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PRECISION SPRAYING IN ORCHARD CROPS: FROM CANOPY PERCEPTION TO CROP PROTECTION OUTCOMES - A CRITICAL REVIEW AND INTEGRATED FRAMEWORK

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Abstract
Precision spraying is increasingly being developed to address the limitations of uniform-rate pesticide application in orchard crops, where substantial spatial variation in canopy structure can lead to excessive application, inadequate deposition and off-target losses. This review critically examines the transition from conventional orchard spraying toward canopy-responsive precision spraying, with emphasis on the complete pathway from canopy sensing to crop-protection outcomes. Technologies including ultrasonic sensors, LiDAR, RGB/RGB-D vision, multispectral sensing and artificial intelligence are evaluated for their ability to characterize canopy size, density and three-dimensional structure. The review further examines how canopy information is converted into spray prescriptions through variable-rate strategies, including flow regulation, pulse-width modulation, solenoid-valve control and spatial prescription mapping. Particular attention is given to the interaction between spray-rate adjustment, droplet deposition, coverage, drift and biological efficacy, highlighting that pesticide-volume reduction alone is insufficient to demonstrate successful precision crop protection. Recent developments in intelligent, autonomous and UAV-based spraying are also assessed alongside their environmental, energy and economic implications. A cross-study synthesis identifies persistent gaps in sensor generalization, canopy-to-spray modelling, sensing-to-actuation synchronization, standardized performance assessment and biological validation. Based on these findings, a Canopy-to-Crop-Protection (C2CP) framework is proposed, linking canopy perception, canopy interpretation, spray prescription, real-time execution, deposition assessment and biological feedback. The framework provides a system-level perspective for developing precision spraying technologies that deliver the required crop protection while minimizing unnecessary pesticide use and off-target losses.

Keywords
Precision spraying; Orchard crops; Canopy sensing; Variable-rate application; Spray deposition; Intelligent crop protection

1.Introduction

Orchard crop protection necessitates the effective application of plant protection products (PPPs) to canopies that are both structurally complex and spatially variable. Unlike the uniformity of field crops, orchard trees exhibit significant differences in canopy height, width, density, porosity, and internal structure, both between individual trees and within a single tree (Mahmud et al., 2021; Y. Wang et al., 2025). Standard spraying systems typically employ fixed settings, failing to adequately address this inherent variability. This mismatch can lead to over-application in sparser canopy areas, insufficient deposition in denser regions, and increased off-target losses due to drift and ground deposition (Mahmud et al., 2021; Y. Wang et al., 2025; Wu et al., n.d.). Consequently, there has been a drive towards developing precision and variable-rate spraying systems that adjust application based on crop and environmental conditions (Mahmud et al., 2021; Y. Wang et al., 2025).

The evolution of precision orchard spraying has progressively integrated canopy sensing, variable-rate control, and automation. Technologies such as ultrasonic sensors, LiDAR, and machine vision have been explored for estimating canopy characteristics to guide spray-rate adjustments (Mahmud et al., 2021; Y. Wang et al., 2025). More recent advancements incorporate artificial intelligence, three-dimensional perception, and real-time control to enhance canopy characterization and spatially responsive application (Y. Wang et al., 2025; Wu et al., n.d.). However, the utility of any sensing technology is contingent upon the subsequent spray-control process. The practical impact hinges on the accuracy of translating canopy information into spray decisions, the responsiveness of the spraying system, and the achievement of adequate droplet deposition on the biological target (Y. Wang et al., 2025; Wu et al., n.d.).

Existing reviews have addressed specific aspects of this field. Earlier work focused on sensing-based PPP application and canopy characterization (Mahmud et al., 2021), followed by reviews on variable-rate spraying technologies, automatic spraying systems, and key detection and control technologies (Wu et al., n.d.). More

recently, research has concentrated on orchard canopy perception, environmental sensing, and variable-rate spraying utilizing LiDAR, vision sensors, multimodal sensing, and intelligent control (Y. Wang et al., 2025; Wu et al., n.d.). While these contributions highlight substantial technological progress, they also indicate a dispersal of literature across sensing, modeling, control, and spraying domains.

The fundamental challenge lies not merely in detecting a canopy, but in effectively converting canopy information into successful crop protection. Increased canopy detection accuracy does not automatically ensure improved deposition, nor does a reduction in spray volume necessarily signify enhanced biological performance. Therefore, the interrelationships among canopy characterization, spray-rate determination, actuator response, droplet transport, deposition, and crop-protection efficacy require integrated evaluation (Y. Wang et al., 2025; Wu et al., n.d.). This distinction is particularly pertinent given ongoing research that continues to identify challenges related to real-time performance, model generalizability, seasonal variability, and the integration of canopy perception with closed-loop spray control (Y. Wang et al., 2025; Wu et al., n.d.).

Consequently, this review offers a critical synthesis of precision orchard spraying, examining the entire pathway from canopy information acquisition to the crop-protection outcome. Instead of treating sensing, variable-rate control, automation, and spraying performance as separate technological categories, this review investigates information transfer between these stages, identifies sources of uncertainty, and analyzes their ultimate impact on spray deposition and application effectiveness. Evidence is compared across various sensing and characterization approaches, spray-decision strategies, control and actuation technologies, droplet transport and deposition, and crop-protection performance. This cross-stage synthesis aims to identify unresolved research gaps and propose priorities for developing precision spraying systems that are not only sensor-accurate but also responsive, deposition-effective, and biologically meaningful.

2. Methodology

2.1. Literature search

A literature search was carried out in an organised manner to find out about precision spraying technologies as applied to orchard crops. Peer-reviewed publications were located using Google Scholar, Scopus and Web of Science. The search was concentrated on studies concerning precision spraying, variable-rate application, canopy sensing, automated spray control and new technologies for the protection of orchard crops. The main search terms used were "precision spraying", "orchard sprayers", "variable-rate spraying", "sensor-based spraying", "LiDAR in agriculture" and "UAV spraying in orchards". Further relevant studies were found by looking at the reference lists of the publications that had been selected.

2.2. Inclusion and exclusion criteria

Studies were selected on the basis of their relevance to precision spraying in orchard crops. The inclusion criteria were peer-reviewed research articles, case studies and review articles published mainly in the last decade that addressed one or more of the following: sensing technologies, canopy characterization, variable-rate application, spray-control systems, automation, application performance, pesticide-use efficiency or environmental sustainability.

Studies that were only focused on field crops that were not relevant to orchard spraying, did not involve precision or technology-assisted spraying, did not have sufficient technical or experimental information to allow for meaningful comparison, or were duplicate publications were excluded. Publications were excluded due to lack of information relevant to the technological development or performance of precision spraying systems.

2.3. Data extraction and synthesis

Data from the selected literature were extracted and organized by the major components of precision orchard spraying. The following data was considered:

- Classification and types of spray technologies • Measured canopy characteristics and sensing technologies
- Spray decisions and control strategies
- Variable rate application & automation.
- Spray deposition, coverage, efficiency and drift
- Water and energy use, pesticide
- Ecological impact
- Technology limitations
- Future research needs

The extracted information was synthesized into the progression from canopy sensing and characterization to spray-rate determination, spray control and application performance. Special attention was given to understanding relationships between canopy information and spray response.

2.4. Comparative analysis

The selected studies were compared on a relative basis considering the reported features and performance of precision spraying systems. The comparison included spray efficiency and uniformity, drift reduction, pesticide use efficiency, time and energy requirements, degree of automation, adaptability to canopy variability and practical field applicability. In cases where quantitative results were available, the reported values were compared in the light of the experimental conditions used in each study. Variations in crop, canopy structure, sprayer configuration, operating conditions and evaluation methods may influence performance and therefore reported values were not interpreted as performance ranges universally applicable.

3. Canopy Sensing and Characterization for Precision Spraying

Orchard canopy structure serves as the primary data source for variable-rate spraying systems, dictating where and how much spray to apply. Parameters such as canopy height, width, volume, density, porosity, and leaf area provide varying representations of target size and structure (Rosell & Sanz, 2012; Sultan Mahmud, Zahid, He, Choi, Krawczyk, Zhu, et al., 2021; Y. Wang et al., 2025). However, these parameters are not equally indicative of spray requirements. A sensing system may accurately describe canopy geometry while offering limited insight into leaf density, internal structure, or plant health (Sultan Mahmud, Zahid, He, Choi, Krawczyk, Zhu, et al., 2021; Y. Wang et al., 2025). Thus, the suitability of a sensing technology should be evaluated not only by its measurement accuracy but also by its capacity to yield information that can be translated into appropriate spray decisions (Y. Wang et al., 2025; Wu et al., n.d.).

3.1. Ultrasonic sensing

Ultrasonic sensors measure target distance by analyzing the propagation time of emitted acoustic waves. They have been investigated for estimating orchard canopy dimensions and density. Their relatively low cost, simple operation, and direct distance measurement make them appealing for practical variable-rate sprayers (Li et al., 2016; Maghsoudi et al., 2015). Early variable-rate systems in orchards utilized ultrasonic measurements to characterize canopy presence and size, subsequently adjusting spray output based on spatial canopy variations (Maghsoudi et al., 2015; Solanelles et al., 2006). However, ultrasonic sensing provides limited structural detail as the measurement reflects the interaction of the acoustic signal with the canopy rather than a detailed three-dimensional reconstruction. Leaf arrangement, branches, gaps within the canopy, and environmental conditions can influence the measured distance (Li et al., 2016; Maghsoudi et al., 2015). Consequently, while ultrasonic sensing can be effective for basic canopy-density estimation, its informativeness diminishes when detailed canopy geometry or internal structure is required (Maghsoudi et al., 2015; Y. Wang et al., 2025).

3.2. LiDAR-based sensing

LiDAR generates three-dimensional point-cloud data by measuring the return time of laser pulses, making it well-suited for characterizing complex orchard structures. It can provide data on canopy height, width, volume, porosity, and spatial distribution, useful for translating heterogeneous canopy structures into spatially variable spray requirements (Rosell et al., 2009; Sultan Mahmud, Zahid, He, Choi, Krawczyk, Zhu, et al., 2021; Y. Wang et al., 2025). A significant advantage of LiDAR over passive vision systems is its reduced dependence on ambient illumination for ranging (Y. Wang et al., 2025). The primary benefit of LiDAR is its ability to represent the three-dimensional geometry of the spray target, rather than solely its measurement accuracy. Nevertheless, acquiring high-resolution point clouds demands substantial computational resources, and occlusion within dense foliage can prevent a complete representation of internal canopy regions (Sultan Mahmud, Zahid, He, Choi, Krawczyk, Zhu, et al., 2021; Y. Wang et al., 2025). Recent research also highlights an ongoing trade-off between canopy model accuracy, processing speed, generalizability, and real-time implementation (Y. Wang et al., 2025). LiDAR-based sensing facilitates the three-dimensional characterization of orchard canopies by producing spatial point clouds. These can be further processed to estimate canopy structure and foliage density (Baltazar et al., 2023; Sultan Mahmud, Zahid, He, Choi, Krawczyk, Zhu, et al., 2021). The acquired point-cloud data can be segmented into spatial regions and converted into canopy foliage-density maps, providing information on the spatial heterogeneity of foliage within a tree (Sultan Mahmud, Zahid, He, Choi, Krawczyk, Zhu, et al., 2021). An illustration of the experimental setup, point-cloud processing, and resulting canopy foliage-density maps is provided in Fig. 1 (Y. Wang et al., 2025).

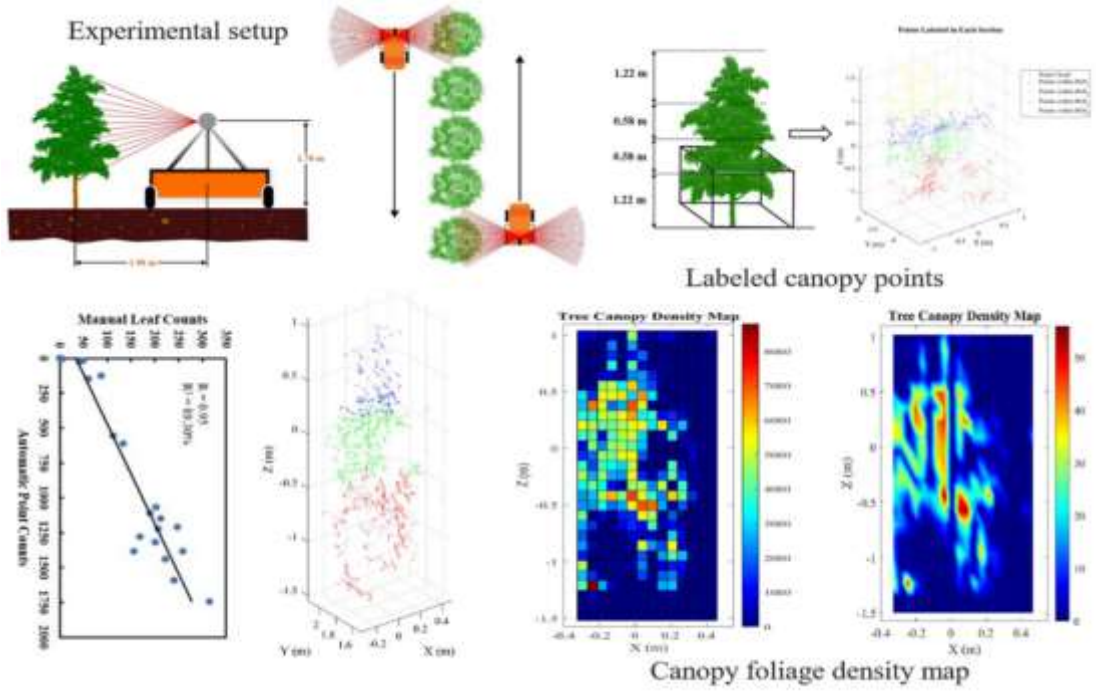


Fig. 1. LiDAR-based acquisition and characterization of orchard canopy structure and foliage-density distribution.

This spatially resolved canopy information forms the basis for adapting spray application to variations in canopy structure, rather than applying a uniform spray rate across the entire tree (Hu et al., 2025; Sultan Mahmud, Zahid, He, Choi, Krawczyk, Zhu, et al., 2021).

3.3. Machine vision and RGB-D sensing

RGB-based vision systems capture colour, texture, and spatial information, which can be used for canopy segmentation and target detection. Their relatively low cost and compatibility with deep learning algorithms have increased their appeal for orchard applications (Y. Wang et al., 2025). RGB-D systems add a depth channel, enabling the combination of two-dimensional canopy segmentation with distance information for three-dimensional characterization (Y. Wang et al., 2025; R. Zhang et al., 2023). Compared to LiDAR, vision-based systems offer richer spectral and visual information at a lower hardware cost. However, their performance is more susceptible to variations in illumination, shadows, occlusion, and changes in canopy appearance (Y. Wang et al., 2025). While deep learning models can improve segmentation and object detection, their effectiveness may decrease when training and deployment conditions differ in cultivar, growth stage, illumination, or orchard architecture (Y. Wang et al., 2025; R. Zhang et al., 2023). Consequently, recent reviews identify generalizability and seasonal adaptability as significant unresolved issues in vision-based canopy perception (Y. Wang et al., 2025).

3.4. Multispectral and multimodal sensing

Multispectral and hyperspectral sensors extend canopy perception beyond geometric characteristics by providing data related to plant physiological condition and stress (Y. Wang et al., 2025; Wu et al., n.d.). This capability allows for the differentiation of areas requiring different treatments, potentially supporting disease- or stress-specific spraying strategies beyond simple canopy size assessments (Wu et al., n.d.). Multimodal sensing integrates complementary information from multiple sensors, such as LiDAR, RGB/RGB-D, and multispectral sensors. The primary advantage lies in information complementarity: LiDAR defines three-dimensional structure, while vision and spectral sensors provide surface and physiological data (Y. Wang et al., 2025; Wu et al., n.d.). However, sensor fusion increases system complexity, calibration requirements, computational demands, and cost (Y. Wang et al., 2025). Current literature consequently highlights multimodal fusion as promising while acknowledging real-time processing and robust integration as ongoing challenges (Y. Wang et al., 2025; Wu et al., n.d.).

3.5. Critical synthesis of canopy sensing

The existing literature indicates that no single sensing technology can provide all the necessary information for precision spraying. Ultrasonic sensors offer simplicity and low cost but limited structural detail; LiDAR delivers detailed three-dimensional geometry but incurs higher hardware and computational expenses; RGB/RGB-D vision provides valuable visual information and supports AI-based segmentation but is more sensitive to environmental conditions; and multispectral sensing can offer physiological insights but adds system complexity (Maghsoudi et al., 2015; Sultan Mahmud, Zahid, He, Choi, Krawczyk, Zhu, et al., 2021; Y. Wang et al., 2025; Wu et al., n.d.). Therefore, sensor selection should be guided by the information required for subsequent spray decisions, rather than solely by sensor accuracy. This distinction is fundamental for the next stage of the precision-spraying process: determining how measured canopy characteristics are translated into spray rate, nozzle

operation, and application decisions. The limitations of individual sensing technologies are summarized in Table 1

Table 1. Limitations of individual sensing technologies

Category	Sub-type	Principle	Key components	Advantages	Limitations	References
Based on control strategy	Constant-rate spraying	Uniform application	Pump, nozzle	Simple, low cost	High chemical wastage	(Matthews, 2000; Sims & Kienzle, 2017)
	Variable-rate spraying (VRT)	Adjusts spray based on canopy	Sensors, ECU, valves	Input savings, better targeting	Requires calibration	(Gil et al., 2013; Luo et al., 2025)
Based on sensing technology	Ultrasonic-based	Distance measurement	Ultrasonic sensors	Low cost, simple	Low resolution	(Gil et al., 2007a)
	LiDAR-based	3D canopy mapping	LiDAR, controller	High accuracy	Expensive	(G. Wang et al., 2025; C. Zhang et al., 2025)
	Vision-based	Image processing	Cameras, AI models	Selective spraying	Sensitive to lighting	(Luo et al., 2025)
Based on platform	Ground-based sprayers	Tractor-mounted/self-propelled	Boom/air-blast	High coverage	Soil compaction	(Matthews, 2000; Sims & Kienzle, 2017)
	UAV sprayers	Aerial spraying	Drone, tank, GPS	Flexible, fast	Limited payload	(Y. Huang et al., 2014; S. Jiang et al., 2026)
Based on automation	Manual	Operator controlled	Basic sprayer	Low cost	Low efficiency	(Matthews, 2000)
	Semi-automatic	Sensor-assisted	ECU, sensors	Moderate efficiency	Operator needed	(Gil et al., 2014)
	Autonomous	Fully automated	AI, robotics	High precision	High cost	(Bechar & Vigneault, 2016)

4. From Canopy Information to Spray-Rate Decisions

The primary objective of canopy sensing in precision spraying is not merely to measure tree structure but to convert spatial canopy information into an appropriate spray requirement. Conventional orchard spraying typically applies a relatively uniform rate across the tree row, despite significant variations in canopy volume and density. Variable-rate systems address this discrepancy by correlating measured canopy characteristics with spray volume, flow rate, or nozzle operation (Escolà et al., 2013; Sultan Mahmud, Zahid, He, Choi, Krawczyk, Zhu, et al., 2021; Y. Wang et al., 2025). Early variable-rate systems in orchards demonstrated this principle by using LiDAR-derived canopy measurements to calculate real-time target flow rates. (Escolà et al., 2013) reported a strong correlation between canopy measurements and required spray flow rate, showing that the variable-rate system could adapt application based on canopy characteristics. More recent LiDAR-based systems have expanded on this by employing three-dimensional canopy information to determine spatially variable spray requirements (Sultan Mahmud, Zahid, He, Choi, Krawczyk, Zhu, et al., 2021; C. Zhang et al., 2025). Three-dimensional canopy characterization can also inform the spatial distribution of spraying units and regulate spray delivery according to canopy structure. By dividing the canopy into vertical or spatial layers, the spraying system can associate different canopy regions with corresponding nozzle positions and application needs (Hu et al., 2025; Y. Wang et al., 2025). Point-cloud information can subsequently be used to optimize the operational parameters of individual spraying units, as depicted in Fig. 2 (Y. Wang et al., 2025).

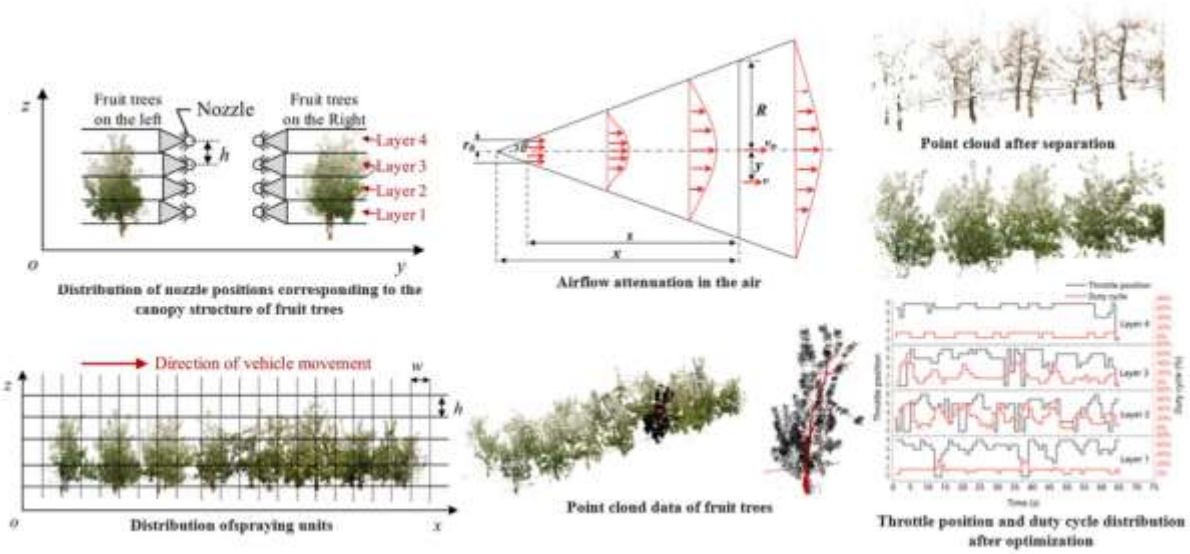


Fig. 2. Conversion of three-dimensional canopy information into spatial spray-unit distribution and variable-rate control.

This approach signifies a crucial shift from mere canopy detection to canopy-informed spray decision-making, as sensing information is directly integrated into the spatial distribution and intensity of spray application (Hu et al., 2025; Y. Wang et al., 2025).

4.1. Canopy volume as a spray-decision parameter

Canopy volume is a widely studied parameter for determining spatially variable spray requirements, offering a geometric representation of the vegetation within a given area (Rosell & Sanz, 2012; Sultan Mahmud, Zahid, He, Choi, Krawczyk, Zhu, et al., 2021). Variable-rate algorithms can combine canopy volume with an application coefficient to estimate the necessary liquid volume for individual canopy sections (Escolà et al., 2013; Sultan Mahmud, Zahid, He, Choi, Krawczyk, Zhu, et al., 2021). However, canopy volume does not directly represent leaf area, foliage density, or the distribution of spray targets within the canopy. Consequently, two canopy regions with similar volumes might possess different foliage densities, leading to differing deposition requirements (Sultan Mahmud, Zahid, He, Choi, Krawczyk, Zhu, et al., 2021; Y. Wang et al., 2025). This limitation suggests that canopy volume should be considered a useful geometric input rather than a complete representation of spray needs. Recent studies illustrate this progression. LiDAR-based systems increasingly utilize three-dimensional canopy data to establish spatially variable spray rates, while newer methods incorporate canopy partitioning and prescription-map-based control to improve the spatial alignment between canopy structure and nozzle operation (Hu et al., 2025; C. Zhang et al., 2025).

4.2. Beyond canopy volume: density and leaf-area information

Canopy density and leaf-area-related parameters can provide supplementary information when canopy volume alone is insufficient. Recent investigations have explored foliage area volume density (FAVD), leaf area, and canopy thickness as decision variables for variable-rate spraying (S. Jiang et al., 2025; Sultan Mahmud, Zahid, He, Choi, Krawczyk, Zhu, et al., 2021). Density-based information can differentiate between canopy regions that share similar external dimensions but vary in foliage quantity. This has the potential to enhance spray requirement estimations and reduce discrepancies between geometric canopy measurements and actual target surfaces (Sultan Mahmud, Zahid, He, Choi, Krawczyk, Zhu, et al., 2021). Nevertheless, the relationship between a measured canopy parameter and the optimal spray requirement remains dependent on crop type, canopy architecture, nozzle characteristics, and operating conditions (Rosell & Sanz, 2012; Y. Wang et al., 2025). The major approaches used to convert canopy information into spray requirements are summarized in **Table 2**.

Table 2. Sensing technologies used for orchard canopy characterization and precision spray decision-making.

Sensor type	Working principle	Application	Accuracy	Cost level	Advantages	Limitations	References
Ultrasonic	Time-of-flight of sound waves	Canopy detection	Moderate	Low	Simple, robust	Low resolution	(Gil et al., 2007a; Schumann & Zaman, 2005)

LiDAR	Laser distance measurement	3D canopy mapping	High	High	Precise, detailed	Expensive	(Sultan Mahmud, Zahid, He, Choi, Krawczyk, Zhu, et al., 2021; Y. Wang et al., 2025; C. Zhang et al., 2025)
RGB camera	Image capture	Canopy/target detection	Moderate–High	Medium	Widely available	Light sensitivity	(Luo et al., 2025; Raja et al., 2020)
Multispectral camera	Reflectance analysis	Crop health detection	High	High	Disease detection	Complex processing	(Mahlein, 2016)
Thermal sensor	Heat radiation	Stress detection	Moderate	High	Early detection	Environmental influence	(Giménez-Gallego et al., 2023; Islam et al., 2023)
GPS/GNSS	Satellite positioning	Navigation	High	Medium	Accurate positioning	Signal issues	(Yue et al., 2024)

5. Spray-Control and Actuation Technologies for Variable-Rate Application

Once a spray requirement is determined from canopy data, the spraying system must translate this into a controllable liquid output. The primary control methods employed in orchard precision spraying include pulse-width modulation (PWM), solenoid valve control, pressure regulation, proportional flow control, and combinations thereof (Escolà et al., 2013; Mercaldi et al., 2017). Their efficacy depends on the system's capacity to rapidly modify nozzle output while maintaining predictable hydraulic and spray characteristics (Fabula et al., 2021; Salcedo et al., 2022). Real-time precision spraying necessitates the integration of canopy sensing, signal processing, and spray-actuation components. Sensor data is transmitted to a processing unit, which calculates the spray requirement and generates control signals for individual spraying components. Pressure and flow sensors provide feedback on hydraulic operating conditions, while electronically controlled solenoid valves adjust spray delivery based on the calculated requirement (Mercaldi et al., 2017). An example of an integrated sensing and actuation architecture is presented in Fig. 3 (Zhang et al., 2025)

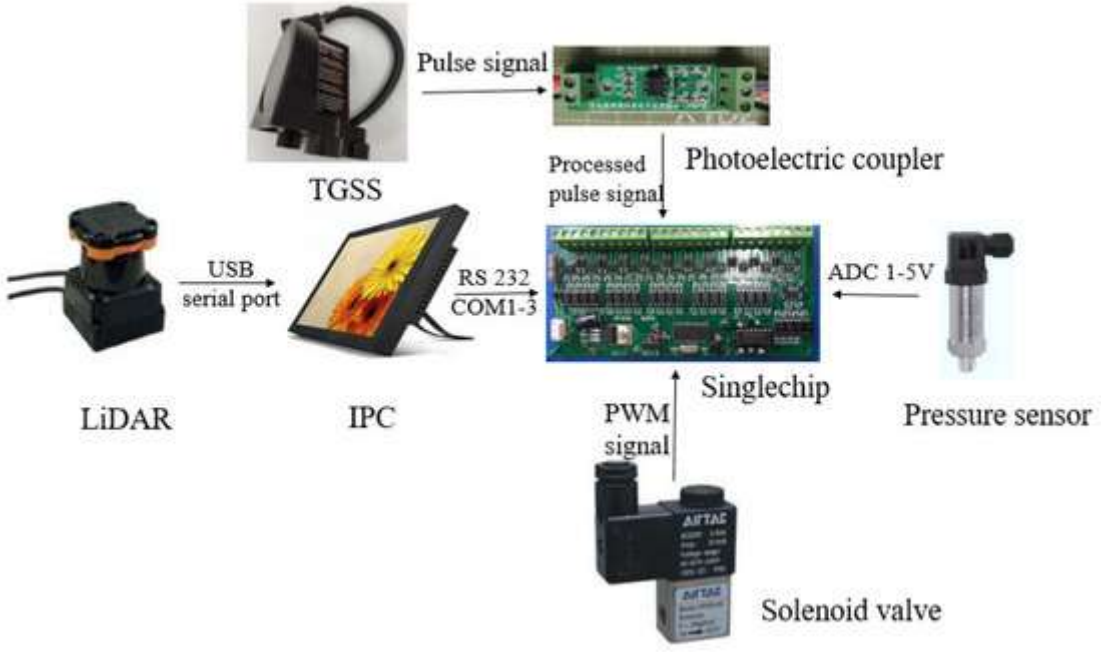


Fig. 3. Integration of canopy sensing, signal processing, pressure measurement and PWM-based solenoid-valve control for precision spraying.

This integration enables the spraying system to adapt to spatial variations in canopy structure by adjusting spray delivery through electronically controlled valves. However, practical performance is influenced by processing

latency, the distance between the sensor and the nozzle, valve response time, hydraulic stability, and synchronization between canopy detection and spray application (Escolà et al., 2013; Mercaldi et al., 2017).

5.1. PWM-based nozzle control

PWM is increasingly adopted for variable-rate spraying, regulating nozzle output by varying the proportion of time a solenoid valve remains open during each control cycle. This approach allows for flow rate modification while maintaining selected operating pressure, making PWM suitable for rapid spatial adjustment of spray output (Giles and Comino, 2009; Fabula et al., 2021). However, the relationship between PWM duty cycle and spray output is not always linear. Experimental characterization of hollow-cone nozzles has shown that flow rate, activation pressure, and activation time are influenced by operating pressure, duty cycle, nozzle configuration, and solenoid valve design (Salcedo et al., 2022). Consequently, accurate variable-rate application requires calibration of the complete valve-nozzle system, rather than relying solely on theoretical duty-cycle relationships (Fabula et al., 2021; Salcedo et al., 2022). Field experiments have demonstrated the potential of PWM-controlled systems for orchard spraying. (Salcedo et al., 2021) compared manual-PWM, laser-guided variable-rate PWM, and conventional constant-rate configurations in a young apple orchard. The laser-guided PWM system achieved more uniform canopy coverage while using significantly less spray volume than the constant-rate configurations. However, the authors emphasized the necessity of biological field evaluation to determine if improved deposition and coverage translate into equivalent pest and disease control (Salcedo et al., 2021). PWM can also impact off-target losses. In a subsequent field study, Salcedo et al. (2021) reported substantially lower airborne and ground losses from PWM-controlled systems compared to the conventional constant-rate configuration in a young apple orchard, indicating that electronic spray control can influence both target application and off-target losses (Salcedo et al., 2021).

5.2. Pressure and flow regulation

Pressure regulation is another method for controlling spray output and is particularly crucial when multiple nozzles are independently switched. Rapid changes in the number of active nozzles can alter hydraulic pressure, thereby affecting nozzle flow rate and droplet characteristics (Fabula et al., 2021). Variable-rate systems have therefore incorporated pressure sensors, flow sensors, proportional valves, and feedback controllers to maintain hydraulic stability under varying spray demands (Luo et al., 2025). A pressure-feedback control system can compensate for pressure fluctuations and sustain the operating conditions necessary for the calibrated relationship between control input and nozzle output (Luo et al., 2025). Consequently, pressure stability is not only a hydraulic requirement but also a prerequisite for predictable variable-rate application. If pressure changes significantly during nozzle switching, the relationship established during calibration between control input and flow rate may become invalid, leading to a discrepancy between the calculated spray requirement and the actual delivered amount (Fabula et al., 2021; Mercaldi et al., 2017).

5.3. Synchronization between sensing and actuation

An additional challenge arises because canopy sensing and spray application do not occur at precisely the same spatial location. The sprayer moves forward while the sensor detects the canopy, processes the information, and generates a control signal. Therefore, the nozzle must be activated after a delay corresponding to the travel speed, sensor-to-nozzle distance, and processing time (Escolà et al., 2013; Mercaldi et al., 2017). This establishes a direct relationship between vehicle speed, sensing distance, and control latency. Even with accurate canopy detection and spray-rate estimation, incorrect timing can misalign the spray pattern with the intended canopy region. Variable-rate systems thus require delay compensation or spatial prediction to synchronize canopy measurements with nozzle operation (Escolà et al., 2013; Hu et al., 2025). This issue becomes increasingly significant as spraying systems operate at higher speeds and employ higher-resolution sensing. The sensing-to-actuation pathway should consequently be evaluated as a spatial control problem, rather than solely a computational one.

5.4. Emerging high-frequency control

Recent research has focused on enhancing the modulation speed and operating range of PWM solenoid valves. Experiments with hollow-cone nozzles have demonstrated that valve design, PWM frequency, duty cycle, and operating pressure can significantly influence the achievable flow-rate modulation range (Salcedo et al., 2022). Other investigations have assessed PWM valves at higher frequencies and pressures to increase the speed of nozzle flow modulation for precision spraying (Campos et al., 2023). The performance of high-frequency PWM systems is therefore dependent on the characteristics of the entire valve-nozzle combination. A higher PWM frequency does not automatically guarantee improved application accuracy if the valve cannot physically respond to the control signal or if hydraulic pressure becomes unstable. Calibration should consequently identify the effective operating frequency and duty-cycle range for the selected hardware (Campos et al., 2023; Salcedo et al., 2022). These developments suggest that future variable-rate sprayers should not assume the actuator to be an ideal component. Valve response time, minimum effective duty cycle, flow nonlinearity, pressure fluctuation, and switching frequency can all affect the accuracy of spray delivery.

6. Spray Deposition, Coverage, and Drift: Linking Precision Control with Crop-Protection Performance

The ultimate goal of precision spraying is not merely to reduce spray volume or enhance canopy detection, but to deliver an adequate quantity of pesticide to the biological target while minimizing losses to non-target areas. Therefore, spray deposition, canopy coverage, and drift should be considered critical performance indicators connecting precision control with crop-protection effectiveness (Gerdan Koc et al., 2025; Gil et al., 2013; Salyani et al., n.d.). Evaluations based solely on pesticide-volume reduction can be misleading if this reduction is

accompanied by inadequate target deposition or increased variability within the canopy (Salcedo et al., 2021; van de Zande et al., 2020). The reported effects of precision spraying on deposition, coverage and off-target losses are compared in Table 3.

Table 3. Variable-rate and intelligent spraying technologies applied in orchard crop protection: operating principles and reported performance.

Performance indicator	Precision-spraying approach	Reported outcome	Main benefit	Reference
Pesticide application	Variable-rate spraying	Reduced application according canopy variability	Reduced unnecessary chemical use	(Mahmud et al., 2021; Nackley et al., 2021)
Spray drift	Targeted/advanced spraying	Reduced off-target losses	Environmental protection	(Gerdan Koc et al., 2025; Otto et al., 2015)
Spray retention	Precision/targeted application	Improved canopy retention reported in some systems	Better target deposition	(Luo et al., 2025)
Fuel consumption	Optimized spraying operations	Reduced operational requirement	Energy saving	(Hołownicki et al., 2017; Llorens et al., 2010)
Water use	Variable-rate application	Application adjusted to canopy requirement	Resource conservation	(Mahmud et al., 2021)
Operator exposure	Targeted application	Lower exposure potential	Improved operator safety	(Kennedy, n.d.)
Carbon/emission impact	Optimized field operation	Potential reduction	Environmental benefit	(Pretty, 2018; Sims & Kienzle, 2017)

6.1. Canopy deposition and coverage

Spray deposition is influenced by canopy architecture, droplet characteristics, spray pressure, nozzle type, air assistance, travel speed, and spray distance (Holownicki et al., 2000; Salyani et al., n.d.; Walklate et al., 2002). Consequently, a reduction in application volume does not automatically signify improved spraying performance. The crucial question is whether the reduced volume maintains sufficient deposition and coverage on the target canopy (Salcedo et al., 2021; van de Zande et al., 2020). Field validation of an ultrasonic-sensor-based variable-rate sprayer in apple orchards underscored the importance of measuring actual canopy deposition rather than evaluating performance solely on calculated spray-volume reduction. The study compared conventional, best-management-practice, and variable-rate spraying across different growth stages, revealing that differences in application rates did not directly translate into proportional differences in normalized deposition (Salas et al., 2025). Similarly, (Salcedo et al., 2021) evaluated conventional and laser-guided PWM-controlled spraying in a young apple orchard. The laser-guided variable-rate system utilized significantly less spray volume while providing more uniform canopy coverage, demonstrating that application reduction can be meaningful when target deposition remains adequate. Earlier work employing ultrasonic sensors in vineyard spraying also indicated that variable-rate application could substantially reduce liquid use while maintaining similar leaf deposition compared to constant-rate application (Gil et al., 2007b). These findings collectively suggest that spray-volume reduction should be interpreted in conjunction with deposition and coverage, rather than treated as an independent measure of spraying success.

6.2. Deposition uniformity within heterogeneous canopies

Uniformity is particularly critical in orchards due to the uneven distribution of foliage in both vertical and horizontal directions. A system may achieve adequate average deposition while still leaving poorly treated regions within the canopy (Salyani et al., n.d.). Therefore, deposition should be assessed across different canopy positions and layers, rather than relying solely on a single average value. Recent variable-rate experiments have increasingly involved spatial deposition assessments. (Whitfield et al., 2025), for instance, compared constant- and variable-rate application in an apple orchard using multiple canopy zones. The variable-rate system reduced deposition variance and established a more consistent relationship between canopy density and deposited spray, highlighting the importance of evaluating spatial variability over mean deposition alone. This leads to a significant distinction between mean deposition and deposition uniformity. A precision sprayer should achieve sufficient deposition across target regions while avoiding excessive deposition in sparse or non-target areas. Consequently, future evaluations should report both average deposition and its spatial variability.

6.3. Spray drift and off-target losses

Spray drift represents a significant pathway through which pesticide application efficiency and environmental performance can be compromised. Droplet size, spray pressure, nozzle characteristics, air assistance, meteorological conditions, and nozzle-to-canopy distance influence droplet transport and the likelihood of droplets leaving the intended target (Gerdan Koc et al., 2025; Otto et al., 2015). Smaller droplets can enhance canopy penetration and coverage under certain conditions, but they may also increase drift potential when environmental and application conditions favour off-target transport (Koc et al., 2023). Variable-rate spraying can reduce off-target losses by decreasing spray output in areas with little or no foliage. However, drift reduction cannot be solely attributed to variable-rate control, as nozzle selection, droplet spectrum, airflow management, and environmental conditions also play a role in droplet transport (Otto et al., 2015; Salcedo et al., 2021). (Salcedo et al., 2021) demonstrated this interaction experimentally in a young apple orchard. Both manual-PWM and laser-guided PWM systems resulted in reduced airborne and ground losses compared to the conventional constant-rate configuration, with the laser-guided system showing particularly substantial reductions in measured off-target losses. Therefore, precision spraying should be viewed as a combined problem of target recognition and droplet management, rather than exclusively a flow-control issue.

6.4. Biological efficacy: the missing link

A major limitation in precision-spraying research is the frequent evaluation of canopy detection, spray-volume reduction, deposition, or coverage without determining whether these engineering improvements lead to equivalent or enhanced pest or disease control. This creates a crucial distinction between engineering performance and crop-protection performance. (Salcedo et al., 2021) specifically noted the need for biological field trials to confirm whether the deposition and coverage achieved by their PWM-based systems translated into equivalent pest and disease control. More recent field research has begun to address this gap. (Whitfield et al., 2025) compared constant- and variable-rate spraying in an apple orchard, measuring spray deposition, drift, and insecticide biological efficacy. The variable-rate system reduced deposition variance and spray drift, while biological efficacy remained comparable between the treatments. This type of study is particularly valuable as it links the complete sequence of canopy sensing, spray rate adjustment, spray deposition, drift reduction, and biological efficacy. Such evidence warrants greater emphasis, as pesticide savings achieved without adequate biological control may represent an apparent improvement in engineering efficiency rather than a genuine enhancement in crop protection.

7. Intelligent, Autonomous, and UAV-Based Precision Spraying

Recent advancements in precision orchard spraying are moving beyond individual sensing or control components towards integrated intelligent systems. These systems combine perception, decision-making, actuation, and increasingly, autonomous navigation to enable spatially responsive crop protection (Góral et al., 2024; Y. Wang et al., 2025). However, the level of intelligence should be assessed based on the complete perception-decision-action cycle, rather than solely on the presence of an AI model or robotic platform.

7.1. Artificial intelligence and machine learning

Artificial intelligence (AI) is increasingly employed to transform image and sensor data into actionable canopy information. Deep learning models can detect trees, segment canopy regions, and estimate structural characteristics used for spray decisions (Góral et al., 2024; Y. Wang et al., 2025). Compared to manually designed image-processing rules, learning-based methods can offer greater adaptability to complex backgrounds and heterogeneous canopy appearances. However, model performance can vary depending on cultivar, growth stage, illumination, canopy density, and imaging conditions (Y. Wang et al., 2025). Recent developments are also extending beyond perception towards AI-supported spray decision-making. AI can potentially integrate canopy characteristics, historical application data, and environmental information to determine spatially variable spray requirements (Y. Wang et al., 2025; Wu et al., n.d.). However, the current literature provides considerably more evidence for AI-based detection than for AI systems that directly demonstrate improved biological crop-protection outcomes. This distinction is important when evaluating claims of intelligent spraying. A significant limitation is therefore the gap between AI accuracy and agronomic utility. High segmentation or detection accuracy does not necessarily imply that the resulting spray prescription is optimal. The AI output must ultimately be linked to calibrated spray requirements and validated through deposition and crop-protection measurements.

7.2. Autonomous ground spraying

Autonomous ground vehicles offer an opportunity to integrate navigation, canopy sensing, and spray control within a single platform. Such systems can maintain a predefined path while continuously acquiring canopy information and adjusting spray output (Góral et al., 2024; S. Jiang et al., n.d., 2024). Recent autonomous orchard systems have incorporated LiDAR, machine vision, GNSS, and sensor-fusion algorithms to improve navigation in complex orchard environments (A. Jiang & Ahamed, 2025; S. Jiang et al., 2024). However, autonomy introduces additional requirements beyond spraying accuracy. The vehicle must maintain appropriate lateral position, travel speed, and sensor-to-nozzle alignment while operating on uneven orchard terrain. Consequently, navigation accuracy and spray-control accuracy become interdependent. A technically accurate variable-rate algorithm may still perform poorly if vehicle motion leads to spatial misalignment between the sensed canopy and the spray target (A. Jiang & Ahamed, 2025; S. Jiang et al., 2024). Recent experimental work also demonstrates the emergence of AI-enabled autonomous orchard spraying robots capable of combining canopy detection with automated spraying. (Gerdan Koc et al., 2025) developed an autonomous orchard spraying robot integrating

YOLOv5-based canopy detection, stereo vision, RTK-GPS, and independently controlled electrostatic nozzles. Field experiments in apple orchards showed the feasibility of combining AI-based canopy detection with autonomous variable-rate spraying. These systems represent a transition from automated components towards integrated autonomous crop-protection platforms. Nevertheless, their validation across different cultivars, canopy architectures, terrains, and environmental conditions remains necessary before widespread field deployment can be assumed.

7.3. UAV-based precision spraying

Unmanned aerial spraying systems (UASS) offer a distinct approach to precision orchard spraying by eliminating the need for direct ground access and enabling application in challenging or irregular terrain (Calderone et al., 2025). Recent reviews have examined the integration of variable-rate spraying with multispectral and hyperspectral sensing, AI-based flow-rate optimization, and UAV operation. A systematic review of UASS applications in orchards found that deposition, drift, and canopy-layer coverage are significantly influenced by operating parameters such as flight height, rotor configuration, and nozzle type. The review also highlighted the importance of downwash and canopy interaction in determining deposition efficiency (Calderone et al., 2025). However, UAV spraying should not be considered merely an aerial equivalent of ground-based variable-rate spraying. The aerodynamic environment differs fundamentally, as rotor-induced airflow interacts with droplets and the canopy. Consequently, UAV precision depends on the coupled effects of flight parameters, downwash, droplet characteristics, canopy structure, and environmental conditions (Calderone et al., 2025; Weicai & Panyang, 2023). Recent evidence also indicates that UAV spraying continues to face challenges in achieving adequate inner-canopy and abaxial deposition. These limitations stem from interactions among rotor-induced airflow, canopy resistance, and droplet transport, suggesting that flight-path optimization alone cannot resolve the deposition issue (S. Jiang et al., 2026). Therefore, future UAV precision spraying should increasingly integrate canopy perception, adaptive flight control, flow regulation, and droplet optimization, rather than treating flight height or application rate as isolated control variables.

7.4. Sensor fusion and closed-loop spraying

A major emerging trend is the integration of multiple sensing modalities. LiDAR can provide three-dimensional canopy structure, RGB or RGB-D cameras offer visual information, and multispectral sensors deliver data related to plant condition. Combining these sources can mitigate the limitations associated with relying on a single sensor (Y. Wang et al., 2025). Recent research specifically identifies multimodal data fusion as a promising direction for orchard variable-rate spraying, as structural, visual, and physiological information can be complementary (Y. Wang et al., 2025). The subsequent step involves connecting multimodal perception with closed-loop spray control. In such a system, canopy information is continuously sensed, interpreted, and converted into a spray command, while the resulting hydraulic or deposition response can potentially be monitored and used for subsequent correction. This would transition precision spraying from an open-loop system based on predefined relationships towards an adaptive system capable of responding to operational uncertainty.

Recent variable-rate research has already demonstrated the integration of sensing, prescription-map generation, and spray control. (Hu et al., 2025), for example, developed a multidimensional prescription-map approach that incorporated three-dimensional canopy information and nozzle-distribution optimization, underscoring the importance of coupling canopy information with the mechanical configuration of the sprayer. The principal challenge, therefore, lies not merely in sensor fusion, but in decision-level fusion and feedback. A practical closed-loop system necessitates reliable synchronization among sensing, modeling, actuation, and feedback, while maintaining acceptable computational costs and response times.

8. Cross-Study Synthesis: What Determines the Success of Precision Orchard Spraying?

The literature reviewed in the preceding sections indicates that precision spraying performance cannot be attributed to a single technology. The final crop-protection outcome results from the interaction among canopy characterization, spray-rate estimation, control response, droplet transport, deposition, and biological efficacy. Recent experimental studies increasingly support this integrated interpretation by evaluating canopy sensing in conjunction with spray control and deposition, rather than treating these components independently (Gu et al., 2025; Hu et al., 2025; Zhao et al., 2025). A cross-study comparison of sensing strategies, spray-decision approaches, control mechanisms, and application outcomes is presented in Table 4.

Table 4. Comparative summary of precision orchard spraying approaches, including sensing method, control strategy, major benefits, limitations and reported application outcomes.

Stage	Current capability	Major limitation	Research priority	Supporting references
Canopy sensing	LiDAR, RGB/RGB-D, ultrasonic, machine vision	Occlusion, illumination, structural variability	Sensor fusion and robust sensing	(Luo et al., 2025; Sultan Mahmud, Zahid, He, Choi, Krawczyk, & Zhu, 2021; C. Zhang et al., 2025)
Canopy characterization	Volume, LWA, density	Weak relationship with actual spray requirement	Validated canopy-to-spray models	(Salas et al., 2024; Wu et al., n.d.)

Spray decision	VRA, prescription maps	Limited real-time adaptation	Dynamic decision models	(X. Huang et al., 2025; Qiao et al., 2024)
Actuation	PWM, solenoid valves	Response delay and synchronization	Faster closed-loop control	(Grella et al., 2022; Qiao et al., 2024)
Droplet transport	Air assistance, electrostatic spraying	Wind, evaporation, canopy penetration	Adaptive droplet management	(Feng et al., 2024; Y. Wang et al., 2025; C. Zhang et al., 2025)
Deposition	Water-sensitive paper/deposition measurement	Limited linkage with sensing/control	Deposition-aware control	(Feng et al., 2024; Godyń et al., 2025)
Crop protection	Spray reduction and coverage	Biological efficacy often not integrated	Efficacy-based evaluation	(Mahmud et al., 2021; Shamshiri et al., 2024)

8.1. Accuracy of canopy information versus practical spray benefit

High sensing accuracy does not necessarily translate directly into improved crop-protection performance. Canopy volume, density, leaf-area-related parameters, and three-dimensional structure represent different aspects of the spray target, meaning different sensing outputs can lead to different spray decisions (Gu et al., 2025; Rosell & Sanz, 2012; Sultan Mahmud, Zahid, He, Choi, Krawczyk, Zhu, et al., 2021). Recent research elucidates why this distinction is important. (Gu et al., 2025) demonstrated that canopy thickness, leaf area, and air velocity influenced spray deposition differently, indicating that canopy volume alone may not fully capture the factors governing droplet deposition. Similarly, (Zhao et al., 2025) showed that leaf-area-density information could be integrated into a prescription map and variable-rate control system to enhance deposition uniformity. This suggests that the relevant question is not simply Which sensor is most accurate?, but rather Which canopy information is sufficient for the intended spray decision? Simple canopy detection might suffice for target/no-target spraying, whereas density- or structure-dependent application requires more detailed characterization.

8.2. Spray-rate reduction versus deposition maintenance

A consistent finding across recent studies is that reducing spray volume alone is insufficient evidence of successful precision spraying. The objective is to minimize unnecessary application while ensuring adequate target deposition and coverage (Salas et al., 2025; Salcedo et al., 2021). Recent field studies provide direct evidence supporting this principle. (Zhao et al., 2025) reported that a variable-rate system based on leaf-area-density information reduced spray use while maintaining the required deposition level and significantly improving deposition uniformity. The system reduced longitudinal deposition CV by 55.75% on adaxial surfaces and 33.22% on abaxial surfaces compared to constant-rate spraying, with a 62.29% reduction in ground runoff. Similarly, a recent FAVD-based target-variable spraying system reported a 64.50% reduction in water consumption while improving deposition uniformity and decreasing ground and behind-canopy losses (S. Jiang et al., 2025) Therefore, chemical or water reduction should be viewed as a secondary outcome, with adequate target deposition remaining the primary engineering requirement.

8.3. Deposition uniformity versus average deposition

Average deposition can obscure significant spatial variability within a tree. This is particularly relevant in heterogeneous orchards, where upper, middle, and lower canopy regions may differ in density, geometry, and accessibility to spray droplets. Consequently, recent experiments have assessed deposition at multiple canopy positions rather than relying solely on a single mean value. (Zhao et al., 2025) demonstrated substantial reductions in longitudinal and transverse deposition variability under variable-rate spraying, indicating that spatial uniformity can be improved even when overall spray volume is reduced. Similarly, (Hu et al., 2025) incorporated three-dimensional canopy information into multidimensional prescription maps and optimized nozzle distribution, showing that prescription-map design and sprayer configuration should be considered together, not independently. Thus, future studies should report mean deposition, coefficient of variation, spatial distribution, and any poorly treated canopy regions. Such measurements provide stronger evidence of whether a precision system is effectively compensating for canopy heterogeneity.

8.4. Engineering performance versus biological efficacy

A particularly significant gap is the limited connection between engineering measurements and actual pest or disease control outcomes. Deposition, coverage, and drift are valuable indicators, but they do not independently demonstrate successful crop protection. This limitation is evident as many precision-spraying studies conclude with sensor accuracy, spray-volume reduction, or deposition measurements. In contrast, (Whitfield et al., 2025) evaluated deposition, drift, and insecticide biological efficacy concurrently, finding that the variable-rate system reduced deposition variance and drift while maintaining similar biological efficacy to constant-rate spraying. This type of evidence offers a more robust basis for evaluating precision spraying because it links canopy information, spray decisions, deposition, drift, and biological efficacy, rather than stopping at the spray-control stage.

8.5. A new interpretation of precision-spraying performance

Based on the reviewed evidence, precision spraying can be conceptualized as a multi-stage information-to-outcome system, rather than simply a variable-flow technology. Overall performance is contingent upon the quality of canopy information, the accuracy of spray decisions, the precision of actuation, the quality of spray deposition, and the resultant biological outcome. An error introduced at any stage can propagate to subsequent

stages. For example, inaccurate canopy characterization may lead to an inappropriate spray prescription; an accurate prescription might fail due to actuator delay or hydraulic instability; and correct spray delivery may still result in inadequate biological control if droplet transport or deposition is suboptimal. This interpretation is supported by recent studies that have integrated canopy sensing, prescription mapping, actuation, and deposition assessment within the same experimental framework (Hu et al., 2025; J. Wang et al., 2026; Zhao et al., 2025) .This framework also explains why results from different studies may not be directly comparable. Variations in crop, canopy architecture, growth stage, sensing resolution, travel speed, nozzle characteristics, application rate, and deposition assessment methods can significantly influence reported performance.

8.6. Research implication

The literature thus suggests that future precision-spraying studies should shift from component-level validation towards system-level validation. Instead of reporting solely sensing accuracy, spray-volume reduction, or nozzle response, experiments should evaluate the complete pathway using common performance indicators, including sensing accuracy, spray-rate accuracy, spatial synchronization, deposition uniformity, drift, and biological efficacy.

A system-level evaluation would enable differentiation between decision precision, how accurately the required spray rate is determined and application precision, how accurately that decision is physically delivered to the intended canopy region. This distinction forms the basis for the proposed Canopy to Crop Protection (C2CP) framework, where the central objective is not merely to minimize pesticide input but to achieve the necessary biological protection with the minimum required input.

9. Research Gaps and Future Priorities

Despite considerable progress in canopy sensing, variable-rate control, and automated spraying, several challenges persist, limiting the reliable field deployment of precision spraying systems. Recent reviews highlight real-time performance, seasonal adaptability, model generalization, multimodal sensing, and intelligent control as significant research obstacles. However, the literature also suggests these challenges are interrelated across the sensing, decision-making, actuation, and spray-deposition stages (Hu et al., 2025; Y. Wang et al., 2025). A primary limitation is the transferability of canopy-sensing models across different orchard environments. Vision-based methods can be influenced by illumination, background complexity, occlusion, and changes in canopy appearance. LiDAR offers more direct three-dimensional structural information but typically requires greater computational and hardware resources. Multispectral and hyperspectral systems can provide additional data on plant condition, yet their integration increases system complexity. Consequently, recent research focuses on multimodal sensing and hybrid modeling as promising approaches to enhance robustness and generalization (Y. Wang et al., 2025).

Another notable gap concerns translating canopy information into appropriate spray requirements. While canopy volume, density, leaf-area-related parameters, and three-dimensional structure have been investigated for variable-rate application, a universally applicable relationship between measured canopy parameters and the spray deposition needed for effective crop protection has not yet been established (Gu et al., 2025; Hu et al., 2025; Zhao et al., 2025). Current systems utilizing canopy volume, foliage density, and multidimensional prescription maps demonstrate that more detailed canopy characterization can improve spatially targeted spraying (Hu et al., 2025; Y. Wang et al., 2025; Zhao et al., 2025). However, these methods require validation across diverse crops, growth stages, and canopy architectures before generalized spray-decision models can be developed.

The delay between sensing and actuation is another critical limitation. Canopy detection precedes nozzle passage, and image or point-cloud processing, decision-making, and valve actuation require additional time. As a result, travel speed, sensor-to-nozzle distance, computational latency, and actuator response can introduce spatial discrepancies between the detected canopy and the actual spray application. Recent intelligent-sprayer research identifies real-time performance as a significant technical constraint, while newer variable-rate systems incorporate spatial compensation and more responsive nozzle-control strategies (Hu et al., 2025; Y. Wang et al., 2025). A further research gap lies in the limited connection between engineering performance metrics and biological crop protection efficacy. Many studies evaluate canopy detection accuracy, spray-volume reduction, deposition, or coverage independently, with fewer studies linking these parameters to pest or disease control. This is particularly relevant because reduced spray volume should not be automatically equated with improved crop-protection outcomes. Recent intelligent-spraying literature therefore emphasizes the need to evaluate deposition and drift alongside the final crop-protection results.

Standardized performance evaluation is also needed. Studies frequently employ differing canopy descriptors, nozzle types, operating pressures, travel speeds, sensing distances, spray volumes, and deposition measurement techniques. These variations complicate direct comparisons of reported pesticide-saving percentages and deposition improvements. A more consistent evaluation framework should encompass canopy-sensing accuracy, spray-decision accuracy, actuator response, deposition uniformity, drift or off-target loss, pesticide reduction, and biological efficacy. Recent reviews supporting this integrated assessment organize intelligent spraying around perception, control, deposition, drift, and autonomous system integration, rather than treating these components in isolation (Y. Wang et al., 2025). Future research should therefore shift from optimizing individual components to validating entire systems. Promising directions include multimodal sensing, edge-based AI, physics-informed and data-driven modeling, adaptive spray prescriptions, responsive nozzle control, and autonomous navigation. However, their practical value must ultimately be demonstrated through field experiments that link canopy perception with spray deposition, off-target losses, and biological efficacy (Hu et al., 2025; Y. Wang et al., 2025).

Overall, the primary research challenge is no longer merely detecting canopy variability, but rather reliably converting that information into the minimum spray input necessary to achieve adequate biological protection under dynamic orchard conditions. This forms the basis for the integrated framework proposed in the subsequent section.

10. Integrated Framework for Next Generation Precision Orchard Spraying

The evidence reviewed suggests that precision orchard spraying is evolving from technologies focused on individual sensors or actuators towards integrated systems that continuously convert canopy information into spatially appropriate spray decisions. While recent studies have demonstrated LiDAR-based canopy-volume estimation, multidimensional prescription maps, leaf-area-density-based control, and real-time variable-rate systems, these approaches are typically evaluated based on individual stages of the spraying process (Hu et al., 2025; Y. Wang et al., 2025; Zhao et al., 2025). Based on the literature, this review proposes a Canopy to Crop Protection (C2CP) framework comprising five interconnected stages: canopy perception, canopy interpretation, spray prescription, real-time execution, and crop-protection feedback.

The first stage involves acquiring canopy information using RGB/RGB-D cameras, LiDAR, ultrasonic sensors, multispectral sensors, or combinations thereof (Jiao et al., 2025; Y. Wang et al., 2025). The second stage transforms raw sensor data into parameters such as canopy volume, density, leaf-area-related characteristics, and spatial canopy structure. Crucially, the chosen parameter should align with the intended spray decision, not solely with sensor availability. Recent canopy-perception research similarly emphasizes the need to link structural information with variable-rate control, rather than treating canopy modeling as an independent objective (Y. Wang et al., 2025).

The third stage converts canopy information into a spray prescription. Instead of a single application coefficient for an entire tree, future systems should generate spatially resolved spray requirements based on canopy size, density, and potentially physiological or pest related data. Recent multidimensional prescription-map research indicates the feasibility of incorporating depth information into spray requirements, while foliage-density-based systems highlight the potential of using more biologically relevant canopy descriptors (Hu et al., 2025; Zhao et al., 2025).

The fourth stage is real-time execution, where the prescribed spray requirement is translated into nozzle flow, PWM duty cycle, valve operation, pressure, or airflow. At this point, sensor-to-nozzle distance, travel speed, processing latency, and actuator response must be considered concurrently. Recent LiDAR-based work has demonstrated adaptive delayed spraying with a reported response time of approximately 160 ms, underscoring the importance of synchronizing canopy detection and spray delivery (Hu et al., 2025).

The final stage introduces a critical element that remains underdeveloped in many current systems: crop protection feedback. Rather than concluding the process after the nozzle delivers the prescribed quantity, future systems should assess whether the application resulted in adequate deposition, coverage, and biological protection.

11. Sustainability, Economic Feasibility, and Adoption Considerations

Precision spraying holds the potential to enhance the environmental and economic sustainability of orchard crop protection by reducing unnecessary pesticide application, spray losses, fuel consumption, and labor requirements. However, these benefits must be weighed against the increased costs, energy demands, and technical complexity associated with sensors, computing systems, actuators, and autonomous platforms. A recent systematic assessment of precision agriculture evidence highlighted that sustainability claims require field or modeling validation rather than being inferred solely from the use of advanced technology (Manono et al., 2026; Nath, 2024).

Recent orchard studies provide evidence that variable-rate spraying can yield measurable environmental advantages. An energy and life-cycle assessment comparing fixed-rate and variable-rate orchard spraying reported reductions in pesticide deposition and improvements in energy efficiency, with a lower global-warming potential under variable-rate operations. Similarly, recent real-time variable-rate spraying research indicated reduced pesticide use, ground losses, airborne drift, and fuel consumption compared to conventional applications (Fathi et al., 2025; Zhao et al., 2025). These findings suggest that the environmental value of precision spraying extends beyond chemical savings to encompass reduced off-target contamination and resource consumption.

Economic benefits, however, are strongly dependent on farm size and the cost of the precision system. A techno-economic assessment of laser-guided variable-rate spraying in commercial apple orchards revealed substantial reductions in pesticide costs, application time, labor, and fuel compared to conventional spraying. Although retrofitting a conventional sprayer increased equipment costs, the resulting savings in pesticide and operational expenses led to a favorable payback period, particularly for larger orchards. More recent economic research similarly indicates that the profitability of precision spraying is influenced by equipment investment, farm scale, pesticide expenditure, operating conditions, and the extent of achievable input reduction (Manandhar et al., 2020).

It is important, however, not to consider pesticide reduction in isolation from economic or environmental benefits. Excessive reduction in application can compromise canopy deposition and biological efficacy, potentially necessitating additional treatments. Conversely, a precision system that maintains crop protection while reducing unnecessary application can generate both environmental and economic advantages. Therefore, appropriate evaluation should consider the combined effects of input reduction, deposition quality, crop-protection efficacy, energy consumption, equipment cost, and operational requirements (Whitfield et al., 2025).

The adoption of intelligent spraying technologies also faces practical obstacles. High initial investment, sensor calibration, computational demands, maintenance, operator training, compatibility with existing sprayers, and limited technical support can hinder adoption, especially for small and medium-sized farms. Recent reviews identify system cost, technical complexity, real-time processing, and the integration of multiple sensing and control components as significant barriers to large-scale implementation (Lochan et al., 2024; Mahmud et al., 2021; Manono et al., 2026).

A key future direction is therefore the development of modular and retrofit-based precision systems. Rather than requiring complete replacement of existing orchard sprayers, sensing and control modules could be added incrementally based on farm needs. This approach could reduce upfront investment and allow growers to adopt canopy sensing, individual nozzle control, flow monitoring, and AI-based decision support progressively (Mahmud et al., 2021; Manandhar et al., 2020).

12. Conclusions

Precision spraying is evolving from conventional uniform-rate application towards integrated systems capable of adapting spray delivery to spatial variations within orchard canopies. Advances in LiDAR, RGB/RGB-D vision, ultrasonic sensing, artificial intelligence, variable-rate control, and autonomous platforms have significantly enhanced the ability to characterize canopy structure and regulate spray application. However, the literature indicates that improvements in individual technologies do not automatically translate to enhanced crop-protection performance.

This review identifies a critical transition from component-level precision to system-level precision. Effective orchard spraying necessitates a continuous link between canopy perception, canopy interpretation, spray prescription, real-time actuation, droplet deposition, and biological efficacy. Recent field studies demonstrate that variable-rate systems can reduce spray volume, deposition variability, and drift while maintaining acceptable crop-protection performance, though their effectiveness still depends on canopy architecture, sensing reliability, actuator response, and operating conditions.

The Canopy to Crop Protection (C2CP) framework proposed here offers an integrated perspective for evaluating next-generation precision spraying systems. The framework emphasizes that pesticide reduction should not be the primary measure of success unless adequate target deposition and biological efficacy are maintained. Consequently, future research should prioritize robust multimodal sensing, transferable canopy-to-spray models, low-latency control, actuator synchronization, standardized performance evaluation, and closed-loop feedback. Recent research trends toward multidimensional prescription mapping, real-time variable-rate control, and integrated sensing provide a strong foundation for this development.

Ultimately, the future of precision orchard spraying lies not merely in reducing pesticide application, but in applying the correct amount, to the right canopy location, at the right time, with sufficient biological effectiveness and minimal off-target loss. Achieving this objective will require closer integration across agricultural engineering, sensing, artificial intelligence, robotics, spray technology, and crop-protection science. Such integration can support economically viable and environmentally responsible orchard production, paving the way toward truly intelligent crop-protection systems.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) and Quill Bot as AI-assisted tools to support literature exploration, information summarization, language refinement, and improvement of manuscript readability. All AI-assisted outputs were carefully reviewed, verified, and edited by the authors to ensure scientific accuracy, originality, and integrity. The authors take full responsibility for the content of this manuscript and all interpretations, analyses, and conclusions presented herein.

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Suthakar B.: Investigation, Writing – review.
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