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Numerical evaluation of the performance of two air distribution systems in a generic multi-layer vertical farm

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Abstract. The uniformity of the environmental conditions in a vertical farm can be poor due to multi-layer cultivation shelves, crop resistance to airflow, and excessive heat generated by artificial lighting, decreasing overall crop yield and quality. This study evaluates the performance of two air distribution systems, i.e., long-side air supply and short-side air supply, in a generic multi-layer vertical farm using a validated computational fluid dynamics (CFD) modeling approach. The simulation results show that under identical airflow rates, the average air temperature in crop regions from short-side air supply is higher than the long-side case. In addition, stagnation regions exist in both scenarios, where the removal efficiency of water vapor and heat is low. Further study is required to improve the uniformity of air distribution in crop regions.

1 Introduction

Extreme climate, rapid urbanization, environmental pollution and public emergencies such as the coronavirus pandemic may result in a shortage of food supplies for urban residents. Therefore, there is an increasing interest in adopting high-tech precisely controlled environment agriculture, i.e., “vertical farms” or “plant factories”, to produce food in a climate-resilient manner [1, 2]. A vertical farm is an indoor farm where the crops are grown in multi-layers with artificial lighting under precisely controlled environmental conditions. The environmental conditions in a vertical farm are important, since it directly affects the crop yield and quality [3, 4]. However, the uniformity of the environmental conditions in a vertical farm can be poor due to multi-layer cultivation shelves, crop resistance to airflow, and excessive heat generated by artificial lighting [5-7].

In the present study, two different air distribution systems, i.e., air supply from the long side of the growing layer and air supply from the short side of the growing layer, are investigated with a validated computational fluid dynamics (CFD) modeling approach. To evaluate the performance of the air distribution systems, average environmental variables in the crop regions are calculated and compared.

2 Description of air distribution systems

2.1 Geometry

A generic indoor vertical farm with six growing layers is used for the CFD simulations, as shown in Fig. 1. The dimensions of the chamber are 7.2×2.4×3.6 m\textsuperscript{3}, and the dimensions of each growing layer are 1.4×6.0 m\textsuperscript{2}. The power density of LED lamps is 66.7 W/m\textsuperscript{2} per growing area.

2.2 Air supply and exhaust

Small circular openings with a diameter of 40 mm (Fig. 1) are used in each layer to supply air at a fixed air temperature (22 °C) and vapor pressure deficit (VPD, 0.8 kPa; 70% in relative humidity). The opening size is set as 40 mm to ensure that the air speeds in the crop regions are within the acceptable range for crop growth under a relatively high airflow rate.

For the scenario of long-side air supply (Fig. 1a), one row of openings is used in each layer along the long side of the growing bed, and the total opening area is 0.452 m\textsuperscript{2}. For the scenario of short-side air supply (Fig. 1b), two rows of openings are used along the short side, and the total area is 0.211 m\textsuperscript{2}. An identical volume flow rate of 3000 m\textsuperscript{3}/h is applied to both scenarios to make it comparable, corresponding to 48.2 air changes per hour (ACH). Due to the difference in the total opening area, the supply air speeds are 1.84 m/s and 3.95 m/s for long-side and short-side air supply, respectively. The selected supply parameters provide acceptable environmental conditions [3] for the growth of lettuce in the crop regions.

Ceiling exhausts above the corridor are used for the simulations, which is a configuration adopted by many real indoor farms. It should be pointed out that the exhaust configuration in this study might not be the best option for the uniformity of air distributions in vertical farms. For future research, different exhaust scenarios will be investigated.

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3 Numerical method

3.1 Numerical model

In the simulations, airflow, heat and moisture transfer are modeled using a validated CFD modeling approach. A crop transpiration model of lettuce [8] was incorporated into the simulation to account for heat and moisture exchange between crops and ambient air. The momentum sink due to the drag effect of the crop is added to the governing equations of air motion [9]. Heat absorption from the crop is considered based on an energy balance analysis.

3.2 Solver settings

Based on best-practice guidelines for CFD simulations of indoor airflows [10, 11], steady Reynolds-averaged Navier-Stokes (RANS) simulations are performed using the RNG k-ε turbulence model [12] with low-Reynolds number modeling to solve the flow until the viscous sublayer (dimensionless wall distance (y*) is lower than 5). The discrete ordinates (DO) model is applied to model the radiative heat transfer. Second-order upwind discretization schemes are used for all variables except the pressure term. For pressure, a staggered scheme called PRESTO! [13] is applied. Convergence is assumed to be reached when the scaled residuals level off. Due to oscillatory behavior, the variables are averaged over 4000 iterations in order to obtain a statistically steady solution.

Fig. 1. Computational geometry of two air distribution systems for a generic multi-layer vertical farm: (a) long-side air supply; and (b) short-side air supply. The supply openings are indicated in cyan, the LED lamps in purple and the crop region in green.

4 Simulation results

4.1 Air distribution in the crop regions

Air speed, air temperature, VPD and CO₂ concentration in the crop regions are important environmental variables that affect crop growth. In this study, we focus on the first three factors. The distribution of air temperature and VPD resemble the air speed distribution. Herein, only the air speed distribution in the middle of crop regions is illustrated in Fig. 2. For both air distribution systems, the air speeds are within the range of 0.1 to 0.5 m/s in most areas. However, there exist stagnation regions for both scenarios. For long-side air supply, stagnation regions are located on both ends and in the middle of the growing bed (Fig. 2a). In contrast, for the short-side air supply, the air speeds at the end of the growing bed are very low (Fig. 2b), reducing the local removal efficiency of excess heat and water vapor.

The influence of wall boundaries on the airflow pattern is significant for the long-side air supply. Two recirculation cells are formed near the sidewalls (Fig. 2b), resulting in high air speeds in the side aisles.
The locations of air exhausts can be adjusted in future studies to improve efficiency in this particular air distribution system design.

4.2 Average environmental parameters

The average air speed, temperature, and VPD in crop regions are 0.158 m/s, 22.9 °C and 0.626 kPa from the long-side air supply. On the other hand, they are 0.167 m/s, 24.3 °C and 0.644 kPa from short-side air supply, which are all larger than the long-side case. In particular, the average air temperature increases by 1.4 °C in the case of short-side air supply, indicating the decrease of heat removal efficiency in crop regions in this configuration. The reason is that there are only openings far from the crop regions for the air distribution system of short-side air supply, resulting in poorly refreshed areas further downstream.

Fig. 2. Distribution of air speed in the middle of crop region in a horizontal cross section: (a) long-side air supply; and (b) short-side air supply.

5 Conclusions

Compared to the air distribution system of long-side air supply, the average air speed, temperature, and VPD in crop regions are all larger from the short-side case. The initial simulation results demonstrate that stagnation regions exist in both air distribution systems, where the local removal efficiency of excess heat and water vapor is low. Future studies will assess a larger range of air distribution configurations, with varying locations of supply and exhaust openings, including alternative air distribution system designs.

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