce growth, canopy environmental factors and heat exchange parameters. The experimental groups used DCAS ventilation with canopy airflow velocities set at 0.6 m s^{-1} (T_1), 0.9 m s^{-1} (T_2) and 1.2 m s^{-1} (T_3) respectively, while the control group (CK) used the conventional side-inlet top-outlet ventilation mode with canopy airflow velocity of 0.2 m s^{-1}. Results showed that compared with CK, the experimental groups demonstrated better performance in lettuce growth, canopy microenvironment and heat exchange with the surrounding environment. Under T_2 treatment, the dry and fresh weights of lettuce shoots increased by 24% and 14%, respectively, compared to those under the CK. The canopy microenvironment and heat exchange reached optimal status under T_3 treatment, where the average relative humidity and air temperature in lettuce canopy decreased by 8.8% and 2.8°C, respectively, compared to those under the CK. Additionally, DCAS ventilation effectively reduced the incidence of tipburn in lettuce. The above results indicate that the DCAS can be considered as an effective system for improving canopy microenvironment, plant growth and reducing tipburn occurrence.

Key words: *plant factory, airflow, CFD, canopy microenvironment, plant quality.*

INTRODUCTION

As plant factories continue to expand in scale and increase cultivation layers, the limitations of traditional ventilation systems focusing on overall environmental control have become increasingly apparent, failing to meet the precise airflow regulation requirements in plant cultivation spaces (Zhang et al., 2024). In conventional ventilation systems, low airflow velocities within cultivation areas, including stagnant airflow zones, lead to uneven distribution of environmental factors such as temperature, humidity, and CO_2 concentration. This results in stunted plant growth and physiological disorders like tipburn (Sago, 2016). Furthermore, insufficient airflow velocity adversely affects exchanges of energy and matter between plant and environment, particularly in CO_2 and H_2O exchange processes, consequently impairing photosynthetic and transpiration rates and hindering plant development (Baek et al., 2015). Therefore, improving ventilation methods and optimizing airflow velocity distribution within plant cultivation spaces currently represent the most effective solutions to these challenges (Zhang et al., 2022).

Airflow is a complex environmental factor that exerts diverse effects on plants, depending on its velocity, duration, and penetration depth into the plant canopy. Sufficient airflow velocity can influence plant development, morphology, and physiological functions. Studies have shown that airflow exerts mechanical stimulation on plants, resulting in shorter but thicker stems and enhanced lodging resistance (Gardiner et al., 2016). Thus, airflow can induce biological adjustments in plant height and elongation. Additionally, uneven airflow distribution may lead to asymmetric plant growth, causing plants to bend away from the direction of stronger airflow. Therefore, the impact of airflow on plant growth is dual-sided—appropriate airflow velocity can promote plant growth and development while improving crop quality. Kitaya, (2005) reported that increasing the horizontal air velocity from 0.005 to 0.8 m s^{-1} enhanced the cucumber transpiration rate by 2.1 times. Previous studies have shown that the optimal airflow velocity range for plant canopies is between 0.3 and 1.0 m s^{-1}, within this range, plants exhibit significantly improved photosynthetic and transpiration rates while also experiencing the lowest probability of disease occurrence.

The objective of this study was to design a double aeration cultivation system (DCAS). CFD software was utilized to simulate the airflow distribution within the cultivation space under different intake air velocities. The optimal intake air velocity was determined through airflow uniformity. Practical plant cultivation experiments were conducted with the above optimal intake air velocity. Finally, the optimal intake air velocity was determined according to the growth of lettuce.

MATERIALS AND METHODS

2.1. Numerical simulation

2.1.1. The model geometry and grid generation

Based on the size of the cultivation shelves, the DCAS was designed with dimensions (length × width × height) of 1.0 m × 0.3 m × 0.12 m. Two DCASs could be placed on each layer. The structure of DCAS was shown in Figure 1.

According to the height of lettuce at maturity, the plant canopy height was set at 0.15 m. Considering the distance between the LED panel and the cultivation board, the air layer was set at 0.25 m. In the Geometry module of Workbench, the DCAS model was established, with the northeast corner of the model as the origin point O (0, 0, 0). The positive east direction was defined as the X-axis, the vertical upward direction as the Y-axis, and the positive north direction as the Z-axis.

The DCAS model (Figure 2), including the plant canopy, air layer, ventilation ducts, and LED heat source, was constructed in the Geometry module of Workbench. The completed DCAS model was then imported into the Mesh module, where the Proximity and Curvature method was applied for grid generation (Figure 3). To improve simulation accuracy, the mesh near the walls of the ventilation ducts was refined. Two different angles generated 254,078 and 257,154 grid cells, respectively. The mesh quality was evaluated using skewness, with an average skewness of 0.21 and a maximum skewness of 0.72, meeting the required standards.

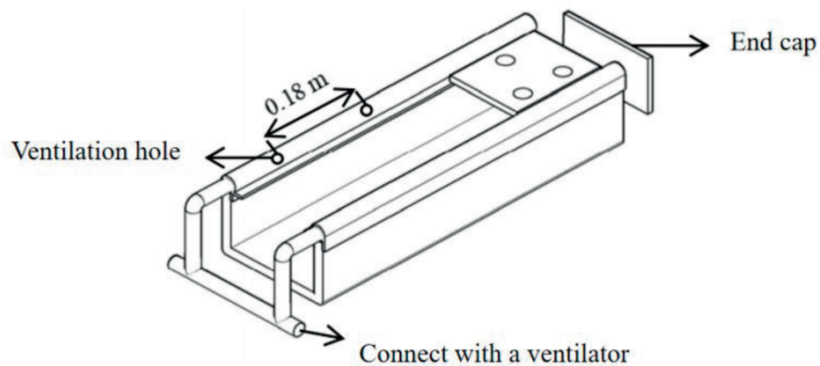

Figure 1 Double channel aeration cultivation system

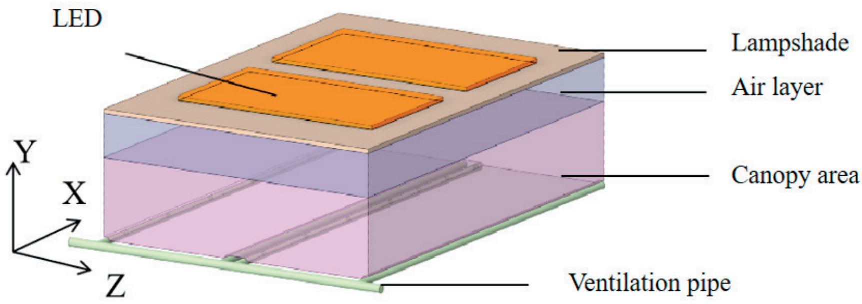

Figure 2. The CFD model of double aeration cultivation tank

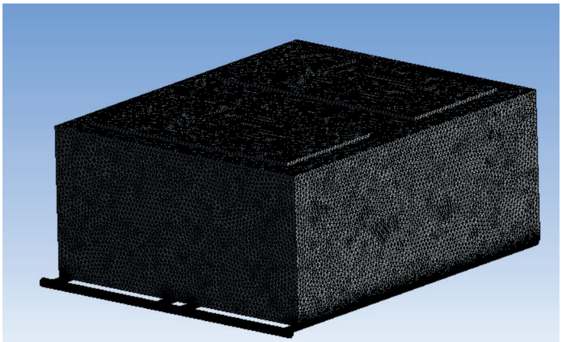

Figure 3. The grid of CFD model

2.1.2. The numerical approach

In this study, the distribution of airflow in the crop canopy was mainly affected by the structure of the cultivation tank and the intake air velocity. The fluid flow in the problem domain was assumed to be a steady-state, incompressible, and three-dimensional turbulent. The numerical calculation of airflow can be seen as a mathematical formula for the conservation law of fluid mechanics. In this model, the momentum equation was used, and turbulence model was selected to solve for the turbulent kinetic energy and the viscous dissipation rate of turbulent energy. The governing equations included the continuity equation, the momentum equation, the turbulent kinetic energy equation, and the dissipation rate equation, these equations can be represented by the following general equations (Versteeg, 1995):

$$\frac{\partial \rho}{\partial \tau} + \frac{\partial}{\partial X_i}(\rho u_j) = 0 \quad (2\text{-}1)$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial X_j}(\rho u_j u_i) = \frac{\partial}{\partial X_i}[-P\delta_{ij} + \mu(\frac{\partial u_i}{\partial X_j} + \frac{\partial u_j}{\partial X_i})] + \rho g_i \quad (2\text{-}2)$$

$$\frac{\partial}{\partial t}(\rho C_a T) + \frac{\partial}{\partial X_j}(\lambda \frac{\partial T}{\partial X_j}) = S_T \quad (2\text{-}3)$$

2.1.3. Boundary conditions

In this experiment, the DCAS model was simplified to reduce computational load, retaining only the ventilation ducts, plant canopy, the air layer above the canopy, and the LED heat source. The plant canopy was modeled as a porous medium, with the viscous resistance coefficient and inertial resistance coefficient set to 25 and 1.3, respectively (Zhang et al., 2019). The air layer was defined as an air medium, and an LED heat source model was embedded above it. The lamp cover (glass) was treated as a conductive material, while the reactor (aluminum) was defined as the heat source, with a volumetric heat generation rate of 34,166 $W·m^{-3}$ (Zhang et al., 2021). The duct inlet was set as a velocity inlet, with airflow velocities of 5, 6, 7, and 8 $m·s^{-1}$, respectively. The outlets around the canopy were defined as pressure outlets (0 Pa). The thermal physical properties of the materials used in the simulation are listed in Table 1 (Wu et al., 2021).

Table 1. Thermal physical parameters of different materials in CFD model

Material	Density (kg m^3)	Dynamic viscosity (kg m^{-1} s^{-1})	Specific heat (J kg^{-1} K^{-1})	Thermal expansion coefficient (K^{-1})	Thermal conductivity (W m^{-1} K^{-1})
Air	1.225	$1.7894×10^{-5}$	1006.43	$3.43×10^{-3}$	$2.42×10^{-2}$
Canopy	998.2	/	4182	/	0.6
Glass	2500	/	670	/	0.74
Aluminum	2719	/	871	/	202.4

2.2. Cultivation experiment setup

2.2.1. Plant preparation

Lettuce seeds (*Lactuca sativa* cv.'Butterhead') were germinated in sponge cubes and incubated for 2 days in a growth chamber in the dark at an air temperature of 23.5°C. On day 3, seedlings were transferred to a plant factory with PPFD of 150 μmol $m^{-2}s^{-1}$ by using fluorescent lamps (ZPDT812WW-75, ZSP Technology Co, China). On day 15, uniformed-size seedlings were selected and transferred to the greenhouse with a planting density of 28 plants/m^2 and a spacing of 0.15 m. Yamazaki lettuce nutrient solution was selected as the nutrient solution.

2.2.2. Plant measurements

On day 28 after transplanting, fresh and dry weights of shoots and roots, number of leaves per plant and total leaf area were measured. The fresh weights of shoots and roots were measured using an electronic scale (GL6202-1SCN, Sartoriu, Germany). Shoots and roots were dried in an oven at 80 °C for 72 h. Total leaf area was measured using a leaf area meter (Li-3100C, LI-COR, Lincoln, NE, USA). Ten plants were chosen randomly from each treatment for measurement.

2.2.3. Environmental parameters measurements

On day 28 days after transplanting, the air velocity in plant canopy were measured by an infrared hot-wire anemometer (Climomaster6501-BG, KANOMAX, JAPAN) along the cultivation tank. Sensors (LR5001, HIOKI, JAPAN) were used to record the air temperature, relative humidity within the plant canopy for 28 days.

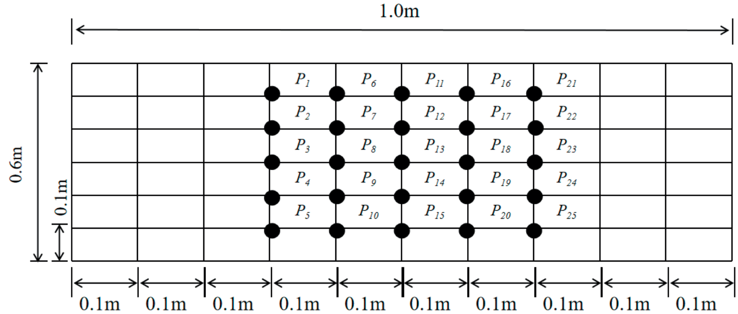

Figure 4. The air velocity measured points in plant canopy

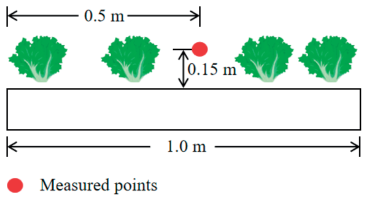

Figure 5. The air temperature and relative humidity measured points within plant canopy

2.2.4. Experiment setup

The experiment comprised four treatments: the control group utilized the existing ventilation system of the artificial light plant factory, generating an average canopy airflow velocity of 0.2 m s⁻¹.

The other three treatments employed the Double Channel Aeration Cultivation System (DCAS) to provide distinct airflow velocities: 0.6 (T_1), 0.9 (T_2), and 1.2 m s⁻¹ (T_3).

These were achieved by connecting a ventilator (JYF-75pqs, Shenzhen) to the duct inlet and operating it at 50%, 75%, and 100% of its rated power capacity respectively.

2.3. Statistical analysis

Statistical analysis was carried out using the SPSS 16.0 (SPSS Inc., Chicago, IL, USA) statistical software. Separation of means was performed using a multiple range test of least significant difference (LSD) at $p \leq 0.05$.

RESULTS

3.1. Model validation

Under a ventilation angle of 45°, the simulated and measured wind speed values at 25 measurement points were compared (Figure 6). When the inlet velocities were set at 5, 6, 7, and 8 m·s⁻¹, the average relative errors between the simulated and measured values were 7.5%, 4.4%, 7.7%, and 3.7%, respectively.

Overall, the simulated results showed good agreement with the measured data, exhibiting similar trends.

Thus, the model's accuracy meets the required standards and can be reliably used for data analysis.

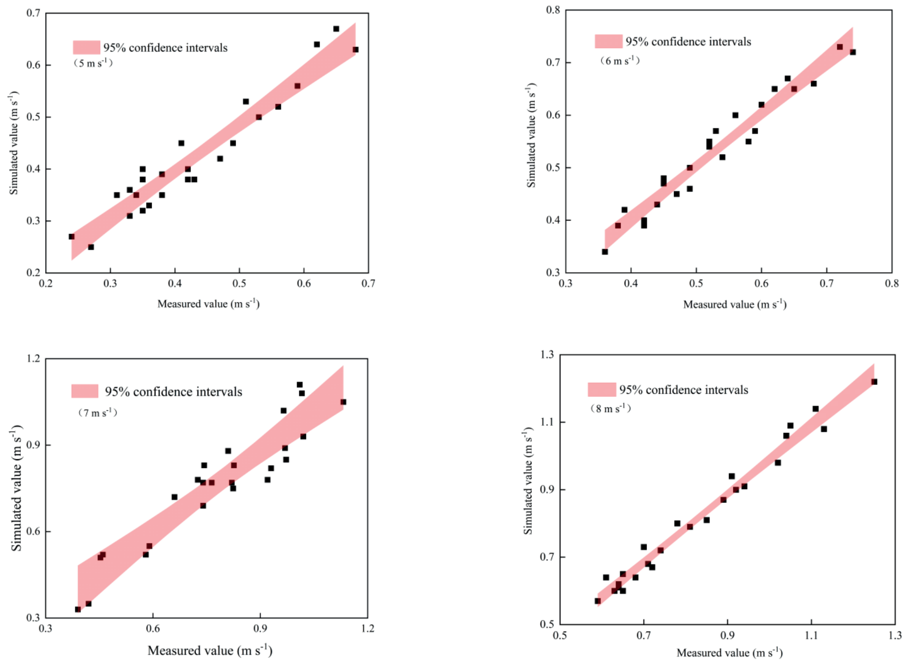

Figure 6. Comparison of simulated and measured values of airflow velocity in plant canopy under different inlet air velocities

3.2. The airflow distribution within plant canopy under ventilation angle of 45°

The analysis was conducted on the Z=0.3 m plane. In this experiment, the coefficient of variation (CV) was employed to evaluate airflow uniformity, where CV is defined as the ratio of standard deviation to mean value. A higher CV indicates poorer airflow uniformity. The airflow formed distinct jets upon entering the canopy, with subsequent velocity gradually attenuating until exiting the canopy. When the inlet velocity increased from 5 to 8 m s^{-1}, the proportion of favorable zone in the plant canopy rose from 64.8% to 71.1%, while the stagnant zone decreased from 35.2% to 28.9%, and the average airflow velocity within the canopy increased from 0.35 to 0.71 m s^{-1} (Table 2). However, this increase in inlet velocity resulted in reduced airflow uniformity throughout the canopy.

Table 2. The proportion of canopy airflow in each area of different intake air velocities under ventilation hole angle of 45°

Intake velocity (m s^{-1})	Volume proportion (%)			CV (%)	AVG (m s^{-1})
	V<0.3 m s^{-1}	0.3 m s^{-1}≤V≤1 m s^{-1}	V>1 m s^{-1}		
5	35.2	64.8	0	57	0.35
6	33.1	66.9	0	60	0.49
7	31.5	68.5	0	64	0.6
8	28.9	71.1	0	70	0.71

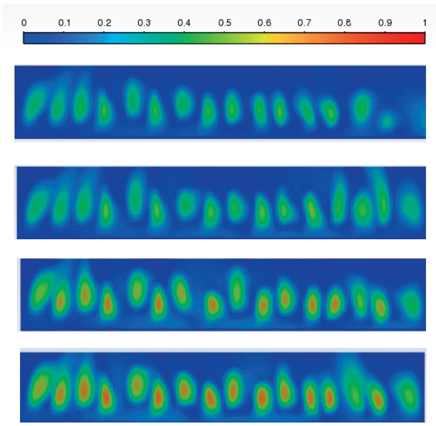

Figure 7. Airflow distribution of canopy in the plane of Z=0.3 m under ventilation hole angle of 45°

3.3. The airflow distribution within plant canopy under ventilation angle of 60°

As the inlet air velocity increased from 5 m s^{-1} to 8 m s^{-1}, the proportion of favorable zones in the plant canopy increased from 51.4% to 58.4%, while the stagnant zones decreased correspondingly from 48.6% to 41.6% (Table 3). Concurrently, the average airflow velocity within the plant canopy rose from 0.31 m s^{-1} to 0.64 m s^{-1}. However, this increase in inlet velocity was accompanied by a reduction in airflow uniformity throughout the canopy.

Table 3. The proportion of canopy airflow in each area of different intake air velocities under ventilation hole angle of 60°

Intake velocity (m s^{-1})	Volume proportion (%)			CV (%)	AVG (m s^{-1})
	V<0.3 m s^{-1}	0.3 m s^{-1}≤V≤1 m s^{-1}	V>1 m s^{-1}		
5	48.6	51.4	0	64	0.31
6	46.5	53.5	0	69	0.42
7	43.2	56.8	0	72	0.55
8	41.6	58.4	0	77	0.64

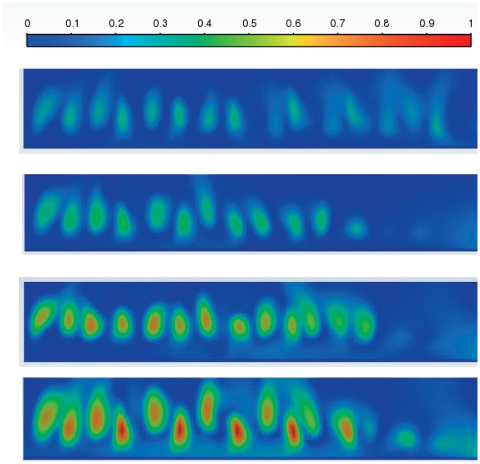

Figure 8. Airflow distribution of canopy in the plane of Z=0.3 m under ventilation hole angle of 60°

3.4. Comparative analysis of airflow distribution under different ventilation angles

The comparison of airflow velocity distribution contours in the canopy plane clearly demonstrates that the 45° ventilation angle configuration produces more uniform airflow from each vent while maintaining superior performance characteristics at equivalent inlet velocities, including a higher proportion of favorable airflow zones, greater average canopy airflow velocity, and lower coefficient of variation compared to other configurations. Both tested vent angles showed increasing proportions of favorable zones with higher inlet velocities without generating any high-velocity zones, though accompanied by reduced airflow uniformity, with the 45° configuration consistently exhibiting better overall performance.

3.5. The environmental parameters as affected by different canopy air velocities

During the experimental period, the temperature in the plant factory ranged from 21-26°C.

As shown in Figure 8, both the relative humidity at the plant canopy and the temperature during the light period varied over time.

The results demonstrated that increasing airflow velocity through the canopy led to corresponding decreases in both relative humidity and light-period temperature.

Compared to the control group, the three experimental treatments showed average relative humidity reductions of 1.59%, 3.7%, and 6.6%, respectively, along with average light-period temperature decreases of 1.7°C, 2.2°C, and 2.8°C.

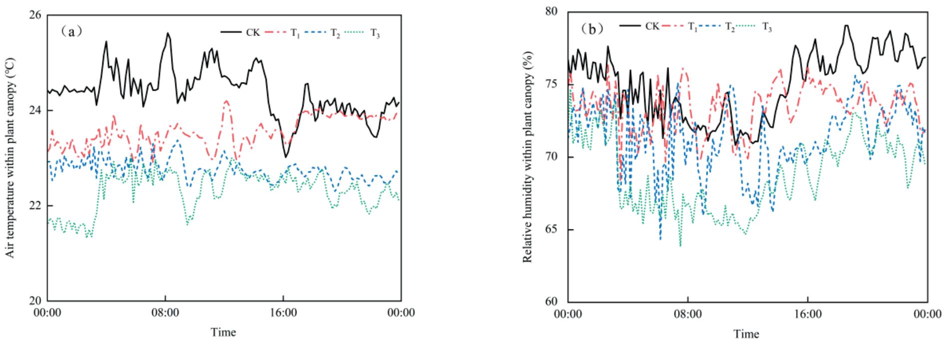

Figure 9. The time course of relative humidity (a) and air temperature (b) within plant canopy on day 21 after transplanting of different treatments

3.6. The lettuce growth and tipburn occurrence as affected by different canopy air velocities

The growth parameters of lettuce are presented in Table 4. As the canopy airflow velocity increased, the fresh weight of lettuce shoots initially increased and then decreased, reaching its maximum value of 56.66 g at a canopy airflow velocity of 0.9 m s^{-1}. The dry weight of shoots followed a similar trend, peaking at 3.14 g under the same airflow velocity. Different canopy airflow velocities showed no significant effect on root growth. Notably, lettuce plants grown under DCAS exhibited no leaf tipburn while the control group displayed this disorder. The number of leaves remained unaffected by variations in canopy airflow velocity.

Table 4. The growth and tipburn occurrence of lettuce under different treatments

Treatments	Shoot fresh weight (g)	Shoot dry weight (g)	Root fresh weight (g)	Root dry weight (g)	Tipburn occurrence(%)	Total leaf number
CK	49.8±1.9c	2.5±0.2b	10.6±0.8a	0.63±0. 1a	20.9±4.5	21±1.0a
T_1	55.2±2.2ab	2.7±0.3ab	9.7±0.6a	0.52±0.1a	0	20±1.0a
T_2	56.7±4.1a	3.1±0.3a	10.2±1.2a	0.57±0.1a	0	21±1.0a
T_3	53.9±4.5b	2.7±0.4ab	9.4±1.5a	0.55±0.1a	0	21±1.0a

DISCUSSIONS

Enhancing both crop yield and quality represents two primary objectives in protected agriculture. In this study, lettuce shoot biomass (both fresh and dry weight) initially increased with elevated canopy airflow velocity, but decreased when velocity exceeded 1.2 m s^{-1}. The yield improvement can be attributed to reduced leaf boundary layer resistance, which enhances CO_2 assimilation and H_2O diffusion (Okayama et al., 2008). However, excessive airflow velocities may induce over suppressed transpiration rates, leading to plant water deficit.

Substantial evidence indicates that insufficient airflow velocities (<0.3 m s^{-1}) compromise photosynthetic efficiency by restricting CO_2 uptake while simultaneously impairing transpiration-driven nutrient transport, ultimately degrading crop quality. Optimal lettuce development typically occurs within 0.3-1.0 m s^{-1} (Lee et al., 2000), with velocities exceeding 0.3 m s^{-1} demonstrably benefiting both photosynthesis and transpiration (Kitaya et al., 2003).

In leafy vegetable production, proper airflow management plays another critical role in mitigating tipburn which is a calcium-related physiological disorder particularly prevalent in lettuce cultivation characterized by necrotic leaf margins and subsequent browning, tipburn incidence correlates positively with growth rate (Borkowski et al., 2016). Under rapid growth conditions, calcium demand for new tissue development often outstrips supply due to limited transpiration-driven calcium transport (White et al., 2003). Conventional facilities with suboptimal airflow (<0.5 m s^{-1}) exacerbate this condition by thickening boundary layers and suppressing transpiration. Notably, the DCAS completely prevented tipburn occurrence by delivering consisten airflow directly to the canopy, whereas conventional ventilation failed to penetrate the canopy effectively, resulting in tipburn.

CONCLUSIONS

A double channel aeration cultivation system (DCAS) was designed and created to improve the airflow distribution within lettuce plant canopy, as well as the complexity of adding ventilation equipment. CFD software was used to simulate the airflow distribution and uniformity within the plant canopy under different ventilation parameters. To validate the practical application of the cultivation troughs, a cultivation experiment was conducted in the plant factory. The effects of DCAS ventilation and conventional ventilation modes on lettuce growth and microenvironment within plant canopy under different airflow velocities were tested and analyzed. The main conclusions are as follows.

1) In the CFD simulation, two ventilation angles were designed. By comparing airflow distribution cloud diagrams and airflow field analyses, the optimal ventilation parameters were determined to be a 45° ventilation angle and an airflow velocity of 8 m s^{-1}.

2) In the cultivation experiment, lettuce grown under conventional ventilation exhibited slow growth and tipburn. In contrast, lettuce grown under the DCAS showed no tipburn, increased yield, and lower canopy temperature and relative humidity compared to the conventional ventilation mode.

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