# Advances in CFD-based fluid computational dynamics for fruit tree model construction method and airflow regulation equipment

Haocheng Lu[1†], Xue Li[2†], Tao Xu[2], Yannan Qi[2], Quanchun Yuan[2], Wei Qiu[1*], Xiaolan Lyu[2*]

(1. *College of Engineering, Nanjing Agricultural University, Nanjing 210031, China*;
2. *Institute of Agricultural Facilities and Equipment, Jiangsu Academy of Agricultural Sciences/Key La-boratory of Modern Horticultural Equipment, Ministry of Agriculture and Rural Affairs, Nanjing 210014, China*)

**Abstract:** Due to its ability to broaden the transport channel of droplets within the plant canopy and enhance their penetration capacity, air-assisted spray technology is widely used in orchard pesticide application. To achieve uniform distribution of pesticide droplets in the tree canopy and obtain a higher pesticide utilization rate, it is crucial to clarify the coupling mechanism of the airflow field and droplet field generated by the air-assisted sprayer. This paper introduces a three-dimensional modeling method of the fruit tree canopy based on CFD (Computational Fluid Dynamics), offering a theoretical basis for analyzing the airflow demand calculation during different growth periods of the canopy. It also examines the interaction between canopy modeling and airflow, highlighting advancements in airflow regulation equipment and the effects of airflow speed and volume on spraying. The study shows that the precise regulation of airflow velocity and discharge rate is of importance for improving spraying efficiency. It finally points out that future research should focus on developing intelligent regulation equipment for efficient airflow-droplet control, using biomass sensing, which involves measuring the growth characteristics of the tree canopy, to meet the needs of orchards with diverse growth stages and canopy structures. This article could provide guidance for the future study of precision air-assisted spraying technology in orchards.

**Keywords:** airflow-assisted technology, airflow field, fruit tree canopy modeling, airflow regulation, airflow-droplet co-regulation

**DOI:** 10.25165/j.ijabe.20251802.9554

**Citation:** Lu H C, Li X, Xu T, Qi Y N, Yuan Q C, Qiu W, et al. Advances in CFD-based fluid computational dynamics for fruit tree model construction method and airflow regulation equipment. Int J Agric & Biol Eng, 2025; 18(2): 1–8.

## 1 Introduction

With the continuous progress of China's agricultural science and technology and the ongoing optimization of its industrial structure, the scale of fruit tree cultivation is steadily expanding. By 2022, the area of fruit tree cultivation had reached 13 010 $km^2$[1-3], and fruit tree cultivation has become a key industry for promoting the rural economy and increasing farmers' incomes. In the process of fruit cultivation, controlling and preventing pests and diseases is crucial[4]. At present, fruit farmers mainly use chemical, physical, and biological methods for pest and disease control. Physical and biological methods are environmentally friendly; nevertheless, they are slow in effect and have limited applications or higher input costs, resulting in the limitation of application. Chemical control methods are characterized by fast effectiveness and easy application, making them the most widely used in pest control for plant production. However, excessive pesticide use not only increases economic costs but also environmental pollution[5]. The spray quality of traditional spraying methods is difficult to guarantee, their droplet coverage is uneven, and pesticide drift and ground loss are more significant issues. In addition, the operating efficiency of spraying equipment is low, increasing the labor burden on fruit farmers and raising the costs of orchard management[6-8]. Accordingly, the orchard air-assisted sprayer is the main method for orchard plant protection. Air-assisted spraying technology improves the penetration and uniform distribution of droplet deposition, making it become a chemical application technology strongly recommended by the United Nations Food and Agriculture Organization (FAO)[9].

The distribution of pesticide droplet deposition in the fruit tree canopy is a key technical indicator for measuring the performance of orchard air-assisted sprayers in orchards. Studies have shown that the distribution of pesticide droplets in the fruit tree canopy is mainly affected by spray volume and air volume[10]. Moderate airflow power can not only improve the uniformity of spray droplet deposition within the fruit tree canopy but also reduce shading caused by dense foliage, improve pharmaceutical penetration, and promote droplet deposition. Currently, most research and equipment, both domestically and internationally, related to variable spray volume and variable application technology are relatively mature. Nonetheless, research into airflow demand and airflow volume regulation and control equipment based on airflow spray technology for fruit tree canopies remains limited. Based on the information characteristics of the fruit tree canopy, airflow and

**Received date:** 2024-11-19 **Accepted date:** 2025-01-14

**Biographies: Haocheng Lu**, Master candidate, research interest: precision spraying technology, Email: 2023812069@stu.njau.edu.cn; **Xue Li**, PhD, research interest: precision spraying technology, Email: neigelee99@163.com; **Tao Xu**, PhD canditae, research interest: plant protection machinery design, Email: xutao@jaas.ac.cn; **Yannan Qi**, Master, research interest: spectral detection and identification, Email: qiyn1020@163.com; **Quanchun Yuan**, PhD, research interest: precision fertilization technology, Email: yuanquanchun@jaas.ac.cn.

†These authors contribute equally to this research.

***Corresponding author: Wei Qiu**, Professor, research interest: pesticide application technology. College of Engineering, Nanjing Agricultural University, Nanjing 210031, China. Tel: +86-25-58606570, Email: qiuwei@njau.edu.cn; **Xiaolan Lyu**, PhD, Researcher, research interest: machinery for plant protection and spraying technology in Fruit Orchards. Institute of Agricultural Facilities and Equipment, Jiangsu Academy of Agricultural Sciences, China. Tel: +86-15062270867, Email:lxlanny@126.com.

droplet synergistic regulation and control remains a shortcoming in the precision application of pesticides in orchards. To this end, through discussing the existing research status of determining airflow demand in fruit tree canopies and the regulation and control equipment for airflow volume, it is pointed out that the focus of airflow-droplet co-regulation lies in understanding the complex interactions between orchard environmental factors, spraying technology, and deposition characteristics. By utilizing advanced modeling techniques and intelligent airflow regulation equipment, further research into the canopy airflow needs of fruit trees is expected to progress. This approach allows for precise airflow adjustments as needed, enhancing spraying efficiency and reducing the environmental impact of pesticide applications.

## 2 Research on fruit tree canopy modeling methods

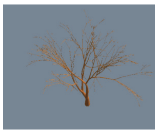
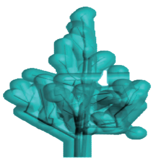
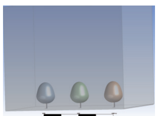
The canopy volume and leaf area index of fruit trees vary across different growth periods, and the required airflow volume differs as well. Obtaining the appropriate airflow volume through field experiments is obviously very difficult. As computer performance gradually improves, the use of CFD simulation technology for airflow field simulation can overcome uncontrollable environmental factors in field experiments, greatly reducing both testing costs and time.

### 2.1 Equivalent modeling of fruit tree canopies

A quantitative description of the distribution and density of fruit tree canopy branches and leaves is a prerequisite for studies on fruit tree canopy airflow demand. Numerous researchers have observed through in-canopy spray deposition experiments that the canopy structure plays a key role in the movement and deposition of droplets. To gain a deeper understanding of the influence of canopy branches and foliage on droplet movement patterns under different airflow loads, it is necessary to first conduct a detailed quantitative study of the morphological characteristics, branch density, and spatial distribution of fruit tree canopies[11].

At present, scholars have taken different approaches to quantify or equivalently represent fruit tree canopies. Endalew et al.[12] developed a 3D fruit tree canopy structure using a plant growth model that considers the plant's phenological growth behavior, as well as the effects of temperature and pruning. Based on this, Endalew et al.[13-16] constructed separate models for the leaves and branches of the fruit tree canopy. They simulated the canopy's effect on airflow by introducing its 3D structure into the model and simulated the leaves' effect on airflow distribution by adding a drag term to the momentum and turbulence energy equations in the porous subdomain surrounding the canopy. Hong et al.[17] improved the equivalent porous medium model for local branches and leaves in the canopy of fruit trees, as proposed by Endalew et al.[12], and introduced a simplified porous medium model, which reduces the model's complexity and significantly decreases computational costs. Wang et al.[18] analyzed the real three-dimensional tree canopy structure and used Visual Basic for Applications (VBA) to generate a novel three-dimensional virtual single-tree microscopic canopy model (MM) containing thick trunks, branches, and "real leaves". The advantages and disadvantages of the four canopy models are analyzed in Table 1. Building on these approaches, existing research predominantly relies on a combination of simulation analysis and field trials to quantify the distribution of airflow within the canopy and estimate the demand for airflow volume, as shown in Figure 1.

**Table 1 Comparison of advantages and disadvantages of fruit tree canopy models**

| Model method | Model sketch | Route to realization | Advantages | Disadvantages |
|---|---|---|---|---|
| Fruit tree 3D branch model |  | Introducing fruit tree growth functions and combining them with practical parameters to generate branching models | In line with the growth pattern of fruit trees, consistent with the actual situation | Effects of branches and leaves on airflow not taken into account |
| Equivalent porous medium model for localized branches and leaves |  | Generate a branch model by inputting parameters in ANSYS and add porous subdomains with different resistance parameters to the corresponding branch | Setting the resistance parameter by region, which better reproduces the effect of the actual branches and leaves on the airflow | No consideration of the effect of local airflow on the simulation |
| Simplified model of full canopy equivalent porous media |  | Leaves and branches are modeled with spheres and trunks with cylinders, and resistance parameters are set | Low computational cost and relative efficiency | Single parameter setting for resistance |
| 3D virtual canopy model[18] |  | Building Virtual Crown Models in CAD with VBA | High resemblance of shape and features to the real tree canopy | Higher computational costs |

At present, most quantitative modeling of fruit tree canopies has been simplified to retain their general outline in order to reduce computational costs. Even so, due to the irregularity of fruit tree canopy branches and leaves, and the complexity of the airflow field within the canopy, a significant gap remains between the model and the real situation. Restoring the real phenotypic characteristics of the fruit tree canopy using the equivalent model remains a challenging problem that needs to be solved.

### 2.2 Research on canopy porosity detection methods for fruit trees

The porosity parameter was originally defined as the volumetric porosity of a porous medium. For the crop canopy, porosity is the ratio between the total volume of organs, such as branches and leaves, and the total volume of space occupied by the canopy[19]. On the other hand, volumetric porosity does not accurately reflect the density of crop canopy branches and leaves and is not suitable for assessing their blocking and retention effects on auxiliary airflow and droplet populations[20]. Therefore, optical porosity is primarily used to explore the effect of porosity on airflow. It is defined as the ratio of the area of the gaps between canopy branches and leaves to the total area of the canopy projection in a given direction[21,22]. Canopy optical porosity intuitively reflects the obstruction of airflow by branches and leaves. Thus, the theoretical calculation of canopy porosity and methodological research on fruit trees have an important impact on determining the air demand of fruit tree canopies.

Since the optical porosity of the canopy is an important indicator for assessing photosynthesis, respiration, droplet transport and retention, and airflow field distribution patterns in crop canopies,-extensive research has been conducted in the academic community on acquiring crop canopy porosity parameters. Based on Beer's law in optical theory, which describes the relationship between an object's physical properties and the absorption rate of light as it passes through, the optical porosity parameters of crop canopies can be obtained by various methods[23]. Presently, the main methods used for detecting fruit tree canopy porosity are hemispherical images, ultrasound, laser point clouds, and infrared hyperspectral data[24-28]. Table 2 compares the advantages and disadvantages of these four methods.

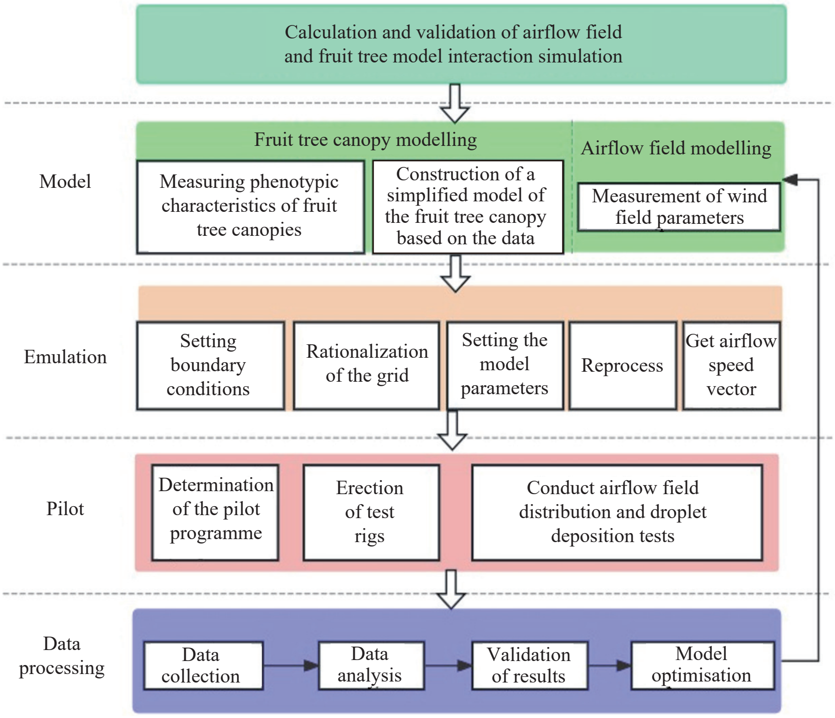
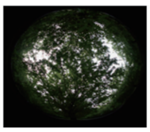
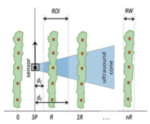
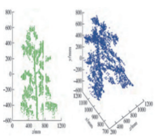
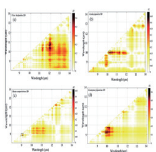



Figure 1 Simulation and verification flowchart

**Table 2 Comparison of advantages and disadvantages of fruit tree canopy porosity measurement methods**

| Detection means | Schema | Data acquisition methods | Advantages | Disadvantages |
|---|---|---|---|---|
| Hemispherical image[24] |  | Taking hemispherical photographs to obtain canopy structure information through optical imaging | Low cost, easier to implement, fast data collection | Low resolution and average accuracy |
| Ultrasound[25] |  | Using acoustic reflection and transmission properties to obtain canopy density and pore information | Relatively simple to handle, allowing a quick initial assessment of porosity | Higher environmental impact and lower accuracy |
| Laser point cloud[27] |  | Generating 3D point cloud models of tree crowns using laser scanning technology | High spatial resolution with high data accuracy to present detailed 3D structure and porosity | Higher costs and more complex data processing |
| Infrared hyperspectral[28] |  | Indirect speculation of canopy porosity by capturing reflected light in different spectral bands and analyzing the spectral properties of leaves and canopy interiors | Can be operated in low light or at night | Porosity cannot be measured directly and requires complex processing |

Although the above sensor-based porosity parameter acquisition methods have advanced the academic community's understanding of the characteristics of crop canopy branches and leaves, they also have some shortcomings, such as higher hardware costs and greater sensitivity to external light conditions. In addition, while optical porosity describes the overall canopy foliage, it only reflects the general condition of canopy foliage density and cannot fully capture the spatial distribution characteristics of the inner canopy foliage or its shading. As a result, the research methods for inner canopy porosity need further improvement.

### 2.3 Research on CFD-based fluid simulation modeling methods

After obtaining the quantified canopy model and resistance parameters, the canopy model must be integrated into a fluid simulation model established using CFD simulation technology[29] to simulate the interaction between the airflow field and the fruit tree. This allows for the derivation of airflow field distribution characteristics inside and outside the canopy, and the determination of the appropriate airflow volume. Accordingly, establishing a suitable airflow field model is crucial[30].

Fu et al.[31] quickly constructed a two-dimensional CFD model of the airflow velocity field distribution of an airborne sprayer and found that changes in inlet airflow velocity had little effect on the airflow field distribution, with the overall shape remaining consistent. As the distance from the fan center increases, the airflow velocity distribution becomes non-uniform. The region with larger longitudinal velocity helps droplets reach the upper level of the fruit tree, while the region with larger transverse velocity facilitates droplet penetration into the lower branches. This lays the foundation for improving spray drift performance and establishing the droplet deposition and distribution model. By comparing the internal duct flow lines obtained through Fluent calculations, Ding et al. found that the airflow field of a single duct is asymmetric, with greater intensity on the right side than on the left. The offset increases with distance. The airflow field of a double duct, however, is symmetric, with equal intensity on both sides, and its concentration domain is located along the center line. The air delivery power is stronger, and the double duct is superior to the single duct in terms of airflow symmetry and uniformity of pesticide application[32]. Dekeyser et al.[33] observed changes in the airflow field of a sprayer under different setup conditions by simulating various nozzles, fan speeds, and deflector positions. They concluded that airflow velocity decreases with distance and that larger nozzles and high-pressure jets produce stronger airflow. The airflow of axial sprayers was concentrated at low heights, while the airflow of cross-flow sprayers was more uniform. Garcia-Ramos et al.[34] demonstrated that the model predicted actual airflow velocity distribution well, especially within 2.5 m of the sprayer, with minimal error. This proved that using overall airflow as the main parameter is an effective method for analyzing spray airflow velocity distribution.

Liu et al.[35] investigated the airflow around single plants with different shapes and resistance coefficients, as well as around multiple plants, by comprehensively analyzing airflow tunnel measurements and computer simulations with computational fluid dynamics (CFD). They found that plant morphology and airflow resistance coefficients significantly affect the airflow field. A canopy shape with a wide bottom and narrow top reduces airflow speed more efficiently, and airflow gradually recovers after passing through the plants. Smaller row and column spacing can inhibit airflow recovery and prolong the airflow speed reduction effect. Zhang et al.[36] developed a CFD model for predicting sinking airflow within the canopy. In the computational domain, the tree canopy was defined as a porous medium, and it was found that the larger the canopy and the lower the height of the tree, the higher the airflow velocity, especially at the top and middle of the canopy. Taller trees are difficult for airflow to penetrate due to the increased drag, resulting in more airflow staying at the top of the canopy. Endalew et al.[14,37] carried out three-dimensional CFD modeling of the airflow within the canopy of a modeled plant. Tree branches passed through the canopy's three-dimensional structure to simulate the effect of airflow, and tree leaves were used to simulate their effect by adding drag terms to the porous subdomain and correcting the momentum and turbulent energy equations. This showed that canopy density significantly affects airflow velocity, with a substantial reduction in airflow velocity within the full-leafed canopy and a lesser reduction in the leafless region. The airflow showed three-dimensional variation within the canopy and was divided by branches and leaves after entering, forming an asymmetric flow field. Duga et al.[38] introduced the three-dimensional canopy structure of pear and apple trees in their airflow field simulation and established a three-dimensional CFD airflow field model for different natural airflow speed conditions. The model showed that increased airflow speed exacerbated the deflection of spray particles away from the canopy, resulting in more spray deposited on the ground. At lower airflow speeds, the spray was more concentrated within the canopy. Different sprayers produced different airflow patterns, with axial sprayers generating upward airflow that tends to drift small particles above the canopy, and cross-flow sprayers generating uniform airflow, which reduces spray deflection.

The attenuation characteristics and distribution patterns of the airflow field within the fruit tree canopy have a direct impact on droplet deposition, while the airflow field outside or above the canopy directly affects aerial drift and ground deposition of the spray[39]. Consequently, it is particularly important to thoroughly analyze the interaction between the airflow field and the fruit tree canopy. Nowadays, there are few studies on the interaction between airflow fields and fruit tree canopies, and the distribution of airflow within the canopy remains to be studied in depth. To address this gap, the development of equipment that can effectively regulate the airflow within the canopy is essential for improving spray efficiency.

## 3 Orchard airflow spraying airflow control equipment

The three elements of airflow power are airflow direction, airflow speed, and airflow volume. Airflow control equipment mainly adjusts the appropriate airflow direction, airflow speed, and airflow volume to increase droplet penetration and adhesion rates while reducing liquid drift. Airflow direction needs to be adjusted based on the shape of the canopy to achieve profiling spray. Airflow speed and airflow volume need to be controlled on demand based on the biomass characteristics of the fruit tree canopy. For example, dense branches and leaves with a smaller canopy volume generally require high airflow speed and low airflow volume, while sparse branches and leaves with a larger canopy volume require low airflow speed and high airflow volume. To realize on-demand control of airflow speed and airflow volume, it is necessary to detect and calculate the airflow speed and airflow volume demand of fruit trees in real time. The airflow actuator is then controlled to supply the appropriate airflow power, ensuring that after the loss of conveying space, the airflow power penetrates the fruit tree canopy effectively[40,41].

### 3.1 Airflow regulation methods

The regulation of airflow direction is usually achieved by rotating the airflow box and adjusting the angle of the deflector plate. The control of airflow speed and airflow volume is mainly accomplished by adjusting the area of the outlet and inlet of the airflow box, as well as changing the fan speed. In addition, the regulation of airflow power supply can also be achieved by adjusting the distance between the nozzle of the airflow box and the spray target[42,43]. The relationship between the four common regulation methods and the changes in airflow speed and airflow volume is listed in Table 3[44].

At present, most airflow speed and airflow volume regulation devices designed by researchers use single regulation, resulting in the mutual coupling of airflow speed and air volume, which prevents independent control of the two. In the single outlet area regulation method, airflow speed and air volume change in opposite directions, whereas in the inlet area regulation and fan speed regulation methods, airflow speed and air volume are directly proportional. Regardless of the single regulation method used, there is a coupling relationship between airflow speed and airflow volume, which is not conducive to precise airflow power regulation. Future studies need to explore the principles of single regulation methods in depth and, at the same time, develop new technologies that combine two or more regulation methods to achieve independent regulation of airflow speed and airflow volume[45].

**Table 3 Airflow speed and volume control methods and interrelationships**

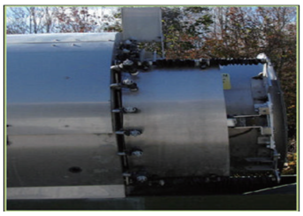
| Control method | Adjustment direction | Airflow speed variation | Air volume variation |
|---|---|---|---|
| Fan RPM | ↓ | ↓ | ↓ |
| Air outlet area | ↓ | ↑ | ↓ |
| Inlet area | ↓ | ↓ | ↓ |
| Fan blade inclination | ↓ | ↓ | ↓ |

### 3.2 Progress of research on airflow regulation equipment

With the continuous advancement of orchard airflow spraying technology towards intelligence and precision, airflow regulation equipment is receiving significant attention from researchers both domestically and internationally.

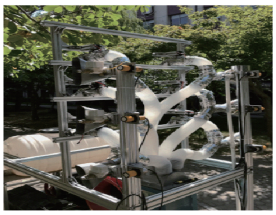
Airflow direction adjustment is mainly achieved by installing adjustable deflector plates and branch airflow pipes at the outlet of the airflow box[46]. Song et al. conducted hydrodynamic simulations of the straight plate deflector device of the 3WFXT-400 tower-type air-fed sprayer and determined the optimal combination of deflector plate mounting parameters. The optimized airflow velocity at the top was significantly improved, with the deflector plate airflow velocity reaching 17.719 m/s. The area of the low-speed region was reduced by 0.065%, and the airflow became more uniform, thus reducing the risk of droplet drift[47]. Suning et al. designed an airflow-guiding device for upright airflow-delivered sprayers, which sprayed liquid to form droplets through nozzles. The axial airflow generated by the rear fan was converted into radial airflow through the airflow box, blowing the liquid droplets to the target seedlings. The maximum spraying distance was up to 10 m, covering 11 acres of land per hour, and greatly improving operational efficiency[48]. Pai et al.[49] proposed a method to adjust the airflow speed and air volume of the air sprayer according to changes in leaf density in orchards and to change the direction of airflow at the outlet by adjusting the tilt angle of the deflector plate.

The air volume and airflow speed are controlled by adjusting the inlet and outlet area of the air box, the power and speed of the fan, and by installing different shapes of shunts. Khot et al. designed a device to control airflow speed and air volume by adjusting the area of the air outlet, as shown in Figure 2a. It adds a layer of cylinder on the outside of the fan and adjusts the position of the cylinder through the expansion and contraction of a motorized actuator to regulate the outlet area of the annular airflow channel, thereby controlling airflow speed and air volume. The airflow channel area is adjusted by controlling the expansion and contraction of the electric actuator to adjust the position of the outer cylinder, thus regulating the air outlet and achieving control of air speed and air volume. Experiments also concluded that using 70% air-assisted spraying improves droplet deposition in the middle and rear, which is better than 100% air-assisted spraying. Reducing the number of nozzles reduces pesticide dosage by 50%, but the spray deposition effect remains equivalent[50,51]. Qiu et al.[52,53] designed a 3WZ-700 self-propelled orchard air-directed sprayer, as shown in Figure 2b, which adopts automatic airflow speed control and a hydrostatic transmission device to achieve stepless regulation of the fan speed in the range of 0 to 2000 r/min. In addition, airflow direction inside the airflow box and at the air outlet was adjusted by installing an airflow guide plate and an airflow regulator plate inside the airflow box[42,54]. Jiang et al.[55] designed and proposed a scheme to regulate airflow through a single fan with multiple air ducts, as shown in Figure 2c. Independent air outlets were set up for different zoned canopies, and reasonable airspeed for each outlet was determined according to canopy characteristics, thereby adjusting the airflow to optimize the spraying effect. In the variable airflow spraying mode, droplet deposition on the fruit tree canopy surface increased by 17.3%, and drift was reduced by 50.9%. Li et al.[56] designed an automatic contour spraying machine for fruit orchards using a LIDAR sensor, as shown in Figure 2d. The device calculates the required airflow volume and pesticide dosage based on the canopy information of fruit trees detected by the LIDAR sensor. Airflow volume and pesticide dosage are controlled by adjusting the speed of the electric fan and the PWM duty cycle of the solenoid valve. Under the operation of the sprayer, the variation coefficients of droplet deposition on the left, middle, and right sides of the canopy were 14.2%, 18.0%, and 13.7%, respectively. The uniformity of deposition on the back side of the canopy was significantly improved.



a. Regulating air velocity and volume of the airflow device by adjusting the outlet area[50]

b. 3WZ-700 self-propelled orchard airflow directional sprayer[53]



c. Single blower multi ducted airborne sprayer[55]

d. Orchard automatic profiling sprayer[56]

Figure 2 Airflow regulation equipment

Qiu et al.[57,58] studied the effects of airflow force on droplet deposition and drift characteristics by adjusting the fan speed to change airflow supply. Through experiments, they found that the highest deposition of droplets in the canopy reached 3.01 $\mu$g/cm$^2$ at a fan speed of 1300 r/min, and the amount of spray drift per tree was 0.40 g at 1800 r/min. The deposition of droplets slightly decreased to 2.92 $\mu$g/cm$^2$ at a fan speed of 1800 r/min, and spray drift increased to 1.11 g. Miranda-Fuentes et al.[59] successfully achieved airflow control by adjusting the fan speed of the airflow-assisted system. Landers developed a sprayer based on infrared targeting technology that uses a louvered structure and an electric actuator to adjust the outlet size, achieving intelligent control of airflow speed and volume. Experiments found that the device increased droplet deposition by 82% and reduced droplet drift by 71%[60]. Osterman et al.[61] designed a fruit orchard airflow-blown sprayer that adjusts velocity and volumetric flow at the target by moving the exit position of the airflow box without changing the outlet airflow force. This reduced droplet drift by 67%. Doruchowski et al. proposed a crop adaptive system (CASA) that adjusts the inlet area using a shutter structure and controls the distribution of outlet airflow volume with guide vanes and an electric actuator. The inlet and outlet are jointly controlled to regulate airflow speed and volume, increasing droplet deposition by 30% and reducing droplet drift by 40%[62,63].

As can be seen from the above studies by domestic and international scholars and enterprises, most airflow regulation devices use a single regulating mechanism. The mechanical structure and control system of these mechanisms are relatively simple and easy to realize. Notwithstanding, due to the mutual coupling between airflow speed and airflow volume, these devices cannot achieve independent control of either parameter[44]. In addition, research on devices for on-demand airflow regulation based on fruit tree canopy information is still limited, and they cannot be adjusted in real time according to actual airflow demand.

## 4 Conclusions

This study reviews the application of airflow-assisted technology in orchards, focusing on the quantitative characterization of airflow volume within and outside fruit tree canopies. Existing research primarily employs a combination of simulation analysis and field trials to quantify airflow field distribution inside the canopy and estimate airflow volume demand. However, a review of these studies reveals limitations in the accuracy of wind field prediction. Based on current quantitative methods and findings, challenges remain in on-demand airflow regulation, canopy modeling accuracy, and the independent control of airflow speed and volume. These include insufficient precision in collaborative airflow and droplet control, limitations in three-dimensional airflow field models, and a lack of commercialized equipment.

Future research should focus on the development of canopy airflow volume models, optimization of modeling methods, and the creation of devices that allow decoupled control of air velocity and flow capacity. These advancements would enhance spray precision, minimize resource waste, and improve the efficiency of orchard management. By enabling real-time, adaptive airflow control, they could have the potential to optimize pest and disease management and to increase fruit yield, providing immediate benefits to modern orchard operations. Specific recommendations are outlined as follows.

1) Airflow-assisted technology is crucial for enhancing droplet distribution uniformity and penetration within fruit tree canopies. As orchard planting becomes more diversified, on-demand wind power control based on canopy biomass information is increasingly essential. An in-depth study of the canopy airflow storage model should investigate the relationships between biomass, foliage, and airflow power at various growth stages of fruit trees. By analyzing factors such as canopy structure and leaf density that influence airflow power requirements, a dynamic airflow regulation model can be developed. This model would allow orchard managers to fine-tune airflow conditions based on specific needs, enhancing spray accuracy and minimizing waste. The result would be more targeted and resource-efficient spraying, improving pest and disease control, reducing chemical and water usage, and ultimately increasing fruit yield and quality. These advancements would directly support sustainable orchard management practices, leading to cost savings and higher productivity.

2) Fruit tree canopies exhibit complex branch and leaf structures, with variable airflow dynamics. Current canopy equivalent models and CFD-based 3D airflow field models require further refinement to accurately replicate these characteristics. Therefore, it is essential to optimize modeling methods while preserving actual canopy features, reduce computational complexity and costs, and propose a more cost-effective modeling approach. Simplifying the modeling process, ensuring precise representation of key parameters, and reducing dependence on computational resources will enable faster, more accurate canopy model construction, providing robust technical support for related research and practical applications.

3) Current airflow regulation primarily relies on single methods such as fan speed and outlet area adjustments, making it difficult to achieve independent control of airflow speed and volume. Most research remains theoretical, and on-demand airflow regulation equipment based on canopy information is limited, with few mature products available. To address the coupling of airflow velocity and discharge rate, decoupling control methods should be explored, along with the development of airflow power devices capable of independent control. Testing these technologies in real orchard environments would direct optimization of their performance, making them more adaptable to varying orchard conditions. This would enable more precise control of wind conditions during spraying, improving pesticide application efficiency, reducing waste, and minimizing environmental impact.

## Acknowledgements

This work was supported by China Agriculture Research System of MOF and MARA (Grant No. CARS-28-21) and Jiangsu Standard Orchard Intelligent Green Agricultural Machinery Research, Production and Application Integration Project (Grant No. JSYTH01).

## [References]

[1] People's Republic of China Bureau of Statistics. 2023 China statistical yearbook. Beijing: China Statistics Press. 2023; 238p. (in Chinese)

[2] Zhang H F, Xu L Y. Summary of research status on orchard sprayer. Journal of Chinese Agricultural Mechanization, 2014; 35(3): 112–118. (in Chinese)

[3] Zhao Y, Xiao H R, Mei S, Song Z Y, Ding W Q, Jin Y, et al. Current status and development strategies of orchard mechanization production in China. Journal of China Agricultural University, 2017; 22(6): 116–127. (in Chinese)

[4] Du X R, Chen N L. Overview of countermeasure suggestions for pollution-free production of Jingning apples. Gansu Agriculture, 2017; 4: 28–30. (in Chinese)

[5] Bian Y L. Design and experimental study of multi-fan wind-driven sprayers for orchards. Master's dissertation. Hebei: Hebei Agricultural University, 2022; 75p. (in Chinese)

[6] Fu X M, Lyu X L, Ding W M, Wu P, Ding S M, Qiu W. Present state and technical requirement about orchard plant protection machinery in China. Journal of Chinese Agricultural Mechanization, 2009; 6: 10–13, 17. (in Chinese)

[7] He X K. Improving severe draggling actuality of plant protection machinery and its application techniques. Transactions of the CSAE, 2004; 20(1): 13–15. (in Chinese)

[8] Su L X. Research and design of key components of orchard sprayer. Master's dissertation. Chongqing: Chongqing Three Gorges University, 2023; 70p. (in Chinese)
[9] Li X H, Wang P F, Li J P, Yang X, Bian Y L. A comparative study on the spraying effect of orchard wind sprayers under different air supply modes. Journal of Fruit Science, 2020; 37(7): 1065–1072. (in Chinese)
[10] Lyu X L, Zhang M N, Chang Y H, Lei X H, Yang Q S. Influence of deflector angles for orchard air-assisted sprayer on 3D airflow distribution. Transactions of the CSAE, 2017; 33(15): 81–87. (in Chinese)
[11] Liu X H. Study on air-assisted droplets penetration in dense canopy based on stratification porosity. PhD dissertation. Taian: Shandong Agricultural University, 2021; 134p. (in Chinese)
[12] Endalew A M, Hertog M, Verboven P, Baetens K, Delele M A, Ramon H, et al. Modelling airflow through 3d canopy structure of orchards. Aspects of Applied Biology, 2006; 77(2): 465–472.
[13] Endalew A M, Hertog M, Delele M A, Baetens K, Persoons T, Baelmans M, et al. CFD modelling and wind tunnel validation of airflow through plant canopies using 3D canopy architecture. International Journal of Heat and Fluid Flow, 2009; 30(2): 356–368.
[14] Endalew A M, Hertog M, Gebrehiwot M G, Baelmans M, Ramon H, Nicolaï B M, et al. Modelling airflow within model plant canopies using an integrated approach. Computers and Electronics in Agriculture, 2009; 66(1): 9–24.
[15] Endalew A M, Debaer C, Rutten N, Vercammen J, Delele M A, Ramon H, et al. A new integrated CFD modelling approach towards air-assisted orchard spraying. Part I. Model development and effect of wind speed and direction on sprayer airflow. Computers and Electronics in Agriculture, 2009; 71(2): 128–136.
[16] Endalew A M, Debaer C, Rutten N, Vercammen J, Delele M A, Ramon H, et al. A new integrated CFD modelling approach towards air-assisted orchard spraying-Part II: Validation for different sprayer types. Computers and Electronics in Agriculture, 2009; 71(2): 137–147.
[17] Hong S-W, Zhao L Y, Zhu H P. CFD simulation of airflow inside tree canopies discharged from air-assisted sprayers. Computers and Electronics in Agriculture, 2018; 149: 121–132.
[18] Wang B Q. Study on airflow and resistance characteristics of a 3D canopy structure. Master's dissertation. Shanghai: Donghua University, 2016; 81p. (in Chinese)
[19] Cao J X, Tamura Y, Yoshida A. Wind tunnel study on aerodynamic characteristics of shrubby specimens of three tree species. Urban Forestry & Urban Greening, 2012; 11(4): 465–476.
[20] Mercer G N. Modelling to determine the optimal porosity of shelterbelts for the capture of agricultural spray drift. Environmental Modelling and Software, 2009; 24(11): 1349–1352.
[21] Loeffler A E, Gordon A M, Gillespie T J. Optical porosity and windspeed reduction by coniferous windbreaks in Southern Ontario. Agroforestry Systems, 1992; 17: 119–133.
[22] Zhu J J, Matsuzaki T, Gonda Y. Optical stratification porosity as a measure of vertical canopy structure in a Japanese coastal forest. Forest Ecology and management, 2003; 173(1-3): 89–104.
[23] Houghton J T. The physics of atmospheres. London: Cambridge University Press. 2002; 203p.
[24] Qu Y H, Meng J H, Wan H W, Li Y T. Preliminary study on integrated wireless smart terminals for leaf area index measurement. Computers and Electronics in Agriculture, 2016; 129: 56–65.
[25] Zarate-Valdez J L, Whiting M L, Lampinen B D, Metcalf S, Ustin S L, Brown P H. Prediction of leaf area index in almonds by vegetation indexes. Computers and Electronics in Agriculture, 2012; 85: 24–32.
[26] Palleja T, Landers A J. Real time canopy density validation using ultrasonic envelope signals and point quadrat analysis. Computers and Electronics in Agriculture, 2017; 134: 43–50.
[27] Zhang M N, Lv X L, Qiu W, Lei X H, Yang Q S, Zhang D X. Calculation method of leaf area density based on three-dimensional laser point cloud. Transactions of the CSAM, 2017; 48(11): 172–178. (in Chinese)
[28] Neinavaz E, Skidmore A K, Darvishzadeh R, Groen T A. Retrieval of leaf area index in different plant species using thermal hyperspectral data. ISPRS Journal of Photogrammetry and Remote Sensing, 2016; 119: 390–401.
[29] Zhou L F, Xue X Y, Jia W D, Ding S M, Sun Z. Application of CFD technology in air-assisted spraying in orchard and analysis of its prospects. Journal of Drainage and Irrigation Machinery Engineering, 2014; 32(9): 776–782. (in Chinese)
[30] Xu T, Lv X L, Qi Y N, Zeng J, Lei X H, Yuan Q C. Research status on equipment and technology of orchard air-assisted sprayer in China. Journal of Chinese Agricultural Mechanization, 2023; 44(7): 69–77. (in Chinese)
[31] Fu Z T, Wang J, Qi L J, Wang H T. CFD simulation and experimental verification of air-velocity distribution of air-assisted orchard sprayer. Transactions of the CSAE, 2009; 25(1): 69–74. (in Chinese)
[32] Ding T H, Cao S M, Xue X Y, Ding S M, Zhou L F, Qiao B Y. Simulation and experiment on single-channel and double-channel airflow field of orchard sprayer. Transactions of the CSAE, 2016; 32(14): 62–68, 315. (in Chinese)
[33] Dekeyser D, Duga A T, Verboven P, Endalew A M, Hendrickx N, Nuyttens P. Assessment of orchard sprayers using laboratory experiments and computational fluid dynamics modelling. Biosystems Engineering, 2013; 114(2): 157–169.
[34] García-Ramos F J, Malón H, Aguirre A J, Boné A, Puyuelo J, Vidal M. Validation of a CFD model by using 3D sonic anemometers to analyse the air velocity generated by an air-assisted sprayer equipped with two axial fans. Sensors, 2015; 15(2): 2399–2418.
[35] Liu C C, Zheng Z Q, Cheng H, Zou X Y. Airflow around single and multiple plants. Agricultural and Forest Meteorology, 2018; 252: 27–38.
[36] Zhang H, Qi L J, Wang J J, Musiu E M, Zhou J R, Lu Z L, et al. Numerical simulation of downwash airflow distribution inside tree canopies of an apple orchard from a multirotor unmanned aerial vehicle (UAV) sprayer. Computers and Electronics in Agriculture, 2022; 195: 106817.
[37] Endalew A M, Debaer C, Rutten N, Vercammen J, Delele M A, Ramon H Nicolaï B M, et al. Modelling pesticide flow and deposition from air-assisted orchard spraying in orchards: A new integrated CFD approach. Agricultural and Forest Meteorology, 2010; 150(10): 1383–1392.
[38] Duga A T, Dekeyser D, Ruysen K, Ruysen D, Bylemans D, Nuyttens D, et al. Numerical analysis of the effects of wind and sprayer type on spray distribution in different orchard training systems. Boundary-Layer Meteorology, 2015; 157: 517–535.
[39] Zhang Y N. CFD modeling research on orchard spatial airflow field and interaction between airflow and tree for orchard spraying. Master's dissertation. Shanxi: Northwest A&F University, 2021; 58p. (in Chinese)
[40] Qiu W, Ding W M, Fu X M, Wang X C, Lv X L, Li Y N. Design and experiment of ring double-channel fan for spraying machine in orchard. Transactions of the CSAE, 2012; 28(12): 13–17. (in Chinese)
[41] Li C, Zhang X, Jiang J, Hu Y Y. Development and experiment of riser air-blowing sprayer in vineyard. Journal of Agricultural Engineering, 2013; 29(4): 71–78. (in Chinese)
[42] Qiu W, Ding W M, Wang X C, Gong Y, Zhang X X, Lyu X L. 3WZ-700 self-propelled air-blowing orchard sprayer. Transactions of the CSAM, 2012; 43(4): 26–30, 44. (in Chinese)
[43] Xu S, Zha C Y, Zhu R X, Guo J J, Li W, Han R Z. Design of an orchard air-assisted sprayer with adjustable spray height. Journal of Northwest A&F University (Natural Science Edition), 2013; 41(11): 229–234. (in Chinese)
[44] Dou H J, Zhai C Y, Chen L P, Wang X. Research progress on airflow adjustment methods of air-Assisted spraying in orchards. Journal of Agricultural Mechanization Research, 2021; 43(7): 10–18. (in Chinese)
[45] Zhai C Y, Zhao C J, Wang N, Long J, Wang X, Weckler P, et al. Research progress on precision control methods of air-assisted spraying in orchards. Transactions of the CSAE, 2018; 34(10): 1–15. (in Chinese)
[46] Niu C Q, Zhang W J, Wang Q, Zhao X X, Fan G J, Jiang H H. Current status and trends of research on adjusting air volume of orchard air spray. Journal of Chinese Agricultural Mechanization, 2020; 41(12): 48–54. (in Chinese)
[47] Song L J, Li J P, Yang X, Wang P F. Optimization design of wind field parameters of tower type wind - Driven orchard sprayer. Journal of Agricultural Mechanization Research, 2020; 42(4): 12–17. (in Chinese)
[48] Su N, Guo K J, Man D W, Wu L G, Zhu J G. Design and test of a vertical air-fed spraying machine. Forestry Machinery & Woodworking Equipment, 2019; 47(5): 28–31. (in Chinese)
[49] Pai N, Salyani M, Sweeb R D. Regulating airflow of orchard airblast sprayer based on tree foliage density. Transactions of the ASABE, 2009; 52(5): 1423–1428.
[50] Khot L R, Ehsani R, Albrigo G, Landers A J, Larbi P A. Spray pattern investigation of an axial-fan airblast precision sprayer using a modified vertical patternator. Applied Engineering in Agriculture, 2012; 28(5): 647–654.
[51] Khot L R, Ehsani R, Albrigo G, Larbi P A, Landers A, Campoy J. Air-assisted sprayer adapted for precision horticulture: Spray patterns and

deposition assessments in small-sized citrus canopies. Biosystems Engineering, 2012; 113(1): 76–85.
[52] Qiu W, He J M, Sun Y H, Liao Y Y, Zhou L F, Liu Y D. Effect of spray angles on profiling-flow field distribution from a multi-channel air-assistant sprayer in fruit tree applications. Journal of Nanjing Agricultural University, 2020; 43(2): 379–386. (in Chinese)
[53] Qiu W. Development and experimental research of Self-propelled Air assisted Orchard Sprayer. PhD dissertation. Jiangsu: Nangjing Agricultural University. 2012; 119p. (in Chinese)
[54] Qiu W, Ding W M, Shen B Y, Shi Q C, Wan N C, Gu J B. Analysis on trafficability of 3WZ-700 orchard sprayer. Transactions of the CSAM, 2012; 43(6): 63–67, 146. (in Chinese)
[55] Jiang H H, Niu C Q, Liu L M, Wang D W, Wang J S. Design and experiment of air volume control system of orchard multi-pipe air sprayer. Transactions of the CSAM, 2020; 51(S2): 298–307. (in Chinese)
[56] Li L L, He X K, Song L J, Wang X N, Jia X M, Liu C H. Design and experiment of automatic profiling orchard sprayer based on variable air volume and flow rate. Transactions of the CSAE, 2017; 33(1): 70–76. (in Chinese)
[57] Qiu W, Zhao S Q, Ding W M, Sun C D, Lu J, Li Y N, et al. Effects of fan speed on spray deposition and drift for targeting air-assisted sprayer in pear orchard. Int J Agric & Biol Eng, 2016; 9(4): 53–62.
[58] Song S R, Hong T S, Sun D Z, Zhu Y Q, Luo C Y. Effect of fan power supply frequency on deposition of air-assisted sprayer. Transactions of the CSAE, 2011; 27(1): 153–159. (in Chinese)
[59] Miranda-Fuentes A, Rodríguez-Lizana A, Gil E, Agüera-Vega J, Gil-Ribes J A, et al. Influence of liquid-volume and airflow rates on spray application quality and homogeneity in super-intensive olive tree canopies. Science of the Total Environment, 2015; 537: 250–259.
[60] Landers A J. Developments towards an automatic precision sprayer for fruit crop canopies. In: Proceedings of the 2010 Pittsburgh, Pennsylvania: American Society of Agricultural and Biological Engineers, 2010; doi: 10.13031/2013.29778.
[61] Osterman A, Godeša T, Hočevar M, Širok B, Stopar M. Real-time positioning algorithm for variable-geometry air-assisted orchard sprayer. Computers and Electronics in Agriculture, 2013; 98: 175–182.
[62] Doruchowski G, Swiechowski W, Godyn A, Holownicki R. Automatically controlled sprayer to implement spray drift reducing application strategies in orchards. J Fruit Ornam Plant Res, 2011; 19: 175–182.
[63] Doruchowski G, Balsari P, Marucco P, Van de Zande J, Wenneker M. Crop adapted spray application (CASA): precise and safe plant protection in fruit growing. Aspects of Applied Biology, 2012; 114: 129–136.