CFD EVALUATION OF UVC AIR-CLEANING INTEGRATION IN GREENHOUSE HVAC SYSTEMS

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ABSTRACT

Greenhouse crops in Taiwan are highly vulnerable to airborne pathogens due to the humid climate and poor ventilation. This study evaluated the integration of UVC air-cleaning devices with the greenhouse HVAC system to reduce pathogen concentrations. A SolidWorks model of the NTU smart greenhouse was constructed, and CFD simulations were conducted to compare three configurations in which four UVC units were placed at the upper, middle, and lower regions of the wet pad. Results showed that the middle placement achieved the highest sterilized airflow rate (0.4972 m³/s), capture efficiency (5.0%), and equivalent air change rate (1.40 h⁻¹), approximately 15% higher than the other placements. The proposed UVC-based approach may also reduce reliance on chemical pesticides and fungicides in greenhouse crop production.

Keywords: Computational fluid dynamics (CFD), greenhouse HVAC system, ultraviolet germicidal irradiation, airborne plant diseases.

INTRODUCTION

The hot and humid climate in Taiwan creates favorable conditions for frequent outbreaks of plant diseases. Greenhouse crops, though of higher economic value, are particularly susceptible because poor ventilation in greenhouses often accelerates the spread of airborne pathogens. For instance, muskmelon production has previously been affected by powdery mildew in the smart greenhouse at National Taiwan University, as shown in Fig. 1. Considering the economic significance of greenhouse crops, effective disease control strategies are urgently needed. This study proposes an approach that combines the greenhouse HVAC system with UVC air-cleaning devices, where airflow passes through UV lamps to reduce pathogen concentrations. Using SolidWorks Flow Simulation, computational fluid dynamics (CFD) analyses were performed to assess the feasibility of three different placement configurations of UVC devices within the greenhouse.

Fig. 1 (A) Powdery mildew-infected muskmelon plants on the right-hand side.
(B) Close-up of a tagged muskmelon fruit showing infected symptoms.

MATERIALS AND METHODS

3D MODELS OF GREENHOUSE AND UVC AIR-CLEANING DEVICE

A SolidWorks model of the NTU smart greenhouse and the UVC air-cleaning device was constructed, as shown in Fig. 2. The greenhouse measures approximately 8.1 m in width, 5.8 m in height, and 31.0 m in length, with a total volume (V) of about 1282 m³. Its HVAC system consists of an evaporative cooling pad (wet pad) at the air inlet and negative-pressure fans at the outlet. The design of the UVC device was adapted from our laboratory's previous study (Chou *et al.*, 2025). A total of four UVC devices were applied in the greenhouse model.
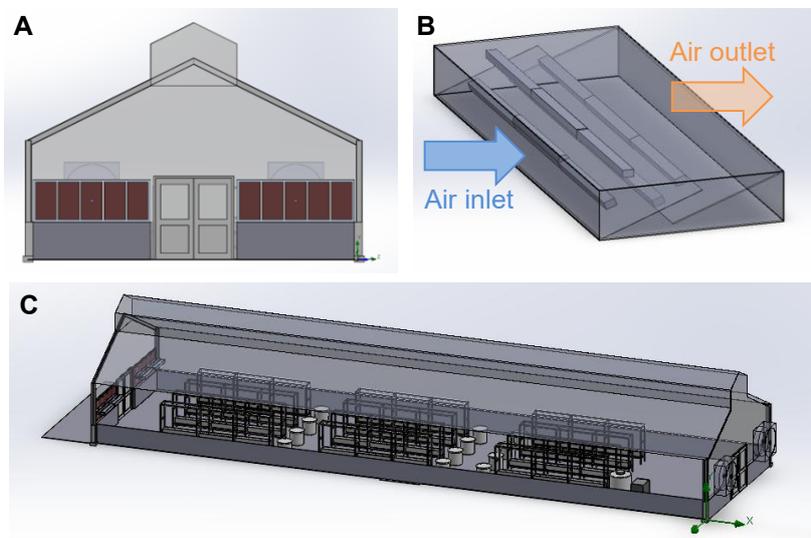

Fig. 2 (A) Front view of the NTU smart greenhouse. (B) Model of the UVC device with dimensions of 1.4 m × 0.4 m × 0.14 m. (C) Isometric view of four UVC units installed inside the greenhouse at the evaporative cooling pad.

KEY PARAMETERS

The following parameters were examined in this study:
- Q_{vent} [m³/s]:Total airflow through the greenhouse ventilation system.
- Q_{UVC} [m³/s]: Purified airflow passing through the UVC air-cleaning units.
- Air Change Rate (ACH) [h⁻¹]: The number of air exchanges per hour in the entire greenhouse driven by ventilation (Memarzadeh *et al.*, 2012).

$$ACH = \frac{Q_{vent}}{V} \times 3600 \tag{1}$$

- Equivalent Air Change Rate ($eACH$) [h^{-1}]: the equivalent number of air exchanges per hour attributable to UVC purification.

$$eACH = \frac{Q_{UVC}}{V} \times 3600 \tag{2}$$

- Capture efficiency (η_c) [-]: the proportion of the total ventilation airflow that is effectively sterilized by the UVC devices.

$$\eta_c = \frac{Q_{UVC}}{Q_{vent}} \tag{3}$$

RESULTS & DISCUSSION

Airflow simulations were conducted with four UVC air-cleaning devices placed at the upper, middle, and lower regions of the greenhouse wet pad. As shown in Table 1, the middle placement achieved the highest capture efficiency (η_c), with about 15% greater than the upper and lower placements. Fig. 3 illustrates the airflow patterns corresponding to each configuration.

Table 1 CFD Results for three configurations

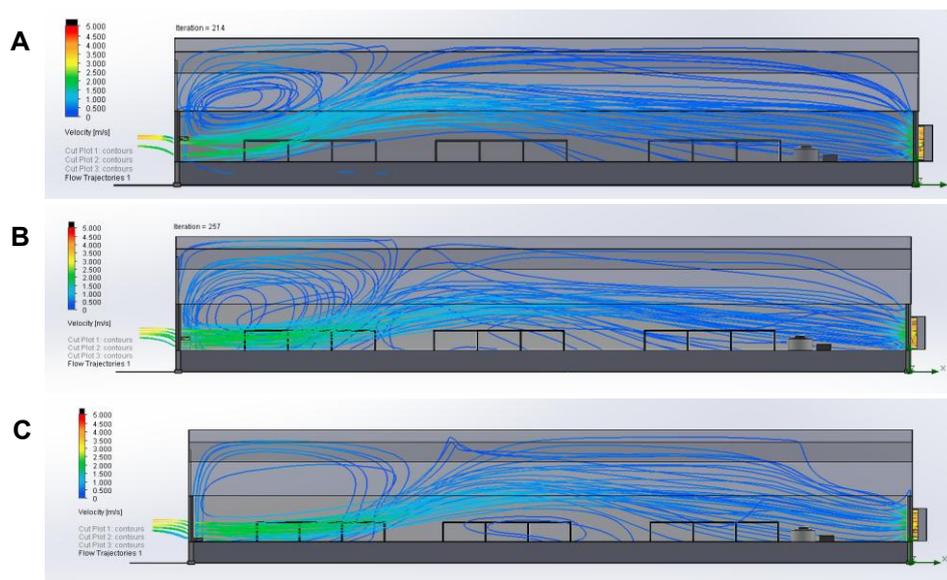| Configuration	Q_{vent} [m³/s]	Q_{UVC} [m³/s]	η_c [-]	ACH [h⁻¹]	$eACH$ [h⁻¹]
Upper region	10.1628	0.4448	4.4%	28.5	1.25
Middle region	10.0188	0.4972	5.0%	28.1	1.40
Lower region	10.1220	0.4352	4.3%	28.4	1.22

Fig. 3 Flow trajectory simulations for UVC devices placed at the (A) upper, (B) middle, and (C) lower regions of the greenhouse wet pad. The middle placement achieves the highest sterilized airflow rate, while the upper and lower placements show reduced airflow penetration into the cultivation zone.

CONCLUSIONS

Among the three configurations, placing the UVC devices at the middle region of the wet pad achieved the highest purification efficiency. Although the purified airflow rates at the upper and lower regions were similar, the upward deflection of airflow in the upper region reduced the proportion of sterilized air passing through the cultivation area. Overall, the optimal placement priority for UVC air-cleaning devices is middle > lower > upper.

ACKNOWLEDGEMENTS

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