agronomy

Review

Anti-Drift Technology Progress of Plant Protection Applied to Orchards: A Review

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Abstract: In orchard plant protection application, an anti-drift strategy can effectively reduce drift in the non-target area, reduce spray drift in the environment, and avoid spray leakage and overspraying. To clarify the future development direction of orchard plant protection mechanization technology, this review introduces the development status of an anti-drift spray nozzle and the impact of different types of spray nozzles on the potential of drift, and then, it analyzes the research progress on air-assisted spraying, recycling spraying, profiling spraying, target variable spraying technologies, and plant protection UAVs. It also provides a general analysis of the above spraying technologies on the amount of drift and the impact of pesticide deposition. Finally, combined with the characteristics of orchard plant protection, the paper presents the research and development of anti-drift nozzles, pesticide adjuvant, air-assisted spraying technology, electrostatic, recycling spraying technology, profiling and target variable spraying technology, and plant protection UAVs. The review provides a reference for the development of an anti-drift strategy for orchard plant protection production.

Keywords: orchard; spraying; drift; pesticides; plant protection machinery; anti-drift strategy

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Citation: Li, S.; Li, J.; Yu, S.; Wang, P.; Liu, H.; Yang, X. Anti-Drift Technology Progress of Plant Protection Applied to Orchards: A Review. *Agronomy* **2023**, *13*, 2679. https://doi.org/10.3390/agronomy13112679

Academic Editor: Xiongkui He

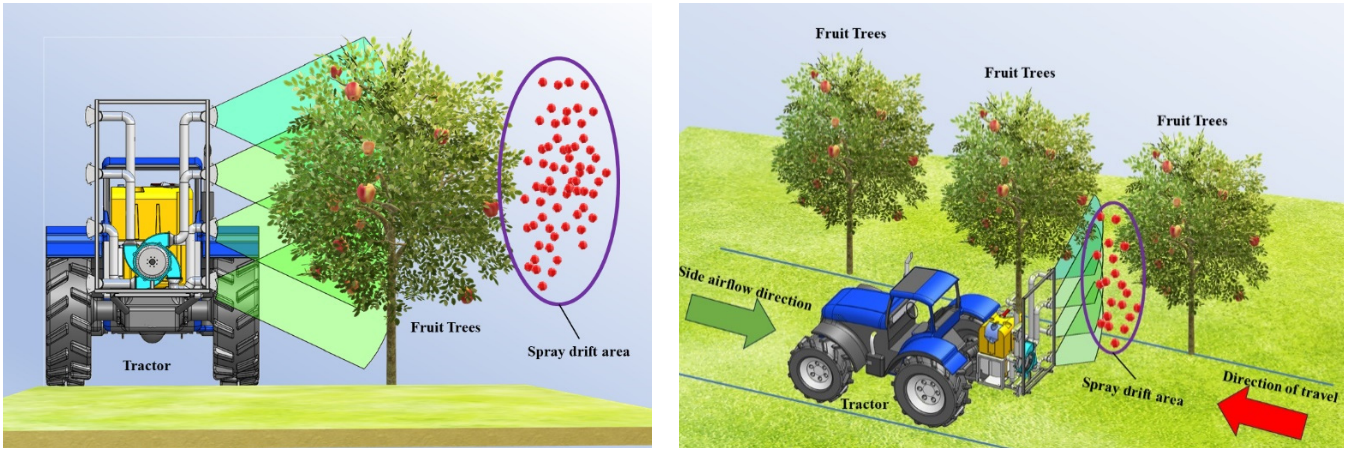
Received: 23 September 2023
Revised: 20 October 2023
Accepted: 24 October 2023
Published: 25 October 2023

1. Introduction

The chemical control of pests and diseases is a key technology and among the most efficient control measures used to eliminate agricultural biological infestations [1]. Currently, pest control mainly relies on chemical pesticides. For example, fruit tree pesticide spraying is carried out 8–15 times a year and accounts for approximately 30% of the total workload of fruit tree management [2]. However, the characteristics of orchard plant protection and field plant protection work are significantly different because the fruit tree canopy is large and has dense branches, leaves, and other plant protection operation characteristics that necessitate higher requirements [3].

Orchard spraying machinery has not yet met the requirements of precision spraying, and drift is now common worldwide [4]. To control pests and diseases and reduce the impact of ambient airflow on the pesticide application operation, applicators typically implement the pesticide application process through overspraying at a high air rate to penetrate the canopy of the fruit tree. A higher rate of the air-assisted airflow causes droplets to penetrate the canopy, prompting the droplets to drift to the other side of the rows of fruit trees. The ambient airflow then causes the droplets to drift to a non-target area, resulting in spray leakage or overspraying and, consequently, more pesticides in the environment, which is a major public concern [5]. The effectiveness of plant protection application is affected by many factors, including the type of nozzle, the amount of pesticide used, application parameters, the density of the target canopy, and the environmental conditions (including temperature, humidity, and airflow rate) [6,7].

Drift can be broadly categorized into two types (Figure 1). One is horizontal drift, which occurs along the direction of spraying owing to inaccurate airflow rate regulation, resulting in part of the droplets penetrating the canopy of the fruit trees and moving to the other side of the affected area. The other side contains a combination of adjacent fruit trees with a sparse canopy, resulting in a change in the attenuation of the kinetic energy of the droplets to the other line of the affected area, which produces heavy spray drift and increases the cost of application. The second type is vertical drift, which occurs perpendicularly to the direction of spraying and along the direction of the ambient airflow vertical drift owing to the influence of the ambient airflow on the movement of droplets. In vertical drift, the ambient airflow strength and direction changes are uncertain, leading to the movement of droplets to non-target areas. The result is the planting of different amounts of deposition of each fruit tree in the operation area, spray leakage, or overspraying, which all have a significant impact on the efficiency and security of the planting. Vertical drift also produces heavy spray drift, which can affect the health of the applicator.



(**a**) horizontal drift (**b**) vertical drift

Figure 1. Types of spray drift [1–4].

In plant protection application, the anti-drift property of droplets plays a key role in ensuring the effect of pesticide application and in protecting the environment, which directly affects the control of pests and diseases. The fact that the movement of the droplets is easily affected by the ambient airflow affects the deposition of droplets in the same row of each fruit tree, resulting in spray leakage or overspraying. In contrast, blindly increasing the strength of the air-assisted flow increases the horizontal drift of the droplets, resulting in heavy environmental pollution and a higher cost of plant protection. Therefore, anti-drift sprayers have a significant impact on the drift prevention of droplets, necessitating a more scientific application program and higher application efficiency. This means that the optimal drift control strategy is essential for droplet deposition and reduction to ensure that the canopy can receive the pesticide at the designed application rate to minimize droplet loss in non-target areas and reduce the operator's entry threshold [8].

The application parameters have a significant effect on the amount of drift [9,10]. The deposition process of droplets is shown in Figure 2, and the factors affecting the amount of droplet deposition are the type of spray nozzle, spray pressure, spray distance, and spraying technical parameters [11]. The spray nozzle determines the atomization effect of the liquid to obtain different distributions of droplet diameters, and smaller droplets can help penetrate the canopy of the fruit tree, enhance the uniformity of droplet deposition, and achieve a better prevention and control effect. However, small droplets also increase the amount of drift. Therefore, the selection of suitable spray nozzles can improve the effective utilization rate of pesticides. Application parameters such as the spraying distance, spraying pressure, and spraying angle also have a significant impact on droplet deposition and drift [12]. The spraying distance has an impact on the amount of droplet deposition and drift; a longer spray distance leads to a surge in the amount of drift, while a shorter spray distance leads to insufficient droplet atomization, resulting in poor uniformity of droplet deposition in the canopy. Furthermore, the spraying pressure significantly affects the droplet particle size; the higher the spray pressure, the smaller the droplets produced. Similarly, the spray angle, to a certain extent, can weaken the ambient airflow and the impact of gravity on the droplet movement and can improve the vertical distribution uniformity of droplets. Furthermore, the application rate has a great influence on the amount of droplet deposition; the larger the application rate, the worse the uniformity of droplet deposition in the canopy. Given the influence of the ambient airflow on the movement of droplets, spray leakage or overspraying has become clear with the increase in the application rate. In summary, the effects of the spraying rate, spraying distance, spraying pressure, and spraying angle on droplet deposition and drift should be considered comprehensively before pesticide application to determine the optimal application parameters [13,14].

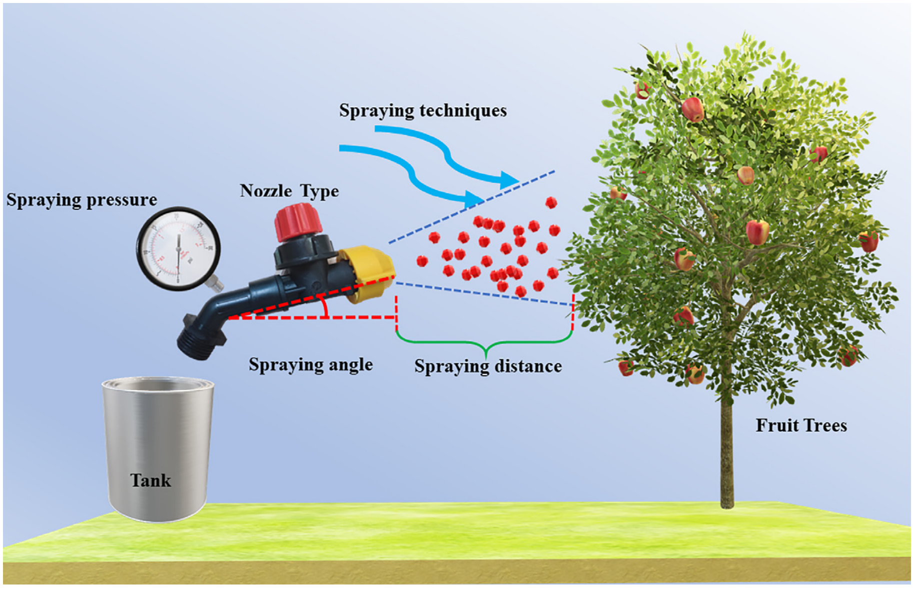


Figure 2. Deposition process of droplets [11,12].

To improve the penetration of droplets, experts have promoted the use of air-assisted spraying technology. For example, the Food and Agriculture Organization of the United Nations recommended a highly efficient application of technology whereby air-assisted spraying technology involving the use of fans and other air-assisted flow generated by the power of the droplets is driven by the conveyor to the target crop. This technology is conducive to the droplets attaching to the surface of the branches and leaves, improving the performance of the application of pesticide. Moreover, the orchard is the mainstream target of spraying in current plant protection application [15–19]. Ordinary air-assisted spraying can weaken the influence of ambient airflow on the movement of droplets, but drift still occurs in a large adjustable space. In recent years, researchers have proposed an improvement scheme for the traditional air-assisted spraying structure, designing the anti-drift airflow to actively counteract the ambient airflow, forming an airflow curtain in the drift path and effectively reducing the longitudinal drift of droplets [20,21]. To further improve the effect of droplet deposition, researchers designed a plant protection sprayer by utilizing recycling spraying technology, profiling spraying technology, and variable spraying technology. Recycling spraying technology can recycle the lost droplets, effectively reducing the application cost and drift while providing a wider range of solutions for the optimization of air-assisted airflow application of Su [22]. Similarly, electrostatic spraying technology can help the droplets attach to the electric charge, and under the action of an electric field force to the fruit tree canopy movement, this technology can effectively enhance the leaf back droplet deposition and, to a certain extent, reduce the droplets of lateral drift [23,24]. Simulation spraying technology can also adjust the spraying unit attitude according to the canopy characteristics, with the same spray distance for the application of pesticide, and it can effectively reduce the longitudinal drift of droplets [25] and aid in spray unit airflow rate regulation. The technology can help avoid an overly large airflow rate, which can cause lateral drift. Moreover, variable spraying technology is an actively researched topic. Sensors can be used to detect fruit tree canopy characteristics and meteorological parameters according to the canopy information to achieve real-time control of the spray system and the airflow delivery system, as well as real-time adjustment of the application program precision application, which can effectively reduce the amount of drift [26].

In the past decades, anti-drift spraying technology has become a research focus and has made significant progress, but there are still technical difficulties to be overcome. In order to promote the research of anti-drift spraying technology in orchards, the research status of anti-drift nozzles, anti-drift adjuvants, and four spraying technologies (air-assisted spraying technology, recycling spraying technology, profiling spraying technology, and variable spraying technology) in orchards are reviewed, and the future development direction of the anti-drift spraying technology in orchards is demonstrated, which provides theoretical basis and practical reference for the application of scientific research institutes and enterprises, and contributes to the accelerated development of the plant protection industry in orchards. The structure of the rest of this review is as follows: Section 2 discusses the current research status of the anti-drift spray nozzle. Section 3 describes the current research status of the air-assisted spraying technology, recycling spraying technology, profiling spraying technology, target variable spraying technology and discusses the droplet anti-drift strategy from the perspective of UAVs. Section 4 summarizes the current research progress in spraying technology and offers future development directions.

2. Progress of Research on Anti-Drift Nozzle Research

Pesticides are atomized into different-sized droplets through a spray nozzle and distributed on the target crop surface. The spray nozzle is an important part of sprayers; it helps ensure the effectiveness of application and affects the pesticides atomization process. Its performance directly affects the spray quality and determines the reliability and economy of the entire application equipment system operation. In the spraying process, under a certain working pressure, airflow rate, and other application parameters, the spray nozzle determines the distribution of the droplet spectrum, including the droplet size, density, distribution, and other characteristics, thus affecting the droplets in the target crop deposition and drift. Table 1 presents the application effect of anti-drift nozzles in various studies.

Table 1. Application effect of an anti-drift nozzle.

Nozzle Type	Branding	Model Number	Specificities	Related Research
Anti-drift nozzle	TeeJet (Wheaton, Illinois, United States)	AIXR11003	Large droplet size, good anti-drift effect	Liu [26] McGinty [27] Zhang [28]
Anti-drift nozzle	Lechler(Metzingen, Germany)	DG11003	Small droplet size, general anti-drift effect	McGinty [27]
Micro-drift nozzle	Hardi (Denmark)	MD 11003	Large droplet size, good anti-drift effect	Zhang [28]
Anti-drift nozzle	Lechler(Metzingen, Germany)	AD12003	Medium droplet size, good anti-drift effect	Li [29]
Hollow cone nozzle	TeeJet (Wheaton, Illinois, United States)	TXVK-4	Very small droplet size, poor anti-drift effect	Liu [26]

To reduce pesticide drift, drift on neighboring crops, and other issues, Germany first began to study how the spray nozzle can reduce drift. Their aim was to reduce the number of fine particles sprayed per unit of time so that the average size of the droplets would be larger, with the aim of achieving higher drift resistance. An anti-drift spray nozzle sprays droplets with a larger average particle size, making the droplet spectrum narrower. Fujie et al. studied the atomization performance of the same-sized heterogeneous spray nozzle and found that the AIXR anti-drift MD micro-drift spray nozzle increased the droplet size by 88.91% and 96.60% compared to the VMD, respectively. The nozzle type and size also had a significant effect on droplet size and velocity; therefore, choosing the right nozzle is one of the key factors to improve the effectiveness of plant protection application.

3. Progress of Research on Anti-Drift Technology of Plant Protection Machinery

Drift prevention and control technology is an important part of precision agriculture that can improve pesticide utilization and reduce the amount of pesticide drift when combined with modern information technology based on the realization of the precise application of pesticides. Thus, promoting the innovation of plant protection machinery industry is of great significance. At present, orchard plant protection spraying technologies mainly include air-assisted spraying technology, recycling spraying technology, electrostatic spraying technology, profiling spraying technology, and target variable spraying technology.

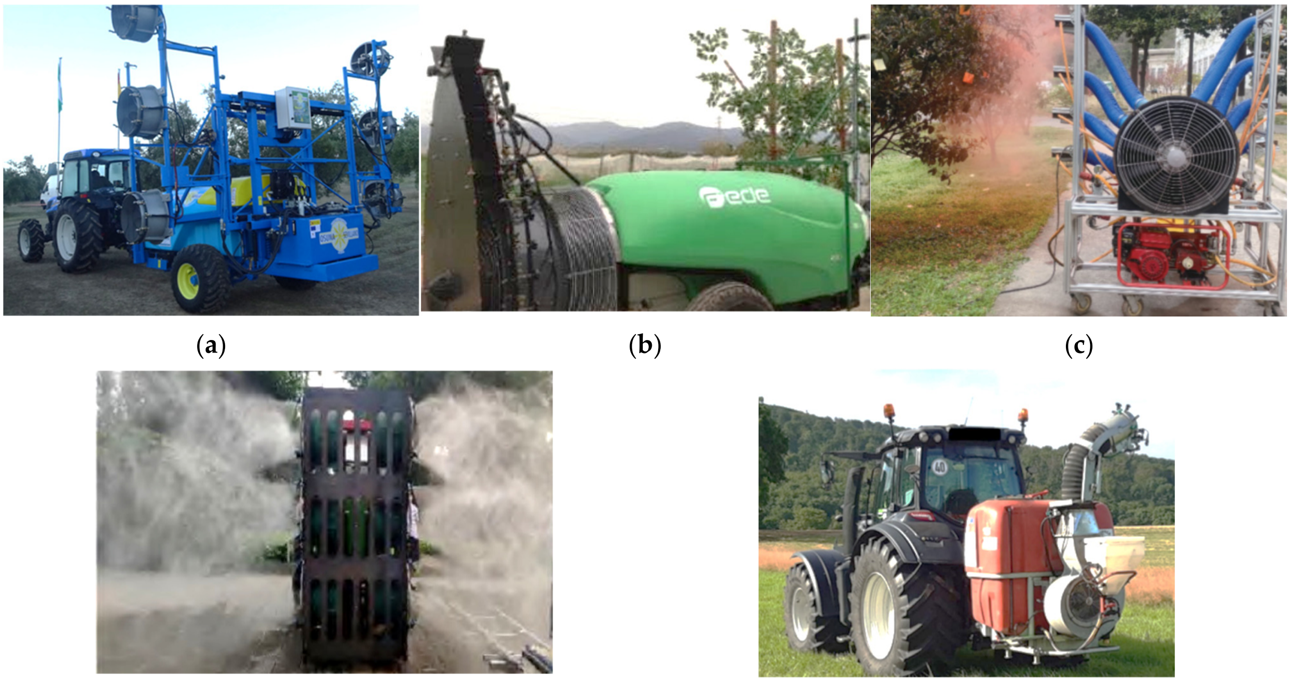
3.1. Air-Assisted Spraying Technology

Air-assisted sprayers can improve the efficiency of application and reduce pesticide waste [30]. Currently, sprayers using air-assisted technology can be divided into multi-fan air-assisted sprayers [31,32]. Researchers worldwide have researched various types of air-assisted sprayers to solve the problems of insufficient droplet penetration and large drift by using air-assisted spraying technology [33,34]. tower-type air-assisted sprayers [35], multi-conduit air-assisted sprayers [36], multi-fan air-assisted sprayers [37], and centrifugal plus agro-cannon sprayers [38].

Air-assisted sprayers can also solve the problem of drift due to the improper application of pesticides and can overcome the limitations of conventional sprayers used in traditional and intensive orchards by enhancing droplet deposition and droplet deposition uniformity, as well as significantly reducing ground drift. This suggests that air-assisted spraying systems are effective in reducing spray drift [35–37]. For example, Wei et al. [36] designed a multichannel directional air-assisted sprayer for orchards of the air-assisted type that can perform an independent adjustment of the height of airflow in each channel. The sprayer solved the problems of difficult droplet penetration and severe drift in air-assisted application of pesticides for fruit trees, improved droplet deposition in the canopy by 47.6%, reduced the coefficient of variation by 34%, and reduced the amount of ground deposition and air drift by 29.9% compared to traditional air-assisted sprayers.

In the spraying process, the air-assisted flow can weaken the influence of ambient airflow on droplet movement. However, the type of air-assisted airflow has a significant effect on droplet movement. Thus, researchers worldwide have studied the effect of application parameters on droplet deposition and drift, and the results show that optimizing application parameters such as pressure, spray medium, and airflow rate can reduce the amount of drift without affecting the amount of droplet deposition [39] (Figure 3).

The application parameters mainly include spray pressure, spray distance, and airflow rate [30,35–38]. Air-assisted spraying technology can improve the uniformity of droplet deposition, but the unreasonable setting of application parameters can lead to an increase in drift [40,41], which is closely related to droplet particle size, airflow rate, and spraying distance. Moreover, drift gradually increases with the increase in spraying distance, spraying pressure, and airflow rate [42]. Thus, studying the mechanism of the reciprocal effect of spraying parameters on drift can reduce drift, improve the efficiency of application, enhance the effectiveness of pest control, and have important theoretical and practical significance for agricultural production. Increasing the spray pressure will lead to a decrease in droplet particle size, increase the application cost, and reduce the application efficiency, resulting in a large amount of deposition in the non-target area [43].



(**a**) (**b**) (**c**)

(**d**) (**e**)

Figure 3. Types of air-assisted sprayers. (**a**) Mir [30]; (**b**) Lu [35]; (**c**) Qiu [36]; (**d**) Li [37]; (**e**) Ranta [38].

However, the above studies only considered the use of single air-assisted spraying, which has the problem of very high or very low airflow rate during the spraying process, generating problems such as pesticide drift or poor penetration [44]. Moreover, they did not consider the use of multiple air-assisted solutions and did not propose an improvement plan for the traditional air-assisted spraying structure.

The principle of active air-assisted flow to prevent drifting is shown in Figure 4. When the unit is traveling against the ambient airflow, the main turbine generates airflow B, which sends the droplets to the canopy of the fruit tree. The front secondary turbine generates airflow A, and airflow B flips the branches and leaves to make the back side face upward and weaken the influence of ambient airflow on the droplets. The rear secondary turbine forms an air curtain along the plant height direction (i.e., the anti-drift airflow C), which reduces the non-target area of the droplets to be drifted and improves the amount of droplet deposition in the canopy of the fruit tree [19].

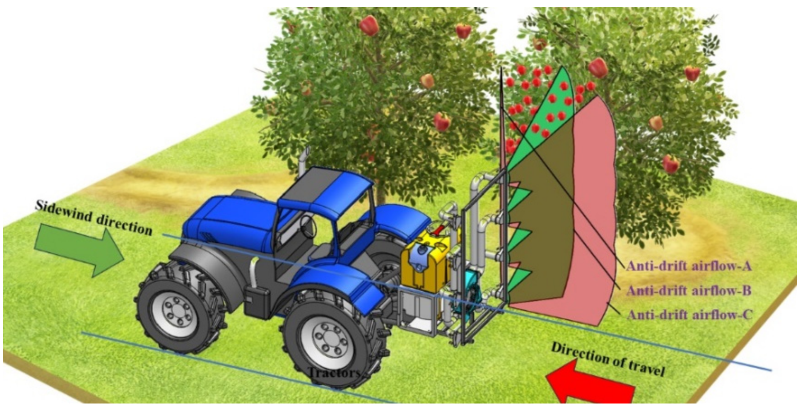


Figure 4. Working principle of active air-assisted flow to anti-drift spraying [19,20].

To improve the orchard affected area deposition and reduce the fruit tree rows of drift, Fan et al. [20] designed a multi-airflow synergistic V-shaped anti-drift spraying device for conventional air-assisted spraying. Compared to a single airflow, the multi-airflow synergistic effect of droplet deposition increased by 17.4%, and the amount of drift was reduced by 21.8%. This kind of air-assisted flow is an innovative form in orchard plant protection application, and the use of active air-assisted flow to offset the influence of ambient airflow on the movement of droplets can effectively reduce the amount of drift, which can greatly contribute to environmental protection.

At present, Europe and the United States, Japan, Korea, and other countries produce an advanced orchard air-assisted spraying technology. Famous manufacturers are Italy CAFFINI company, Denmark HARDI company, and South Korea ASIA TECH company. Overall, Europe and the United States orchards are mostly for traction and suspension, wherein the large- and medium-sized air-assisted sprayer is the main power with a long range, tank volume, high fan air volume, and suitable for wide rows, narrow plants, and high canopy standardized orchards; Japan and South Korea orchard planting is similar to China, being mostly self-propelled and the small- and medium-sized air-assisted sprayer is the main power, which is lower than Europe and the United States, with a compact structure, good trafficability characteristic, etc. [45–48].

3.2. Recycling Spraying Technology

To spray pesticides safely and effectively, the sprayer must ensure that sufficient liquid is deposited on the target area while minimizing pesticide loss. Recycling spraying technology is one of the technologies that best meets the requirements of environmentally friendly spraying techniques. Recycling spraying technology uses pesticides recovery devices to intercept and collect undeposited pesticides. Thus, recycling spraying has emerged in a wide variety of types: the "Π" type cover type, collector type, reflective type, and air circulation type.

By the 1990s, the improvement in the traditional orchard sprayer had basically completed. To further increase the pesticide deposit rate, researchers aimed to develop a new type of sprayer, leading to the rapid development of the "Π" type recirculating sprayer. Many studies have aimed to improve the system to further enhance the working performance of the sprayers [49].

The research on recirculating sprayers has mainly focused on droplet deposition, pesticide loss, and the recovery rate. To address the problems of low pesticide utilization, Jianli et al. [50,51] designed and tested the performance of a "Π" type sprayer, and the results show that staggered spraying on both sides of the spray bar could improve the pesticides recovery rate by 44.0% and reduce the amount of ground drift within the drift distance by 99.3% compared with a conventional orchard air-assisted sprayer. Furthermore, Ade et al. [52,53] developed the "Π" type sprayer and showed that it consumed less pesticides and had significantly lower drift than the conventional sprayer. Moreover, Jamar et al. [54] and Soriano et al. [55] compared droplet deposition in orchards under a recirculating spray system, a conventional hydraulic spray system, and a conventional air-assisted spray system and found that the recirculating spray system could effectively reduce the amount of drift compared to other spray systems.

With the development of technology and the integration of multiple technologies, the difference between the sprayer types is no longer clear, and a combination of the "Π" type cover type and airflow circulation types has emerged. Gianfranco et al. [56] designed a tunnel-type air-assisted spraying machine that reduced the drift rate by 8.1% and could recover at least 30% of the drift. Moreover, Qiu et al. [57] designed a recirculating air-assisted sprayer adapted to low-growth orchards, and the average coverage of droplets on the front side of canopy-rifled blades was increased by 42.9%, while that on the back side of blades was increased by 40.4%, reducing the pollution of pesticides to the environment (Figure 5).

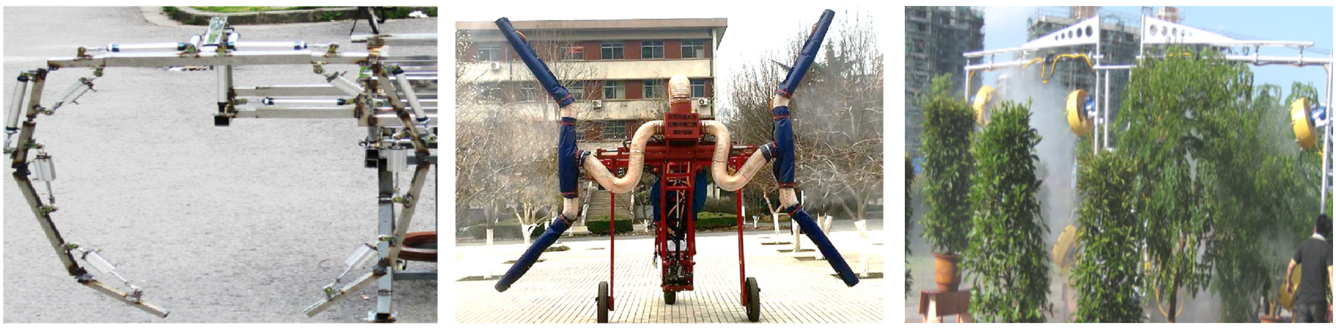
(**a**) (**b**) (**c**)

Figure 5. Circulation sprayer. (**a**) Ade [52,53]; (**b**) Gianfranco [56]; (**c**) Qiu [57].

Nestor cyclic sprayer is one of the typical recycling sprayers, which is connected to the back of the tractor by traction, with a tank capacity of 2000 L, an operating width of 0.94–2.70 m, and a canopy height of 2.10–2.35 m [58]. In addition, according to LIPCO company, information shows that its production of recycling sprayer in the fruit tree sparse branches and leaves have a liquid recovery rate of 70%, while the branches and leaves also have 20% liquid recovery rate; MUNKHOF company manufactured recycling sprayer according to the degree of dense branches and leaves have a liquid recovery rate from 30% to 60% [59]. In summary, the recirculating sprayer has been found to significantly reduce the amount of drift and ground loss, resulting in effective recovery of droplets and improvement in the utilization rate of pesticides. However, because it is mainly applicable to specific dwarf plantations, the current universality of recirculating spraying technology is poor. Moreover, the technology has a complex structure and a high cost of manufacturing, leaving much room for improvement in its development.

3.3. Profiling Spraying Technology

To improve the quality of droplet distribution and reduce the deposition in the non-target area, the integrated profiling mechanism of the spraying machinery needs to be increased, as shown in Figure 6. Moreover, the manual adjustment of the spray unit folding position can achieve a uniform envelope of the fruit tree canopy to uniformly stabilize the spraying distance and the distribution of the pesticides, thereby improving the effect of spraying.



(**a**) (**b**) (**c**)

Figure 6. Profiling sprayer. (**a**) Yu [60]; (**b**) Zhang [61]; (**c**) Zhou [62].

To solve the problems of the poor adaptability of the sprayers to the canopy of fruit trees, Yu et al. [60] combined the application requirements of tree profiling sprayer and designed an orchard profiling sprayer that can change the spray angle and spray distance according to the tree's spacing, height, and crown shape, thereby ensuring precise spraying, improving pesticide use efficiency, and reducing drift. Zhang et al. [61] designed a trinity multifunctional sprayer, combined with air-assisted spraying technology to reduce the impact of natural airflow on the drift, forcing droplets into the inner layer of the canopy to improve the amount of deposition and uniform distribution of the droplets, which can reduce the loss of the liquid to protect the environment. Zhou et al. [62] designed a combined disk-type air-assisted sprayer for fruit trees. It can adjust the spraying position according to the shape of fruit trees, thus improving the quality and efficiency of the operation and providing new techniques for the control of fruit tree diseases and pests. Their work can provide a reference for the improvement in the design of the air-assisted sprayer in orchards. Furthermore, Li et al. [63] compared the performance of profiling spray and conventional air spray in orchards, and the experimental results showed that, compared with conventional spraying, the profiling spray effectively improved the pesticide utilization rate. Additionally, the spray drift of the profiling variable spray machine was reduced by 23.2% and the saving of liquid solution was 45.7%.

Thus, the development of profiling spraying technology is important for realizing a precision application, improving pesticide utilization, and reducing production costs in orchards [16]. Profiling spraying technology reduces the averaged spray distance and improves the uniformity of droplets deposition, but drift remains at high levels due to the influence of factors such as large differences in characteristics between nearby canopies and between canopies. Li et al. [64] designed an orchard automatic profiling sprayer based on the variable rate spraying. The sprayer allows the applicator to adjust the airflow rate and nozzle flow rate in real time by detecting the canopy volume of fruit trees so that they can realize the profiling variable application according to the canopy information. The results show that the minimum number of droplets on the left and right sides of apple trees was 46.2 droplets/cm^2, which meets the requirements of application. The results provide a theoretical and methodological reference for the structural design and performance optimization of precision planting and protection implements. Aljaž et al. [24] designed a variable geometry air-assisted sprayer that can be positioned in real time for orchard sprayers, where the nozzles of the profiling spraying device are in the optimal position. To design a real-time adjustable application altitude and spray distance of the profiling spray mechanism, through mathematical modeling and software optimization, the researchers derived kinematic equations of the spraying point. The results show that the average value of the profiling spray droplet coverage reached 43.85%.

3.4. Target Variable Spraying Technology

Variable spraying has received more attention in recent years as one of the means to realize a precise application. Figure 7 shows the working principle of the target sprayer, which obtains relevant information about the target crop, such as the fruit tree pest area, crop row spacing, plant density, and other target crops through sensors, as well as real-time acquisition of relevant information about application parameters such as the position of the application equipment, application rate, and spray pressure. Then, the sprayer comprehensively handles all kinds of information about the crop and spraying device to realize the precise application of target crops according to the demand [65–67]. Compared with the traditional large airflow spraying technology, variable spraying technology can alleviate the problem of pesticide overuse, save pesticides while reducing the risk of drift in the spraying process, improve pesticide prevention and control efficiency, save labor and application costs, and promote the sustainable development of agriculture [68–70]. Table 2 shows the principle of target detection technology and its advantages and disadvantages, and Table 3 shows the variable control system and its operational effects.

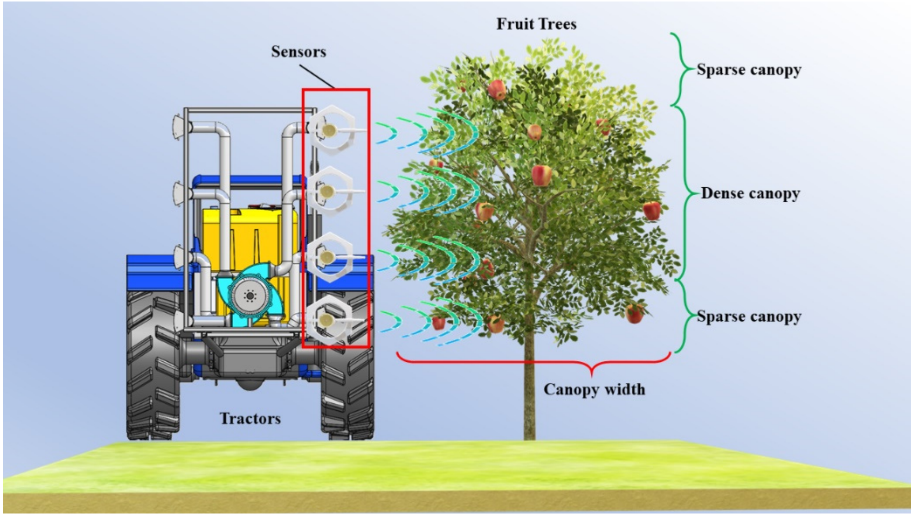


Figure 7. Working principle of operation of a target variable sprayer [65,68,70].

Table 2. Principles of target detection techniques and their advantages and disadvantages.

Detection Technology	Measuring Principle	Specificities
Ultrasonic sensing method [71]	Judge the existence and position of the target according to the ultrasonic propagation speed and the round-trip flight time between the launching point and the launching target, and then calculate the spraying distance.	Measurement accuracy of 10 mm and cost effective, but the response time is longer, achieving a distance of not less than 30 cm [72].
Laser sensing method [73]	Judge the existence and position of the target by laser irradiation or scanning a measurement area, obtain the distance and relative angle between the target point and the sensor, and process and model these distance point cloud data to determine the position and shape of the target.	Measurement accuracy of 10 mm and recognition spacing of 2 cm can be used to obtain 3D images of the canopy, but the price is high and the working environment is more demanding [74]. It is not suitable for use in foggy or humid environments.
Machine vision method [75]	Use a binocular digital camera to obtain the image of the tree crown and the parameter information such as the volume of the tree crown through the image-processing algorithm.	Can be used to obtain 3D images of the canopy but has high ambient light requirements and is not suitable for measuring thicker canopies.
Infrared sensing method [76]	Use an infrared photoelectric detector to emit and receive reflected infrared rays to the crop, determine the target position, and then transmit signals to the control system to control the corresponding spray nozzle spraying operation.	Cost effective and fast response speed, but the detection distance is close and the ambient light requirements are high.

Table 3. Variable control systems and their operational effects.

Control System	Principle	Effect
Spray volume control system [77]	Spray volume regulation through pressure flow regulation, variable nozzle flow regulation, PWM flow regulation, and other technologies.	Effective, flow detection error within 0.05 L/min range.
Airflow rate control system [73]	Adjusting the fan speed to change the spray air velocity, thus realizing the spray airflow rate adjustment.	Owing to the long response time and difficulty in controlling the airflow distribution of high-speed fans to adjust to changes in canopy structure, current research has mainly focused on changing the form of the airflow path to match the airflow distribution with a specific canopy.

Drift during spraying cannot be completely eliminated by plant protection sprayers, but it can be reduced by developing new techniques [78–80]. For example, Bayat et al. [81] designed and developed a novel servo-controlled spraying system, which can change the nozzle's directional angle in real time and automatically, opposite to the direction of the airflow, to minimize ground spray drift. Salcedo et al. [82] used a 3D ultrasonic anemometer to dynamically assess the airflow produced by an axial fan airflow delivery system. Studying the interaction of airflow rate with canopy and ambient airflow, predicting the trend of airflow attenuation within the canopy [83], and adjusting the spray angle in real time can ensure the effectiveness of plant protection application without negatively affecting the environment.

Variable spraying is an efficient application technique recommended by the Food and Agriculture Organization of the United Nations, which can effectively improve the deposit rate in the canopy and reduce drift. Aiming at the difficulty of modeling airflow in the canopy of fruit trees and the lack of airflow control models, Gu et al. [84,85] investigated airflow loss modeling in the canopy of fruit trees. Sensors were utilized to measure the number of leaves in the target canopy, and the spray volume was controlled according to the canopy consistency, which could ensure uniform spraying of canopies of different sizes and densities [86]. Moreover, Ryszard et al. [87] designed a variable air-assisted system, which was able to continuously adjust the airflow rate and spraying system in real time, and the targeted airflow adjustments significantly reduced the amount of drifting. Similarly, Dou et al. [88] evaluated the performance of spraying systems with laser and ultrasonic sensors, and the results show that both targeted spraying systems were effective in reducing ground deposition and off-target deposition, with photoelectric (trunk) and ultrasonic (canopy) directed spraying reducing ground deposition on young trees by 50.63% and 38.74%, respectively. Overall, research on variable sprayers for orchards has generally focused on the modular addition of variable spray systems to existing sprayers. At present, orchard variable sprayers have achieved industrialized development and small-scale application in some countries and regions in Europe and America.

Gil et al. [89] integrated the variable spraying system into the LE-600 sprayer produced by HARDI. The variable spraying system reduced overspray and 22% of application cost. Overall, the research on variable sprayers for orchards is generally fused through the modular addition of variable spraying systems to established sprayers. At present, the orchard variable spray machine in Europe and the United States in some countries and regions has achieved industrial development and small-scale application. However, the relevant experimental research on precision variable spraying is based on an ideal environment due to the complexity of field application, jagged fruit tree canopies, and interactive overlap. Thus, precision spraying technology is still in the theoretical research stage. The reliability of target detection, stability, and other deficiencies presents challenges to the realization of real-time precision sprayer adjustment, which can serve as future research directions.

3.5. Plant Protection UAVs

Compared with the ground plant protection machinery, plant protection UAV has become an important plant protection machine due to its good adaptability to complex terrain, not restricted by fields and other limitations. However, in the plant protection operation, the researchers found that the problem of drift is very serious. To reduce the environmental pollution caused by spray drift and improve the spray efficiency of orchard, the researchers carried out a series of researches from the aspects of nano-pesticide, spray adjuvants, nozzles, rotor wind field and operation parameters, etc., respectively [90–92].

To reduce the pollution of pesticides to the environment and enhance the efficacy of pesticide control, researchers have developed nano-pesticides in combination with nanotechnology. Polymer-based formulations have received the greatest attention, followed by formulations containing inorganic nano-particles and nano-emulsions [93]. Nano-pesticides can be used to combat pest resistance and can be targeted against a specific organism [94,95]. Nano-pesticides also increase toxicity to target organisms and improve the selectivity of pesticides to organisms [96], and have better penetration, adhesion, and degradation capabilities [97]. It can reduce the impact of pesticides on the environment, contribute to the protection of the environment, and provide a new solution to improve the efficiency of pesticides [98].

However, Gao et al. found that nano-pesticides are characterized by smaller droplets size, higher permeability, and higher utilization compared to traditional pesticides [99]. Minor droplets are more likely to be affected by environmental airflow, which puts higher requirements on spraying technology. Therefore, researchers need to combine nano-pesticides with anti-drift technologies to reduce spray drift.

The nozzle types and spray adjuvants can affect the droplet particle diameter, which is the main sector of the UAV plant protection operation of the droplet deposition efficiency, because the minor droplets are more sensitive to the environmental airflow and rotor wind field. To reduce the quantity of minor particles sprayed from the nozzle per unit time and reduce the quantity of spray drift, the researchers designed two methods:

Researchers have developed anti-drift nozzles. US Lechler produced anti-drift nozzle AD, wherein after the relevant spray test, the detected droplet diameter spectrum is narrower than the standard nozzle. Guo et al. [100] utilized the Venturi principle to design anti-drift nozzle (IDK), which showed that the spray drift was significantly lower than the conventional nozzle, and improved droplet penetration in the canopy.

Pesticide adjuvants can change the properties of the liquid, and provide new ideas for reducing spray drift [101]. Some researchers have found that the addition of methylated [102], mineral oil [103], non-ionic adjuvants [104], normaton [105], emulsion [106], and other adjuvants to the liquid can reduce the proportion of minor droplets that are easy to drift, improve the distribution of droplet diameter, and increase the amount of droplet deposition, which has a significant effect on the reduction in pesticide pollution.

Rotor wind field is one of the major factors affecting the effect of deposition. During the operation of multi-rotor and single-rotor UAVs, the wind field has an impact on spray drift [107]. Zhang et al. [108] found that the direction of UAV operation parallel to the airflow direction of environment can effectively reduce the amount of spray drift. Chen et al. [109] found that the airflow field below the rotor has a significant impact on the droplet deposition and spray drift.

In terms of operational parameters, some researchers have designed UAV spraying experiments, and the results show that plant protection UAV has the optimal operating height range [110], the optimal operating velocity range [111], and the droplet deposition density will be significantly reduced when it exceeds or is lower than the optimal range. For the application parameters, choosing the appropriate spray pressure [112] and flight altitude [113] can significantly reduce the amount of spray drift. It can be found that the application parameters of plant protection UAVs are important factors affecting the effect of droplet deposition, and selection of the optimal operating parameters is of great significance in achieving the optimal plant protection efficiency. Some scholars have researched the nozzle, adjuvant, rotor wind field, and operational parameters of plant protection UAVs, and found that plant protection UAV can meet the demand of orchard plant protection, but the problems of spray drift and uneven distribution of droplets need to be further solved.

4. Summary and Future Scope

Since the start of the 21st century, people's awareness of environmental protection has increased, and several scholars have carried out research on how to reduce the amount of pesticide application and improve the level of plant protection technology. From the above literature analysis, it can be seen that although a large amount of research results are available, a large gap exists between current orchard spraying technology and equipment and the requirements of precision spraying.

One of the reasons is that the orchard sprayer anti-drift nozzle research is less. To reduce the amount of spray drift, researchers should research anti-drift nozzle, optimize the particle size distribution of droplets, reduce the proportion of small droplets in the droplet size spectrum, and should give priority to the development of the nozzle with which it is suitable for different operating environments. Adjuvant can change the physical and chemical properties of the liquid [95]. In the spraying process, anti-drift nozzle can more effectively reduce the drift and evaporation [114–116], and can increase the effective deposition of droplets [117]. However, the current research on adjuvant has mainly focused on the development of pesticides and on UAV plant protection application. Thus, the interaction between pesticide adjuvant and spray nozzles and application parameters can be investigated for air-assisted sprayers in the future.

In the orchard plant protection application, the trail of the droplets is easily affected by the ambient airflow, and the droplets will produce vertical drift. To solve this problem, researchers have utilized the air-assisted spraying technology or adjusted the application parameters to weaken the influence of the ambient airflow on the droplets' movement, but the effect of the drift reduction is not satisfactory. In field plant protection applications, some researchers have utilized mechanical or air-assisted shields to reduce drift [118–120]. This approach should also be applied to orchard plant protection applications and develop positive air-assisted anti-drift technologies for orchards. The phenomenon of horizontal drift is also serious, and researchers utilize recycling spraying technology, electrostatic spraying technology, profiling spraying technology, and variable spraying technology to reduce the spray drift, but they have their own limitations. Recycling sprayers are poorly adapted and are mainly suitable for specific dwarf plantations, and researchers need to develop spraying equipment suitable for different crops. Some researchers discovered that electrostatic spraying technology can increase the attraction of droplets to the canopy and reduce the horizontal drift [121–124]. But, salcedo et al. [125] demonstrated that the anti-drift effect of electrostatic spraying technology is not significant. Therefore, researchers need to explore the interaction between the electrostatic field and the droplet airflow field, and design relevant experiments to study the deposition characteristics of droplets and the anti-drift effect of electrostatic spraying.

The profiling sprayer achieves the envelope of the fruit tree canopy by adjusting the positions of multiple spray units, but the level of profiling still has a large amount of space for improvement, and the researchers should combine the online detection technology and variable spraying technology to design a sprayer that can change the position in real time and automatically adjust the parameters of the application, and ultimately achieve the uniform envelope of the canopy of the fruit tree, which can significantly reduce spray drift. In consideration of the development of targeted variable spraying technology and online detection of leaf density, the degree of pests and diseases should be developed in the future to realize automation, intelligence, and precision. According to the feedback signal obtained from the detection, the variable spraying system should be designed to adjust the spraying pressure and the rate of airflow in real time, in order to obtain the application parameters that match the real-time environmental parameters and the characteristics of the canopy, and to minimize the quantity of drift. Considering the limitations of the above spraying technologies, we believe that we should combine the air-assisted spraying technology, the profiling spraying technology, and the variable spraying technology to design an anti-drift sprayer which can guarantee the effectiveness of plant protection while reducing the pollution to the environment.

To enhance the effect of UAV plant protection, most of the current research is focused on the optimization of UAV operation and application parameters, which can reduce the drift, but the influence of environmental airflow on the movement of droplets is still relatively serious. Researchers should develop a category of nano-pesticides that are highly bio-selective, as well as a technology to synthesize nano-pesticides in large quantities with low cost and high efficiency, and combined with anti-drift spraying techniques to reduce spray drift. Researchers should combine online detection technology to detect real-time environmental parameters, establish mathematical modeling of spray drift paths, and adjust the UAV operation path in real time according to the drift distance. Moreover, it is essential to study the UAV variable spraying technology. The continuous upgrading of the orchard anti-drift spraying strategy can reduce the quantity of spray drift, which has a profound impact on the development of modern precision agriculture.

Author Contributions: Conceptualization, J.L. and X.Y.; methodology, J.L. and X.Y.; software, S.L., P.W. and H.L.; formal analysis, S.L., J.L., X.Y. and P.W.; investigation, S.L. and J.L.; resources, J.L., X.Y. and P.W.; writing—original draft preparation, S.Y. and J.L.; writing—review and editing, J.L. and S.L.; visualization, S.L., X.Y., P.W. and J.L.; supervision, P.W. and J.L.; project administration, P.W. and J.L.; funding acquisition, P.W. and J.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by grants from the Earmarked Fund for Hebei Apple Innovation Team of Modern Agro-industry Technology Research System (No. HBCT2023120202) and Earmarked fund for CARS: (No. CARS-27).

Data Availability Statement: Not applicable.

Acknowledgments: Thanks to Zhang Kuo and Liu Shuteng for their assistance in the literature search.

Conflicts of Interest: The authors declare no conflict of interest.

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