



Research article

Simulation spatial model for analyzing cooling effects of downwash turbulence on maize canopies to enhance pollination efficiency using thermal imaging data collected from unmanned aerial vehicles

Rattana Boonprasert^a, Piyatida Siriak^a, Piyaat Vijuksungsith^{b,*}, Tiwa Pakoktomb^c, Gunn Panprayun^a

^a Faculty of Environment and Resource Studies, Mahidol University, Nakhon Pathom 73170, Thailand

^b Central Laboratory and Greenhouse Complex, Research and Academic Service Center Faculty of Agriculture at Kamphaeng Saen, Kasetsart University, Kamphaeng Saen Campus, Nakhon Pathom 73140, Thailand

^c Department of Agronomy, Kasetsart University, Kamphaeng Saen Campus, Nakhon Pathom 73140, Thailand

Article Info

Article history:

Received 13 May 2025

Revised 24 February 2026

Accepted 6 May 2026

Available online 17 June 2026

Keywords:

Downwash turbulence on maize canopy,

Land surface temperature (LST),

Pollination of maize,

Thermal imaging,

Unmanned Aerial Vehicles (UAVs)

Abstract

Importance of the work: Maize pollination is sensitive to canopy microclimate, including temperature, humidity, and airflow. UAV-assisted pollination may improve pollen dispersal; however, the effects of UAV-induced downwash turbulence on canopy cooling and pollen movement remain unclear.

Objectives: To develop a simulation model to analyze the cooling effects of UAV-induced downwash turbulence on maize canopies, using thermal imaging to optimize pollination efficiency.

Materials and Methods: Advanced techniques (the lattice Boltzmann method (LBM) and finite-difference time-domain (FDTD) simulations) were used to evaluate the impact of UAV airflow on canopy temperature and pollen dispersion during sensitive pollination stages. Data from UAVs equipped with thermal cameras (DJI Matrice 300 RTK and Zenmuse H20T) were combined with global navigation satellite systems to capture spatial variations in land surface temperature and airflow patterns.

Results: UAV-induced turbulence reduced canopy temperature and humidity, enhancing pollination success, while cooling the surrounding soil and vegetation.

Main finding: These findings highlight the importance of UAV airflow management in precision agriculture, demonstrating its potential to improve crop health and pollination outcomes through advanced environmental monitoring and control.

* Corresponding author.

E-mail address: rdiprv@ku.ac.th (P. Vijuksungsith)

online 2452-316X print 2468-1458/Copyright © 2026. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>), production and hosting by Kasetsart University Research and Development Institute on behalf of Kasetsart University.

<https://doi.org/10.34044/j.anres.2026.60.3.14>

Introduction

Unmanned aerial vehicles (UAVs) have revolutionized agricultural practices, particularly in the realm of maize pollination (Clark, 2007). A key aspect of UAV-based pollination is the downwash flow field created by the rotor blades, which serves a dual purpose. First, it effectively disperses pollen across the maize canopy, ensuring comprehensive coverage and penetration, especially vital for dense or hybrid varieties (Brewer et al., 2022). This targeted distribution greatly enhances the probability of successful pollination, a crucial factor for increasing crop yields. Second, the downwash airflow plays a pivotal role in regulating the microclimate within the canopy (Guo et al., 2020). By promoting increased evaporation and air mixing, the airflow lowers canopy temperatures, thereby mitigating heat stress that can adversely affect pollen viability during critical pollination phases (Brewer et al., 2022). The integration of UAV-generated downwash airflow into agricultural systems exemplifies a major advancement in precision farming. By optimizing the microclimate and improving pollen distribution, UAVs not only enhance pollination efficiency but also address pressing challenges such as labor shortages and climate variability. The ability to fine-tune flight parameters, such as altitude, speed and rotor intensity, allows for targeted applications that maximize effectiveness while minimizing resource waste. Furthermore, this technology aligns with sustainable agricultural practices, providing a viable alternative to traditional methods that often rely on chemical interventions (Mustafa et al., 2024). As agricultural UAVs (Ag-UAVs) continue to evolve, their potential to transform crop management and improve agricultural productivity becomes increasingly evident, making them indispensable tools.

Materials and Methods

Thermal and red-green-blue imaging systems fitted to unmanned aerial vehicles and their agricultural prototypes

The key parameters were examined of a UAV system designed for capturing thermal and red-green-blue (RGB) images, utilizing the DJI Matrice 300 RTK DJI, Shenzhen, China, as shown in Fig. 1A, a vertical take-off and landing multirotor platform equipped with an advanced thermal

imaging system, including the DJI Zenmuse H20T thermal camera and the D-RTK High Precision global navigation satellite system (GNSS) mobile station (DJI, Shenzhen, China), which enhanced the accuracy and effectiveness of imaging for agricultural applications. Specifically, the DJI Matrice 300 RTK equipped with the Zenmuse H20T was used to measure the land surface temperature (LST), according to Elfarkh et al. (2023). The Zenmuse H20T features multiple camera types, including zoom, wide-angle and thermal sensors, allowing for comprehensive thermal imaging and environmental analysis. This combination enables precise temperature data collection across various areas of interest, with key specifications summarized. The integration of UAVs and advanced imaging payloads is crucial in modern precision agriculture, as shown in Fig. 1B. Utilizing infrared sensors, these cameras detect non-contact temperature variations within the 800–1400 nm wavelength range, supporting tasks such as plant health assessments and irrigation optimization (Bertalan et al., 2022). Accurate thermal imaging necessitates consideration of factors such as distance, relative humidity, emissivity, reflected temperature and ambient temperature (Mustafa et al., 2024). Proper calibration and adjustment of these parameters are essential for reliable measurements, with cameras capable of operating within a wide temperature range of -40°C to 80°C, according to Li et al. (2010) as shown in Fig. 1.

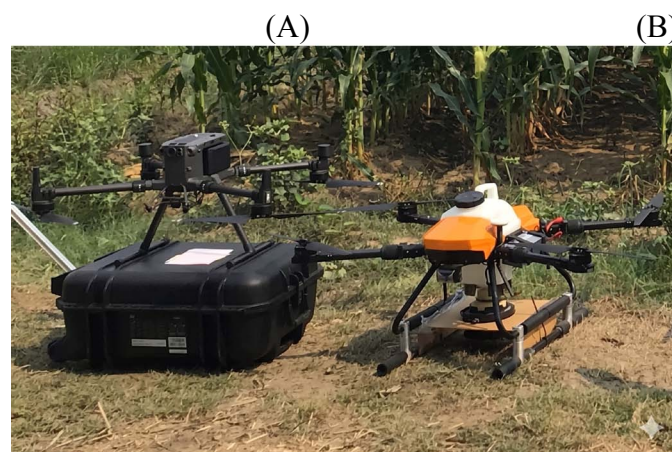


Fig. 1 Unmanned aerial vehicles (UAVs) used for recording and collecting data: (A) thermal and red-green-blue imaging systems (DJI Matrice 300 RTK and Zenmuse H20T); (B) agricultural UAV prototype with 4-blade propellers.

Experimental verification of effects of induced turbulence from agricultural unmanned aerial vehicle prototype on maize canopy

Computational fluid dynamics (CFD) simulations were used to validate the modeled effects of the Ag-UAV's induced turbulence on the maize canopy based on the airflow and canopy measurements from experimental tests (Guo et al., 2020). These simulations provided detailed data on the turbulence model and dynamic mesh technology that was used to develop an effective three-dimensional CFD in the downwash airflow field on the canopy, offering important insights into its underlying dynamics (Guo et al., 2020). Advanced computational techniques, including the lattice Boltzmann method (LBM; Viggien, 2014), were applied to model and analyze the intricate airflow interactions, enhancing the accuracy and reliability of the findings. This study investigated the use of thermal imaging to assess the impact of the downwash airflow field on the canopy from Ag-UAVs on the temperature of the maize canopy during pollination. By capturing temperature fluctuations resulting from the interaction between the Ag-UAV's induced airflow and the maize canopy (Guo et al., 2020), the research should offer valuable insights into the underlying dynamics of this process. The experimental area was structured to evaluate the influence of various environmental factors (particularly the wind generated by the wings of the Ag-UAV) on the pollination of maize. Essential instruments used were the Testo 405i (Testo, Titisee-Neustadt, Germany) a Bluetooth-enabled device for measuring wind speed and temperature, as well as portable equipment designed for sampling airborne particles and assessing air quality.

Simulation method

Advanced simulation techniques, such as LBM and the XFlow simulation method (Chang et al., 2023), were used to analyze spatial variations in the downwash airflow field on canopy and evaluate its influence on the temperature distribution within the maize canopy, as shown in Figs. 2A and 2B. XFlow uses LBM, utilizing a computational domain represented as a uniform cube ($2.50 \text{ m} \times 2.50 \text{ m} \times 2.50 \text{ m}$), as shown in Fig. 3, composed of cells measuring $0.50 \text{ m} \times 0.50 \text{ m}$, as shown in Fig. 2C. The numerical framework adopted a three-dimensional, 19-velocity lattice configuration (D3Q19) within the lattice Boltzmann method. Field measurements of wind speed and canopy temperature were obtained during two controlled UAV flight trials. The UAV maintained a constant flight speed of 3.00 m/s , while the ambient wind speed was measured at 0.34 m/s , as shown in Fig. 4. The onboard autonomous flight control system ensured a stable altitude of 2 m above the canopy surface. Each flight lasted 5 min , as shown in Figs. 2A and 2C. Major components of the setup included: one discrete velocity vector centered at the origin; t is a dimensionless relaxation parameter (e_0) shown in Fig. 2(A), 6 vectors extending from the center to the faces of the lattice (e_1 – e_6), 12 vectors connecting the center to the midpoints of lattice edges (e_7 to e_{18}) and 6 vectors stretching from the center to the lattice vertices (e_5, e_{11}, e_{15} and e_{18}). Compared to the conventional approach (Guo et al., 2020), this approach introduces higher-order spatial segmentation for enhanced accuracy, as shown in Fig. 2C. The method uses LBM equation as its foundational solution, discretizing the transport equation over the lattice in Equation 1 and Equation 2 (Chang et al., 2023):

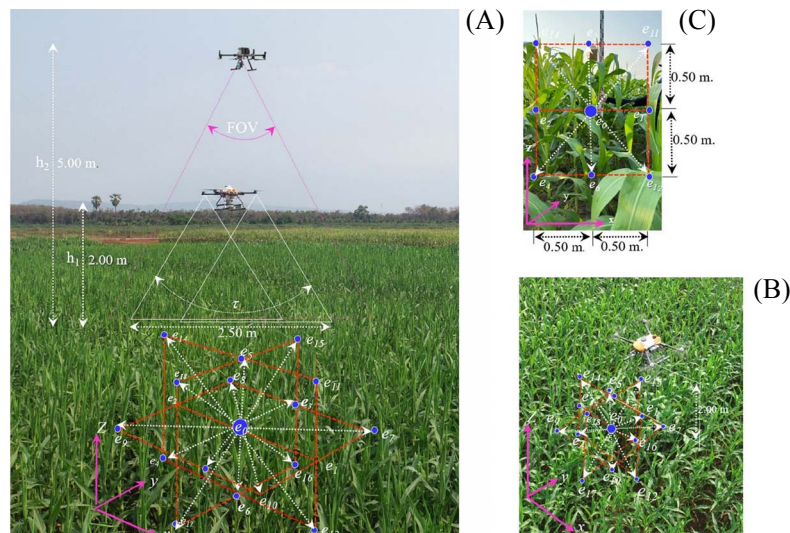


Fig. 2 Schematic diagrams of boundary of downwash airflow field on canopy: (A) simulation method, where in lattice Boltzmann method models, XFlow adopts a three-dimensional lattice structure of crop canopy airflow; (B) incorporation of 19 velocity vector directions (D3Q19) within lattice framework; (C) six vectors stretching from center to lattice vertices ($e_5, e_{11}, e_{15}, e_{18}$). FOV = field of view.



Fig. 3 Plot, numbered rows and plant layout, with mobile radiation measuring station

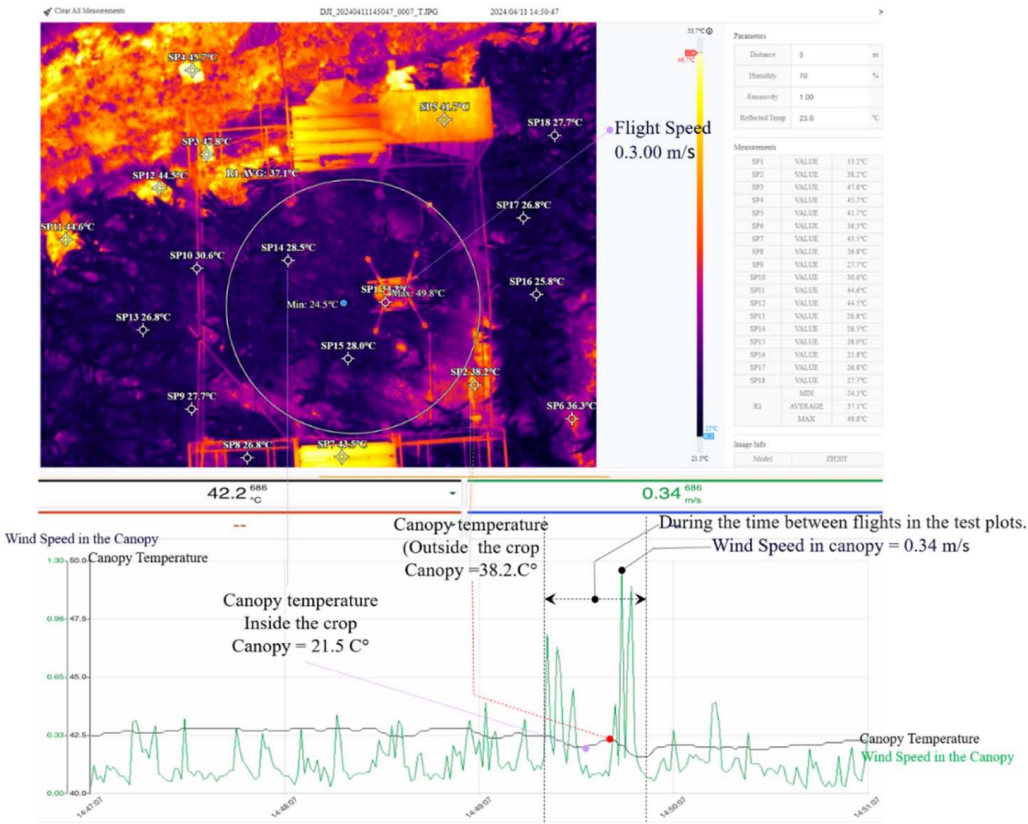


Fig. 4 Field measurements of wind speed and canopy temperature obtained during two controlled UAV flight trials, where unmanned aerial vehicle maintained constant flight speed of 3.00 m/s and ambient wind speed was 0.34 m/s.

$$f_i(x+e_i, dt) = f_i(x, t) + W_i(x, t) \quad (1)$$

$$W_i = \frac{1}{\tau} (f_i - f_i^e) \quad (2)$$

Where f_i is the particle velocity vector distribution function, e_i is the velocity of the particle in the direction I , dt is the time step, $f_i(x, t)$ is the velocity distribution function of the particle in i the direction at x point at t time, W_i is the collision operator, is the one particle equilibrium distribution function and τ is a dimensionless relaxation parameter e_0 as shown in Fig. 2A

Evaluation of effects of agricultural unmanned aerial vehicle-induced turbulence on maize canopy

Thermal imaging is a powerful tool for studying the effects of downwash airflow produced by Ag-UAVs. The propeller-induced turbulence or “downwash” generated by Ag-UAVs can influence crop health, soil conditions and the effectiveness of aerial applications pesticide spraying or seed dispersal (Ludovisi et al., 2017). Understanding this interaction is crucial for optimizing UAV operations in precision agriculture (Casas-Mulet et al., 2020). Thermal imaging is an effective method for analyzing the impact of downwash airflow generated by Ag-UAVs on canopy temperatures (Brewer et al., 2022). The turbulence created by Ag-UAVs propellers (commonly referred to as downwash) can influence thermal dynamics within canopies, particularly during sensitive of maize canopies during pollination stages (Clark, 2007) as shown in Fig. 2A.

Thermal imaging analysis to estimate land surface temperature and turbulence effects on maize canopy

This study applied thermal imaging to estimate LST (Casas-Mulet et al., 2020) and to evaluate the effects of UAV-induced turbulence on the maize canopy (Liu et al., 2024). The analysis focused on four critical factors: Ag-UAV operational parameters, maize canopy temperature conditions, factor of maize canopy during pollination stages and soil characteristics. The downwash airflow field on the canopy was evaluated using LST models, considering operational factors, such as airflow velocity, flight altitude and proximity to the canopy, as shown in Fig. 2A. The cooling effect of airflow maintains an optimal thermal environment for pollination, with the role of temperature variations captured through thermal imaging (Guan and Grote, 2023). During pollination, the interaction between turbulence effects and thermal changes was assessed to determine its influence on the transfer of

male pollen to female flowers after 3 hr of UAV operation, based on Equation 1 and Equation 2, as shown in Fig. 2B.

Crucial role of airflow in maintaining optimal thermal environment for pollination

By applying a spatial query method, it is possible to identify the maximum ($T_{\max}$) and minimum ($T_{\min}$) LST values in a simulation spatial model corresponding to a specific vegetation index (VI). Additionally, equations for vegetation canopy cover (VI_{Cover}) can be derived for both the dry and wet sides of the feature space using linear regression, as illustrated in Equation 3.

A spatial query method can be used to find the highest ($T_{\max}$) and the lowest ($T_{\min}$) LST under the same VI_{Cover} . Combined with VI_{Cover} , equations for the dry side and wet side of the feature space can be obtained using a linear fitting method (Equation 4), as shown in Fig. 5.

$$T_{\max} = a1 + b1 \times VI_{\text{Cover}} \quad (3)$$

$$T_{\min} = a2 + b2 \times VI_{\text{Cover}} \quad (4)$$

where $a1$, $b1$ and $a2$, $b2$ are fitting coefficients of the dry side and wet side, respectively.

The dry side is the most arid region of the monitoring area. Generally, the temperature vegetation dryness index (TVDI) value of the dry side is set to 1, while that of the wet side (being the most humid region) is set to 0. Hence, the TVDI at any point in this feature space can be expressed, according to Li et al. (2010).

Airflow plays a crucial role in maintaining an optimal thermal environment for pollination by regulating temperature variations (Ludovisi et al., 2017). These cameras detect infrared radiation emitted by objects, enabling non-contact temperature measurements within the 800–1400 nm wavelength range coverage, as shown in Figs. 5A and 5B. This capability supports critical tasks, such as assessing plant health and optimizing irrigation, by identifying subtle temperature variations. This cooling effect helps to reduce heat stress on crops, creating more favorable conditions for successful pollination. Through thermal imaging, these variations can be monitored effectively, providing insights into how the airflow influences canopy temperature (Zhen et al., 2021). Thermal cameras, equipped with infrared sensors, are invaluable in Ag-UAVs applications, as shown in Figs. 5C and 5D and in Equation 5 and 6:

$$TVDI = \frac{LST - LST_{\min}}{LST_{\max} - LST_{\min}} \quad (5)$$

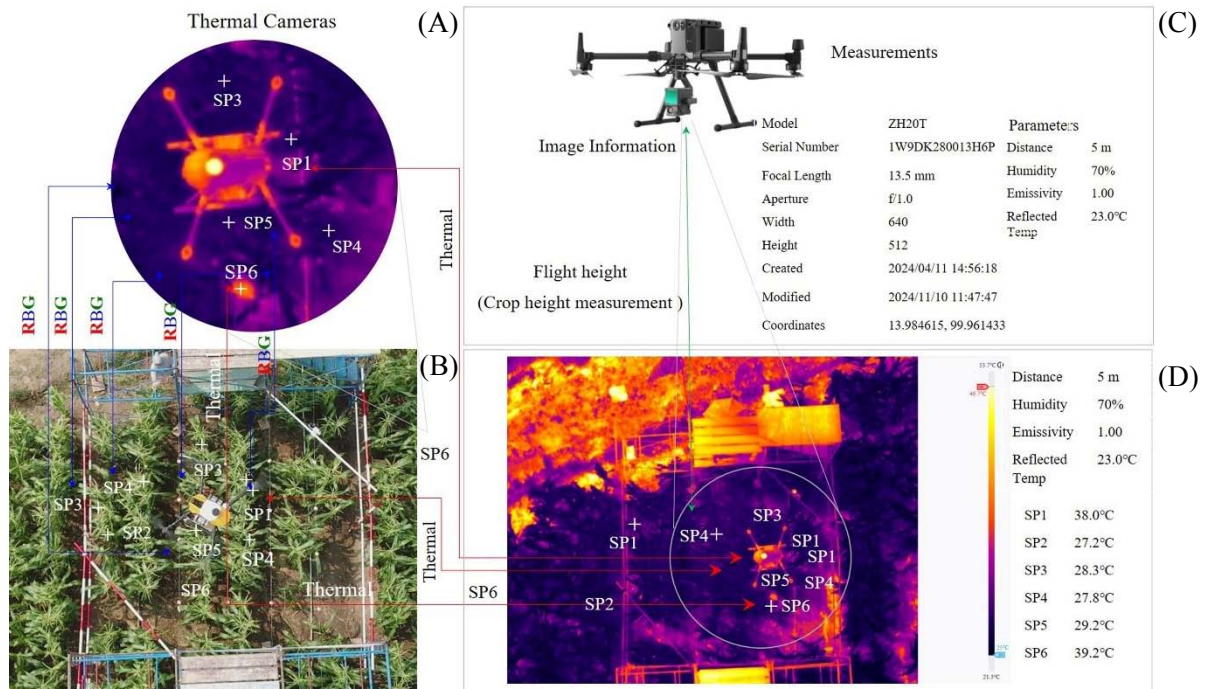


Fig. 5 Calibration of canopy temperatures derived from UAV thermal images. (A, B) Thermal and RGB images showing sampling points used for temperature calibration; (C) UAV-mounted thermal-imaging system and imaging geometry; (D) calibrated thermal-image interface showing canopy temperature measurements and selected regions of interest.

where LST is the land surface temperature at a given pixel, LST_{min} is the minimum LST for a given normalized difference vegetation index (NDVI) value (wet edge) and LST_{max} is the maximum LST for a given NDVI value (dry edge).

The key steps are: 1) plot the LST versus NDVI for the study area; 2) identify the wet edge (low LST) and dry edge (high LST) by fitting linear relationships to the lower and upper boundaries of the scatterplot: wet edge, where $LST_{min}(NDVI) = a_{wet} \cdot NDVI + b_{wet}$, and dry edge, so $LST_{max}(NDVI) = a_{dry} \cdot NDVI + b_{dry}$; and 3) substitute these linear equations into the TVDI formula to calculate it for each pixel.

A simplified version can be expressed using (Equation 6):

$$TVDI = \frac{LST - (a_{wet} \cdot NDVI + b_{wet})}{(a_{dry} \cdot NDVI + b_{dry}) - (a_{wet} \cdot NDVI + b_{wet})} \quad (6)$$

where this method allows for the computation of the TVDI, which serves as a spatial measure for assessing drought intensity and soil moisture levels, as shown in Fig. 5D. The linear coefficients (such as a_{wet} , b_{wet} , a_{dry} , b_{dry}) are determined through regression analysis of data points.

Key elements involved in this process are: 1) LST, which represents the temperature value at specific pixels within the analyzed region; and 2) the wet edge minimum LST, which

corresponds to the lowest land surface temperature associated with a particular NDVI value, indicative of well-hydrated areas (Guan et al., 2022); the dry edge (maximum LST): Represents the highest land surface temperature observed for a given NDVI value, which typically indicates arid or stressed conditions (Guan et al., 2022).

By leveraging these parameters, TVDI provides a comprehensive framework for identifying variations in soil moisture and drought conditions across landscapes. This tool supports precision agriculture by guiding irrigation strategies and assessing environmental stress on crops, as shown in Fig. 5D.

Results

Crucial role of airflow in maintaining optimal thermal environment for pollination

The results of the model showed that the wind force distribution effect on the maize canopy area was estimated from the wind force generated by flying the Ag-UAVs at a height of 2.00 meters above the top of the test plot. From testing the wind force distribution pattern from the canopy area and

the ability of the wind force distribution on the ground of the maize canopy with reference to the temperature measurement device of the thermal camera (as shown in Fig. 6A) and the wind speed measurement (as shown in Fig. 6B), it was found that the corn canopy under or near the flight had a temperature change in a decreasing direction, causing the wind under the wings to blow down on the corn plants to reduce the humidity, resulting in increasing the rate of pollen panicle breakage. In addition, the soil voids in the plot had a decrease in temperature). The soil area of the test plot while the drone was flying over had a temperature that cooled in the same direction as the wind force distribution on the ground of the maize canopy.

Results of thermal imaging analysis to estimate land surface temperature and turbulence on maize canopy

Fig. 5A presents the results of modeling using the collected thermal data in the flight test area to assist the pollination of corn based on quantitative and qualitative factors of male flower pollination. The finite-difference time-domain (FDTD) simulation technique with a direct numerical model for turbulent flow in a rectangular tube used the LBM method to evaluate the efficiency of the wind blowing under the blades of the Ag-UAVs. The resultant dispersion of the maize canopy in

the test area is shown in Fig. 5B. The reference temperature of the thermal camera and the temperature change in the test area of the flight test area were used to collect thermal imaging data to determine the extent of the efficiency of the wind blowing under the blades of the prototype UAV tested in the test area as shown in Figs. 5C and 5D.

Result of qualitative data analysis based on suspended corn pollen

The spatial distribution was investigated of wind forces over a corn canopy during agricultural UAV flights. The evaluation focused on the effects of UAV-generated wind at a height of 2 m above the test plot, as shown in Fig. 7A and Fig. 7B. Temperature variations, captured by the thermal camera, along with wind speed measurements, revealed a cooling effect in areas directly beneath or near the UAV, as shown in Fig. 7C. The qualitative data analysis focused on suspended corn pollen and the concentration of airborne pollen particles both within and outside the experimental plot. The findings indicated that the UAV-generated airflow at an altitude of 2 m created a localized cooling effect over the corn canopy, resulting in reduced moisture levels and increased pollen panicle detachment, as shown in Fig. 7D and Fig. 7E (Tesfahuney et al., 2013; Wu et al., 2016).

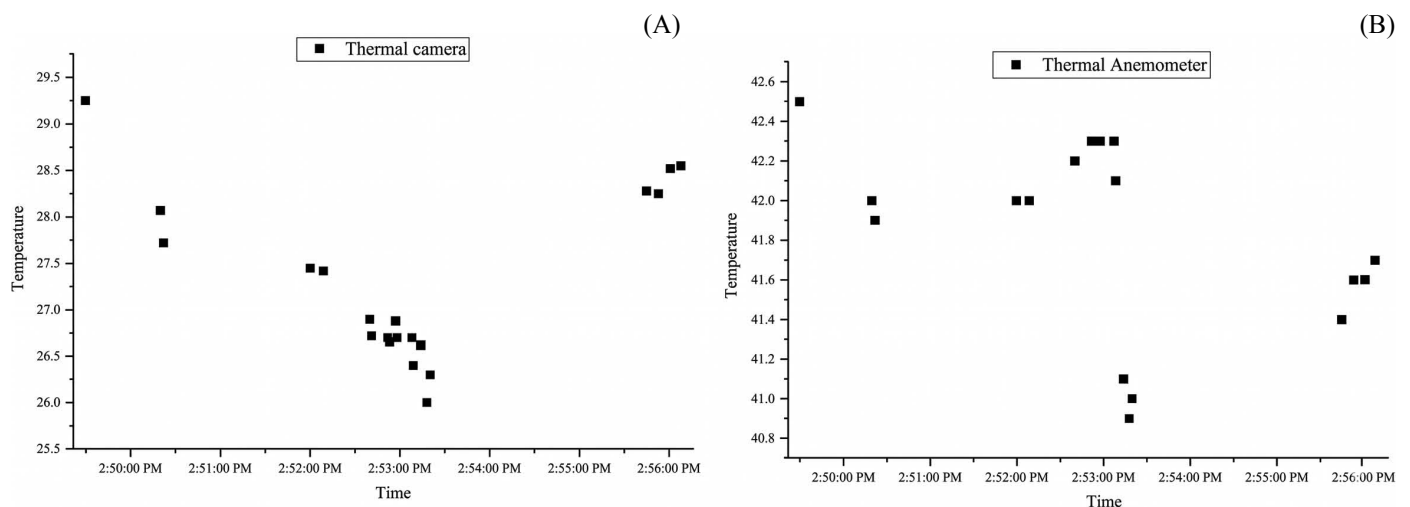


Fig. 6 Results of the downwash airflow field on the canopy obtained using the simulation method. In the LBM model, XFlow adopts a three-dimensional lattice structure to simulate airflow over the canopy. (A) Temperature measured using the thermal camera with 19 velocity-vector directions (D3Q19) within the lattice framework; (B) Wind speed measured using six vectors extending from the center to the lattice vertices (e_5 , e_{11} , e_{12} , e_{15} , and e_{18})

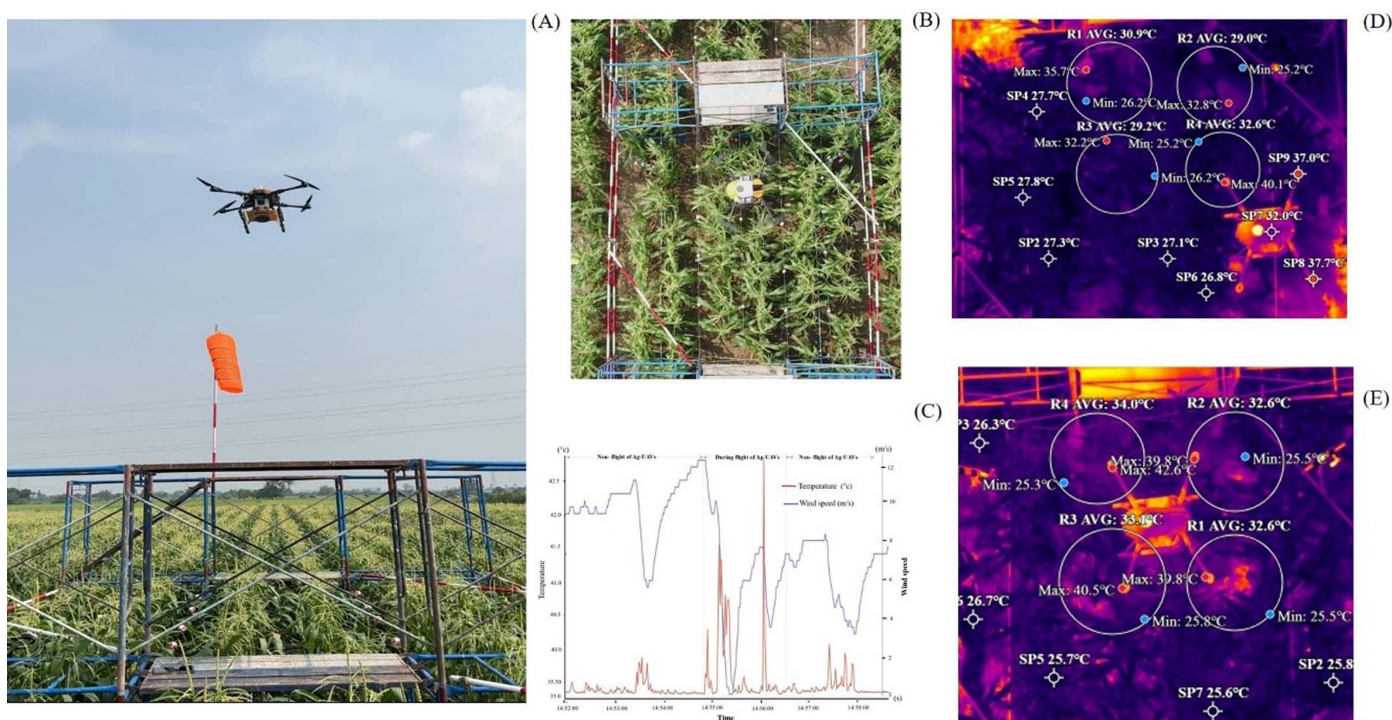


Fig. 7 Effects of unmanned aerial vehicle (UAV)-generated wind at 2 m in the maize crop: (A) general view; (B) above test plot (B); temperature in canopy under or near flight path showing decreasing temperature; (D) visualized temperature in maize canopy with UAV activity

Effects of unmanned aerial vehicle-induced downwash turbulence on maize canopy cooling and impact on efficiency of pollination enhancement

A simulation model was developed to investigate the effects of UAV-induced downwash turbulence on maize canopy cooling, with the aim of enhancing pollination efficiency. Based on the thermal imaging and wind force distribution results, airflow played a critical role in maintaining optimal thermal conditions for the maize crop pollination by regulating temperature variations and reducing heat stress. The FDTD simulation and LBM modeling demonstrated that UAV-induced airflow effectively cooled the canopy, reducing humidity and enhancing pollen dispersion. These findings underscore the potential of Ag-UAVs to optimize pollination efficiency through precise environmental management.

The thermal imaging data revealed a uniform wind force distribution, which contributed to temperature reductions in both the canopy and of the exposed soil. These findings emphasize the critical role of optimizing UAV parameters, such as flight altitude and speed, to maximize pollination performance and resource efficiency in modern agricultural practices.

Qualitative assessment of suspended maize pollen, together with quantitative measurements of airborne pollen particle concentrations, inside and outside the experimental plot, were conducted using a portable personal air-sampling pump equipped with filters. The analysis revealed distinctive spatial and temporal patterns. Within the experimental plot, pollen concentrations averaged 5.42 mg/m^3 and increased to 7.29 mg/m^3 during the peak observation period. In contrast, pollen levels outside the experimental plot were consistently lower, with recorded concentrations of 4.25 mg/m^3 .

Effects of unmanned aerial vehicle-induced downwash on canopy microclimate and thermal dynamics

The wind force distribution generated by the Ag-UAV at a flight altitude of 2.00 m above the maize canopy influenced both canopy and near-surface thermal conditions within the experimental plot. As shown in Fig. 6A and Fig. 6B, areas located directly beneath and adjacent to the flight path had lower canopy temperatures than areas farther from the UAV trajectory. The spatial distribution of the temperature changes generally corresponded with the downwash airflow pattern observed, indicating UAV-induced canopy cooling generated more favorable microclimatic conditions for pollination.

Lower canopy temperatures may help sustain pollen viability and longevity and improve silk receptivity, pollen tube growth, and successful fertilization.

In addition to the canopy response, reductions in surface temperature were also observed in exposed soil areas within the plot during UAV operation. The cooling pattern detected on the soil surface followed a distribution similar to that observed for the canopy, particularly within zones receiving greater downwash influence. The results showed that the airflow created by the UAV influenced the thermal environment of the crop canopy and the soil surface below. Although the effects of rotor-induced downwash on evapotranspiration, canopy energy balance, moisture fluxes, humidity dynamics, and pollination effects were not directly assessed in this study, they may lower canopy temperature and humidity through turbulent mixing, improved ventilation, heat dissipation, moisture transport, and boundary-layer disruption.

The observed temperature reductions suggest that the downwash airflow promoted air movement within the canopy and near-ground layers, resulting in measurable changes in the thermal characteristics of the experimental area. However, humidity, evapotranspiration, pollen dispersal, pollen viability, fertilization success and grain yield were not directly measured in the current study. Therefore, the current results are limited to the observed spatial patterns of airflow distribution and associated temperature responses within the maize canopy and soil surface.

Discussion

Based on the results, there was a substantial impact from the UAV-induced turbulence on the maize canopy, particularly in optimizing conditions for pollination. The DJI Matrice 300 RTK, equipped with a thermal imaging system, was used to analyze downwash airflow patterns and their influence on canopy temperature and humidity. Advanced simulation techniques, including the lattice Boltzmann Method and XFlow, provided detailed insights into the spatial variations in airflow and temperature distribution within the maize canopy. These simulations revealed the critical role of Ag-UAVs downwash turbulence in regulating the canopy microclimate during pollination-sensitive stages. Key findings highlighted that UAV-induced airflow reduced both canopy and soil temperatures by dispersing heat and lowering humidity, based on the thermal imaging. The temperature reduction beneath and around the UAV flight path promoted pollen dispersion and

improved pollination efficiency. Additionally, the integration of thermal imaging with GNSS data allowed precise mapping of land surface temperature and airflow patterns, emphasizing the potential of UAVs in enhancing precision agriculture practices. These findings underscore the importance of effective UAV airflow management to improve crop health and pollination outcomes.

The observed reduction in canopy temperature is particularly relevant during the maize reproductive stage because pollen release, pollen viability, silk receptivity and pollen tube growth are highly sensitive to environmental conditions. Other studies have reported that elevated temperatures during anthesis and ~~silking~~ silk can impair pollen shedding, reduce pollen viability, shorten pollen longevity and decrease the receptivity of maize silks, ultimately limiting successful fertilization and kernel development (Waqas et al., 2021; Wang et al., 2022; Liu et al., 2023). Furthermore, excessive heat stress may disrupt pollen tube growth and reproductive processes, resulting in reduced fertility (Gong et al., 2024). Therefore, the localized canopy cooling observed beneath and adjacent to the UAV flight path may contribute to more favorable microclimatic conditions for maize reproduction. However, because pollen dispersal, pollen viability, fertilization success and grain yield were not directly measured in the current study, the potential benefits for pollination should be interpreted as indirect and require further experimental validation.

The reduction in canopy and soil temperatures observed in the current study can be explained by the aerodynamic effects of UAV-generated downwash. Other investigations have demonstrated that rotor-induced airflow enhanced turbulent mixing and convective heat exchange between crop canopies and the surrounding atmosphere, thereby facilitating the dissipation of accumulated sensible heat and improving canopy ventilation (Liu et al., 2021; Zhu et al., 2022; Chang et al., 2023; Zhang et al., 2023). In addition, increased air circulation may accelerate moisture transport from the canopy boundary layer to the atmosphere, contributing to localized reductions in humidity and thermal accumulation. Consequently, it was likely that the cooling effect observed in the current study was associated with enhanced air exchange and redistribution of heat and moisture within the canopy environment. Nevertheless, the current experiment did not directly quantify humidity dynamics, evapotranspiration rates or canopy energy balance components. Therefore, the proposed mechanisms should be considered plausible explanations supported by previous aerodynamic studies rather than direct evidence derived from the current experiment.

Conclusion

Airflow played a critical role in maintaining optimal thermal conditions for maize crop pollination by regulating temperature variations and reducing heat stress. The equipment used was effective at capturing thermal imaging from the UAVs equipped with advanced cameras (DJI Matrice 300 RTK and Zenmuse H20T), coupled with precise GNSS systems, as well as wind force distribution across maize canopies. The finite-difference, time-domain simulation and LBM modeling demonstrated that the UAV-induced airflow effectively cooled the canopy, reduced humidity and enhanced pollen dispersion. These findings underscore the potential of Ag-UAVs to optimize pollination efficiency through precise environmental management, as evidenced by thermal imaging data and airflow calibration.

Conflict of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

This research project was funded by Mahidol University (Fundamental Fund: fiscal year 2021 by National Science Research and Innovation Fund (NSRF)) and the project is undertaken within the research framework on scaling up appropriate technology to enhance household income and strengthen the grassroots economy for the 2025 fiscal year. The project is supported by the Science, Research, and Innovation Promotion Fund (TSRI) and the Program Management Unit for Area-Based Development (PMU), Thailand (PMU-A, Bangkok, Thailand).

References

- Bertalan, L., Holb, I., Pataki, A., Négyesi, G., Szabó, G., Szalóki, A.K., Szabó, S. 2022. UAV-based multispectral and thermal cameras to predict soil water content—A machine learning approach. *Computers and Electronics in Agriculture* 200: 107262. doi.org/10.1016/j.compag.2022.107262
- Brewer, K., Clulow, A., Sibanda, M., et al. 2022. Estimation of maize foliar temperature and stomatal conductance as indicators of water stress based on optical and thermal imagery acquired using an unmanned aerial vehicle (UAV) platform. *Drones* 6: 169. doi.org/10.3390/drones6070169
- Casas-Mulet, R., Pander, J., Ryu, D., Stewardson, M.J., Geist, J. 2020. Unmanned aerial vehicle (UAV)-based thermal infra-red (TIR) and optical imagery reveals multi-spatial scale controls of cold-water areas over a groundwater-dominated riverscape. *Frontiers in Environmental Science* 8: 64. doi.org/10.3389/fenvs.2020.00064
- Chang, K., Chen, S., Wang, M., Xue, X., Lan, Y. 2023. Numerical simulation and verification of rotor downwash flow field of plant protection UAV at different rotor speeds. *Frontiers in Plant Science* 13: 1087636. doi.org/10.3389/fpls.2022.1087636
- Clark, C.A. 2007. Numerical simulations of maize pollen dispersal. Ph.D. Sc. thesis, Faculty of Agricultural Meteorology. Iowa State University. Ames, IO, USA.
- Elfarkh, J., Johansen, K., Angulo, V., Camargo, O.L., McCabe, M.F. 2023. Quantifying within-flight variation in land surface temperature from a UAV-based thermal infrared camera. *Drones* 7: 617. doi.org/10.3390/drones7100617
- Gong, W., Zhang, H., Wang, X., Li, Y., Zhao, J. 2024. Heat-stress-induced reactive oxygen species in maize silks impair pollen tube growth and reduce fertility. *iScience* 27: 110081. doi.org/10.1016/j.isci.2024.110081
- Guan, Y., Grote, K. 2023. Assessing the potential of UAV-based multispectral and thermal data to estimate soil water content using geophysical methods. *Remote Sensing* 16: 61. doi.org/10.3390/rs16010061
- Guan, Y., Grote, K., Schott, J., Leverett, K. 2022. Prediction of soil water content and electrical conductivity using random forest methods with UAV multispectral and ground-coupled geophysical data. *Remote Sensing* 14: 1023. doi.org/10.3390/rs14041023
- Guo, Q., Zhu, Y., Tang, Y., Hou, C., He, Y., Zhuang, J., Zheng, Y., Luo, S. 2020. CFD simulation and experimental verification of the spatial and temporal distributions of the downwash airflow of a quad-rotor agricultural UAV in hover. *Computers and Electronics in Agriculture* 172: 105343. doi.org/10.1016/j.compag.2020.105343
- Li, H., Li, C., Lin, Y., Lei, Y. 2010. Surface temperature correction in TVDI to evaluate soil moisture over a large area. *J. Agric. Food Environ.* 8: 1141–1145.
- Liu, X., He, X., Song, J., Zeng, A., Zhang, S., Lang, E. 2021. Distribution regularity of downwash airflow under rotors of agricultural UAV for plant protection. *Int. J. Agric. Biol. Eng.* 14: 34–42. doi.org/10.25165/j.ijabe.20211403.4036
- Liu, Z., Gao, R., Zhao, Y., et al. 2024. Study on the characteristics of downwash field range and consistency of spray deposition of agricultural UAVs. *Agriculture* 14: 931. doi.org/10.3390/agriculture14060931
- Ludovisi, R., Tauro, F., Salvati, R., Khoury, S., Mugnozza Scarascia, G., Harfouche, A. 2017. UAV-based thermal imaging for high-throughput field phenotyping of black poplar response to drought. *Frontiers in Plant Science* 8: 1681. doi.org/10.3389/fpls.2017.01681
- Mustafa, G., Liu, Y., Khan, I.H., Hussain, S., Jiang, Y., Liu, J., Arshad, S., Osman, R. 2024. Establishing a knowledge structure for yield prediction in cereal crops using unmanned aerial vehicles. *Frontiers in Plant Science* 15: 1401246. doi.org/10.3389/fpls.2024.1401246
- Tesfahuney, W.A., Walker, S., Van Rensburg, L.D., Everson, C.S. 2013. Water vapor, temperature and wind profiles within maize canopy under in-field rainwater harvesting with wide and narrow runoff strips. *Atmosphere* 4: 428–444. doi.org/10.3390/atmos4040428

- Viggen, E.M. 2014. The lattice Boltzmann method: Fundamentals and acoustics. Ph.D. Sc. thesis, Faculty of Information Technology, Mathematics and Electrical Engineering, Norwegian University of Science and Technology. Trondheim, Norway.
- Wang, N., Wang, E., Wang, J., Huang, M., Luo, Z. 2022. Impacts of heat stress around flowering on growth and yield formation of maize. *Front. Plant Sci.* 13: 1023241. doi.org/10.3390/plants11243515
- Waqas, M.A., Wang, X., Zafar, S.A., Noor, M.A., Hussain, H.A., Nawaz, M.A., Farooq, M. 2021. Thermal stresses in maize: Effects and management strategies. *Plants* 10: 293. doi.org/10.3390/plants10020293
- Wu, C., Cui, K., Wang, W., Li, Q., Fahad, S., Hu, Q., Huang, J., Nie, L., Peng, S. 2016. Heat-induced phytohormone changes are associated with disrupted early reproductive development and reduced yield in rice. *Scientific Reports* 6: 34978. doi.org/10.1038/srep34978
- Zhang, H.Y., Wen, S., Chen, C.L., Liu, Q., Xu, T.Y., Chen, S.D., et al. 2023. Downwash airflow field distribution characteristics and their effect on the spray field distribution of the DJI T30 six-rotor plant protection UAV. *Int. J. Agric. Biol. Eng.* 16: 10–22. doi.org/10.25165/j.ijabe.20231602.8094
- Zhen, Z., Chen, S., Yin, T., et al. 2021. Using the negative soil adjustment factor of soil adjusted vegetation index (SAVI) to resist saturation effects and estimate leaf area index (LAI) in dense vegetation areas. *Sensors* 21: 2115. doi.org/10.3390/s21062115
- Zhu, Y., Guo, Q., Tang, Y., Zhu, X., He, Y., Huang, H., Luo, S. 2022. CFD simulation and measurement of the downwash airflow of a quadrotor plant protection UAV during operation. *Comput. Electron. Agric.* 198: 107286. doi.org/10.1016/j.compag.2022.107286