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REVIEW SMART MANAGEMENT SPRAY TECHNOLOGY APPLICATIONS IN ORCHARD TREE

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Abstract: Paper summarizes advances in smart spraying technologies for orchard crop management and their role in improving efficiency, sustainability, and resource use in modern agriculture. Rapid progress in precision spraying systems, electrostatic sprayers, unmanned aerial vehicle (UAV) applications, and automated sprayers has improved pesticide application methods. These technologies rely on advanced sensing and computational tools to increase spray accuracy and optimize input use. Sensing technologies supporting precision spraying include camera-based vision systems, ultrasonic sensors, and laser scanning devices used for canopy detection and characterization. When integrated with variable-rate technology, spray applications can be adjusted according to canopy characteristics such as height, width, density, and volume. This targeted approach reduces pesticide and water consumption while maintaining effective pest control. Precision spraying systems can reduce spray volumes by 34-88% and decrease spray drift by up to 85% compared with conventional sprayers. Autonomous platforms, including robotic sprayers, improve operational safety and reduce labor requirements. Variable-rate systems integrated with pulse-width modulation technology provide rapid response and stable droplet formation under variable canopy conditions.
These developments support sustainable pest management by reducing plant protection products by 15-44%. Future research should integrate machine learning and deep learning techniques to improve sensor accuracy and pest detection in orchards.

Keywords*: Spray technology, orchard tree management and sensing technologies*

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INTRODUCTION

Agriculture is rapidly evolving due to technological innovations that help maintain productivity under increasing environmental pressures and climate variability. Among the major challenges is the extensive use of pesticides, which has raised serious concerns about environmental contamination and human health. Societal awareness of these risks has grown in recent years, prompting the European Union to set ambitious targets within the Farm to Fork Strategy of the European Green Deal. The strategy aims to reduce both the use and risk of chemical pesticides, including highly hazardous compounds, by 50% by 2030 (European Commission, 2020). Achieving these objectives requires technological innovation, enhanced operator training, and broader adoption of precision agriculture practices. Horticultural systems, particularly orchards, present unique challenges for pesticide application due to the structural complexity and variability of tree canopies. Traditional air-assisted sprayers, widely used in orchards and nurseries, typically apply a constant volume of spray per hectare, irrespective of canopy size, density, or volume (Hong et al., 2018). Such uniform applications often result in inefficient deposition and significant off-target losses. For instance, studies have shown that conventional axial-fan sprayers deposit only about 43% of the applied pesticide onto the target foliage (Duga et al., 2015). Spray drift and ground deposition can extend well beyond the intended treatment zone, with measurable off-target contamination observed up to 30 m from treated rows and airborne particles several meters above ground level (Grella et al., 2017). In some cases, pesticide residues were detected more than 50 m from the application site (Kasner et al., 2018), exceeding the recommended 30 m exclusion zone defined by the Worker Protection Standard (Fishel and Sanchez, 2016). Such inefficiencies not only reduce application effectiveness but also pose significant environmental and human health risks. Pesticide residues have been reported in soil, air, surface water, groundwater, and drinking water (Kim et al., 2017), while long-term exposure has been linked to respiratory disorders, metabolic diseases, and various cancers (Kim et al., 2017). Excessive pesticide use also affects ecosystems by reducing biodiversity, promoting pest resistance, and diminishing populations of beneficial organisms, including pollinators and natural enemies (Koleva et al., 2011). Recent advances in precision spraying technologies offer solutions to these challenges by integrating sensing systems, automated control, and data-driven decision-making. Sensor-based systems including machine vision cameras, ultrasonic sensors, and LiDAR allow detailed characterization of canopy structure and facilitate variable-rate spraying (VRT), adjusting pesticide application according to canopy volume, height, and density. These approaches can reduce pesticide use by 34-88% while improving deposition efficiency and minimizing drift. Further improvements in spray control, such as pulse-width modulation (PWM), allow rapid adjustment of nozzle flow rates without compromising droplet size, enhancing responsiveness to variable canopy structures.

Autonomous and robotic sprayers offer safer and more efficient operations. Integrating machine learning and deep learning algorithms with these systems can optimize canopy detection, pest monitoring, and real-time spray decisions, supporting intelligent and adaptive spraying operations.

In summary, the transition from conventional to sensor-based precision spraying represents a crucial step toward sustainable orchard management.

Continued development of canopy sensing, automated control, and data-driven algorithms is essential to maximize the efficiency, environmental sustainability, and safety of pesticide applications in modern horticultural production.

Spraying Technologies in Orchards

Precision Spraying

Precision spraying has significantly advanced orchard crop protection by overcoming the inefficiencies of conventional constant-rate systems. By integrating real-time sensors, GPS mapping, and automated flow control, precision sprayers optimize the timing, location, and volume of agrochemical application. This approach is particularly effective in orchards with heterogeneous or dense canopies, where traditional air-assisted sprayers often result in uneven coverage and substantial off-target deposition (Escolà et al., 2013; Gil et al., 2013). The operation of precision sprayers relies on real-time canopy characterization. Ultrasonic sensors, LiDAR, cameras, and laser rangefinders measure canopy height, width, density, and volume, providing input for variable-rate application (VRA) systems. Pulse-width modulation (PWM) valves allow dynamic adjustment of nozzle flow without compromising droplet uniformity, ensuring efficient and accurate deposition. Field evaluations demonstrate that precision spraying can reduce chemical input by 34-88% while maintaining or enhancing deposition efficiency. High-resolution canopy data enable the generation of Tree Row Volume (TRV) or Leaf Wall Area (LWA) based prescriptions, aligning spray volumes with actual vegetation and supporting regulatory goals such as the EU Green Deal's 50% pesticide reduction target by 2030 (European Commission, 2020). Precision sprayers allow site-specific, variable-rate applications that enhance coverage efficiency, minimize chemical use, and reduce environmental impact. Autonomous platforms, combined with machine learning algorithms, further enhance operational precision and reduce labor demands.

Electrostatic Sprayers

Electrostatic spraying improves deposition by imparting an electric charge to droplets, promoting adhesion to leaf and branch surfaces. This method reduces drift and ensures more uniform coverage, particularly in dense canopies. In agricultural studies, electrostatic fungicides have provided effective control while using significantly lower chemical volumes compared to conventional systems (Law & Cooper, 2001). Electrostatic systems have also been applied in food safety, effectively reducing microbial contamination on food surfaces. Electrochemically activated chlorine solutions and sodium hypochlorite sprays have been shown to decrease Salmonella and Campylobacter populations by 1-4 log10 CFU per unit, demonstrating broad applicability for antimicrobial delivery (Yang et al.). Despite these advantages, few studies systematically explore the factors affecting electrostatic spray efficiency.

Variables including spray charge, nozzle orifice, air pressure, spray duration, and distance from the target can influence deposition. Tools such as response surface methodology (RSM) can optimize these parameters, supporting the development of standardized application protocols tailored for both agriculture and food industry applications.

Table 1. Selected precision spraying technologies, sensors, dose control strategies, and key outcomes.

Reference	Crop	Technology	Control Strategy	Result
Anglund & Ayers (2003)	Orchards	Pressure-based	Variable-rate via pressure	Reduced pesticide/water use; droplet uniformity affected
Campos et al. (2019); Manandhar et al. (2020)	Orchards	Sensor-based precision sprayers	Variable-rate application	34-88% spray reduction; equal or improved deposition
Wei et al. (2022)	Tree crops	On-board canopy sensors	Structure-based VRA	Reduced off-target losses; improved leaf deposition
Llorens et al. (2011)	Tree crops	LiDAR	3D canopy mapping	High-precision canopy characterization
Chen et al. (2012, 2013a, 2013b)	Apple orchards	Laser-guided sprayer	Real-time geometry-based	80–93% reduction in ground/airborne losses
Rayamajhi et al. (2024)	Ornamental trees	Stereo vision + deep learning	Canopy volume & trunk diameter estimation	MAE < 12%; precise variable-rate application
Xun et al. (2023)	Apple orchard	TRV-based precision sprayer	Real-time canopy-volume adjustment	43% spray reduction; 23–85% drift reduction
GUSS-Automation	Orchards	Autonomous air-blast sprayer	Automated precision spraying	Increased efficiency, safety, and labor reduction
European Commission (2020)	Orchards, vineyards		TRV & LWA models	Supports pesticide reduction targets (50% by 2030)

UAVs, Remote Sensing, and Smart Flow Control

UAVs equipped with precision nozzles and imaging sensors are increasingly adopted for orchard spraying. They provide access to difficult-to-reach canopy regions, improve spray uniformity, reduce labor, and minimize soil compaction. Modern UAVs integrate multispectral, optical, and hyperspectral cameras, enabling high-resolution canopy characterization and the generation of prescription maps for variable-rate application.
NDVI and other vegetation indices derived from UAV imagery inform Decision Support Systems (DSS) such as DOSAVIÑA®, which translate canopy data into zone-specific spray volumes.
Field studies in vineyards and orchards report chemical savings of 15-44% with UAV-assisted VRA, while maintaining or improving leaf coverage uniformity (Campos et al., 2019, 2020; García-Ruiz et al., 2023).

Satellite-based remote sensing offers a scalable alternative for canopy mapping and VRA prescription, with high-resolution imagery providing reliable field-level assessment when combined with ground-truth data (Campos et al., 2021; PIVOS Project). Flow rate regulation is critical for accurate VRA. Pressure-based systems adjust nozzle output according to canopy size, whereas PWM valves provide rapid response, stable droplet size, and precise flow control. PWM-controlled sprayers have demonstrated faster responsiveness and higher uniformity compared to traditional pressure-based systems, supporting effective site-specific applications (Salcedo et al., 2022a, b; Campos et al., 2023). The integration of UAVs, remote sensing, and smart flow control facilitates precise, environmentally sustainable, and resource-efficient orchard spraying, aligning with regulatory targets for pesticide reduction while optimizing biological efficacy.

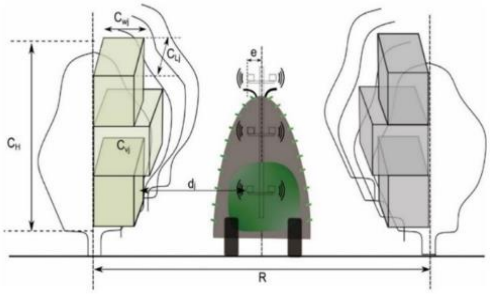


Figure 1. Working principle of the developed precision spraying system integrated on the Fede tower sprayer. (C_H is the total canopy height; C_{wj} is the canopy width for section j; CL_j is the slice canopy length at section j; C_{vj} is the canopy volume to be treated per unit time at section j; d_j is the distance measured between the ultrasonic sensor and the outer surface of the vegetation; e is the distance between the sensor and the central axis of the sprayer; and R is the row space).

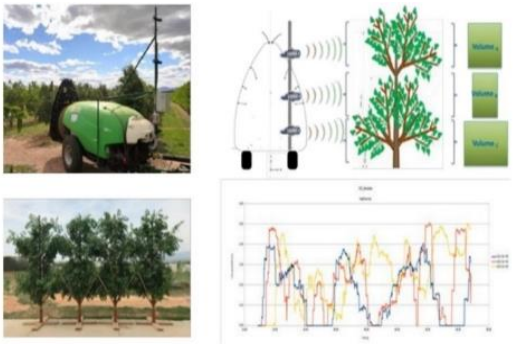


Figure 2. Orchard sprayer developed for VRA in apple trees plantation. The sprayer has been developed by UMA research group (UPC) within the activities carried out for the OPTIMA European Project

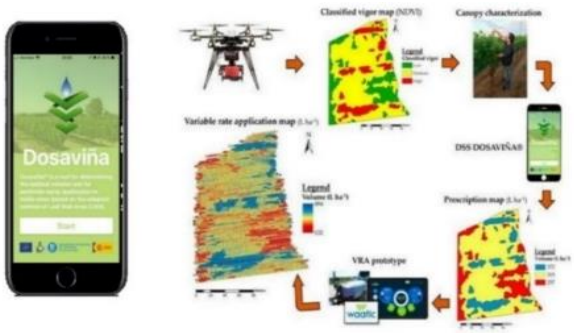


Figure 3. Left: image of DOSAVINA DSS, free available APP (Android and ISO) to determine the optimal application rate for vineyard plantations; right: cycle o VRA based on canopy imagery generated with UAV. The system has been proven to reduce PPP from 15 to 40% depending on the conditions.



Figure 4. VRA cycle developed within PIVOS project, UAV and satellites have been used to generate accurate correlation to estimate canopy parameters. Furthermore, based on values these values, VRA technologies have been already implemented in field conditions, IN all case it has been demonstrated a promising technology with good results in terms of PPP reduction.

Intelligent spray systems

AI-driven intelligent spray systems integrate real-time data analysis, sensors, and machine learning to optimize spray applications. In table 3 provided on AI-driven, robotic, and intelligent variable-rate spraying systems, with emphasis on sensor fusion, machine learning, control strategies, and performance outcomes.

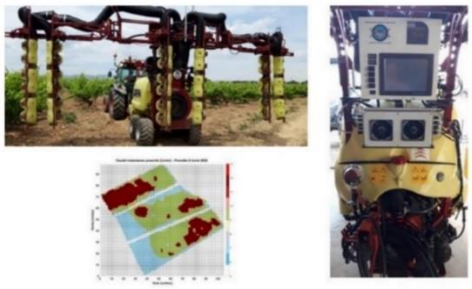


Figure 5. VRA sprayer developed within PIVOS project. The system is equipped with PWM nozzles to follow the prescription map previously developed after satellite imagery.

The integration of artificial intelligence (AI), advanced sensing, and robotic platforms is redefining precision spraying in specialty crops. Modern intelligent sprayers employ real-time data acquisition, multi-sensor arrays (ultrasonic, LIDAR, RGB cameras, and more), and machine learning algorithms to detect canopy characteristics, including size, shape, and density, as well as pest or disease presence. These inputs allow dynamic adjustment of spray volume and droplet delivery, ensuring targeted applications, reduced chemical use, and minimized environmental impact. Ultrasonic and RGB cameras provide rapid canopy dimension assessment, while LIDAR-based systems guide nozzle positions in real time, significantly reducing ground deposition (up to 93%) and airborne drift (up to 80%). Variable air-assisted sprayers modulate airflow based on canopy density, optimizing spray deposition and improving penetration into dense foliage. Advanced PWM (Pulse Width Modulation) solenoid valves control nozzle output, maintaining uniform droplet size and rapid response to canopy changes. These mechanisms reduce pressure fluctuations and ensure consistent droplet formation across variable canopy structures. Robotic and semi-autonomous platforms extend the capability of intelligent spraying systems, particularly in complex terrains such as steep vineyards. Systems integrating human-robot collaboration leverage operator input alongside AI-driven sensing for selective spraying, achieving up to 50% reduction in chemical use while enhancing safety and precision. Image processing and vegetation indices (e.g., NDVI) facilitate site-specific detection of crop health, weed presence, and canopy volume, improving spray flow decisions and reducing over-application. Premixing in-line injection systems have been introduced to maintain constant chemical concentration under rapidly changing flow conditions, addressing limitations of conventional direct-injection sprayers. These systems ensure accurate delivery of agrochemicals even in dynamic operational environments, supporting continuous variable-rate applications. Laser- and LIDAR-guided sprayers coupled with PWM valves are among the most mature intelligent spraying technologies, capable of reducing pesticide losses by up to 90% while maintaining uniform deposition. Human-robot collaborative systems and autonomous platforms also significantly lower labor requirements and increase precision in irregular terrains.

Future trends in AI-driven orchard spraying focus on multi-sensor fusion, advanced machine learning models for real-time pest and disease severity assessment, and integrated control of spray rate, droplet size, airflow, and chemical concentration under dynamic meteorological conditions. These innovations aim to enhance precision, sustainability, and operational efficiency in modern horticulture.

Table 2. Selected AI-driven, robotic, and sensor-fusion spray systems for specialty crops

Reference	Crops	Sensors & AI	Spray Control	Results
Hołownicki et al. (2017)	Orchards	Canopy sensing	Variable air assistance	Improved penetration, reduced drift
Chen et al. (2013a, b)	Apple trees	Laser scanning	PWM-based VRA	90–93% ground loss reduction; 57–80% drift reduction
Oberti et al. (2013, 2016)	Specialty crops	Vision + AI	Selective spraying	65–85% pesticide reduction; 85–100% diseased area coverage
Cantelli et al. (2019)	Vineyards & greenhouses	Sensors + kinematics	Optimized distribution	Improved efficiency of agrochemical application
Baltazar et al. (2021)	Steep vineyards	SVM + vision	Leaf-density-based spraying	High accuracy; feasible for small robots
Wei et al. (2023)	Orchards	Multi-sensor fusion + AI	PWM, pressure, variable air	PWM widely adopted; high future potential
Zhang et al. (2021)	Orchards	Laser + PWM	Variable concentration	MAPE = 6.96%; CV = 3.35%
Shen & Zhu (2015)	Orchards	Laser + ultrasound	PWM + premixing injection	Maintained chemical concentration under variable flow



Figure 6. Sprayer assembled on the robot



Figure 7. Intelligent sprayer prototype

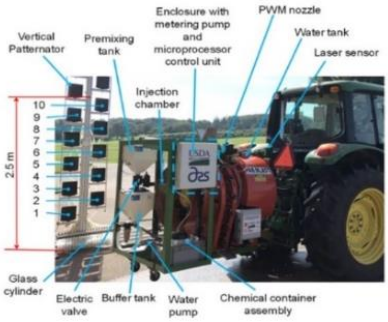


Figure 8. Premixing on-line injection system retrofitted on a laser-guided variable-rate orchard spryer.



Figure 9. The LIDAR measurement system, (a) data in Cartesian coordinates, (b) data in polar coordinates (c) pear orchard, (d) different views of the 3D structure.

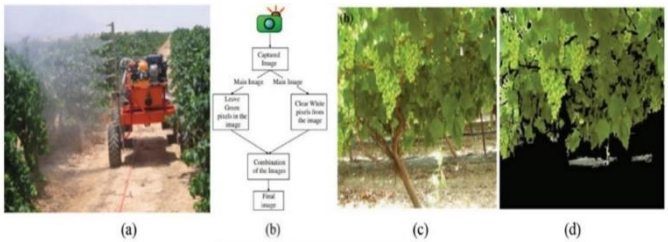


Figure 10. (a) vineyard spraying robot, (b) block diagram of the algorithm, (c) captured image, (d) final foliage image (Berenstein et al. 2010)

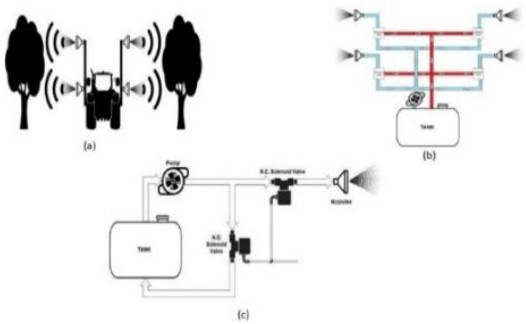


Figure 11. The developed system consists of four ultrasonic sensors, four 3-ways solenoid valves, and a motherboard



Figure 12. Attachment of components of the premixing in-line injection system to the laser-guided variable-rate orchard sprayer.

Smart Nozzle, Variable Air, Sensor Fusion, and Future Prospects in Orchard Spraying

Modern orchard spraying technologies integrate smart nozzles, variable air supply, sensor-based control, and AI-driven systems to maximize precision and minimize chemical use. Smart nozzles adjust droplet size, spray angle, flow, and pressure in real time, significantly reducing off-target losses. Cost-effective ultrasonic and infrared sensors detect canopy width, density, and presence, while LIDAR and machine-vision systems provide high-resolution 3D canopy reconstruction for precise flow control. PWM-controlled nozzles dominate current systems due to rapid response, stable droplet spectra, and compatibility with map- or sensor-guided variable-rate applications (VRA). Depth and stereo cameras offer low-cost alternatives for canopy and tree attribute estimation, supporting real-time adjustments through in-line injection systems to maintain consistent pesticide concentrations and avoid leftover tank mixtures. Variable air supply is critical for air-assisted sprayers. Matching airflow speed, direction, and volume to canopy structure, pest or disease severity, and meteorological conditions improves droplet penetration and uniform deposition. Traditional systems often operate with constant air rates, limiting performance and increasing drift risk. Current control methods include fan speed regulation, air inlet/outlet adjustments, and nozzle-to-canopy distance modulation. Integration of turbidity sensors in premixing in-line injection systems enables precise monitoring of spray mixture concentration.

Tests demonstrated relative errors under 4.7%, ensuring uniform application across variable flow rates. Multi-point sensor deployment along the system further enhances reliability and reduces chemical waste. AI, robotics, and multi-sensor fusion are advancing precision spraying in orchards. LIDAR, ultrasonic, and RGB-D sensors, combined with machine learning, allow real-time detection of canopy volume, tree density, pest distribution, and non-target areas. Autonomous and semi-autonomous platforms, including UAVs, enhance operational efficiency, enabling selective spraying and reducing labor and chemical input by up to 50-85%. Convolutional Neural Networks (CNNs) and deep learning algorithms improve canopy detection, fruit localization, and disease recognition. Environmental sensing with spectral imaging (multi- and hyperspectral) captures vegetation reflectance across visible and near-infrared wavelengths, supporting pest detection, tree health assessment, and site-specific pesticide application. RGB-D cameras, using structured light or time-of-flight principles, provide stable depth data in low-light or shaded conditions, enabling accurate canopy, leaf, and fruit measurements.
Sensor fusion strategies, combining LIDAR, RGB-D, and spectral data, enhance real-time VRA decision-making. Recent AI algorithms improve prediction accuracy, optimize spray paths, and facilitate precision applications under variable field conditions. These integrated approaches align with sustainable agriculture goals, reducing pesticide use, minimizing drift, and enhancing environmental and economic efficiency in orchard management.

Table 3. Selected smart nozzle and sensor-based control systems for orchard and vineyard spraying

Reference	Crops	Sensors & AI	Spray Control	Results
He et al., 2011	Orchards	Infrared	Electrostatic targeting	50-75% pesticide reduction; improved utilization
Planas et al., 2011	Groves	Ultrasonic	Canopy measurement	Interference at spacing <60 cm
Gil et al., 2013	Vineyards	Ultrasonic	TRV-based VRA	21.9% pesticide savings
Rosell et al., 2009	Agriculture	2D LIDAR	3D canopy reconstruction	High correlation with manual volume (R^2 = 0.976)
Shen et al., 2017	Orchards	Laser + PWM	Sensor-guided VRA	21.9–87.9% pesticide reduction
Escolà et al., 2013	Orchards	LIDAR	Canopy-volume VRA	R^2 = 0.935 (intended vs applied flow)
Xiao et al., 2017	Orchards	Depth camera	Depth + color-based control	Accurate leaf wall distance estimation
Zhang et al., 2020	Orchards	Premixing injection	Automatic dosing	Reduced waste; accurate concentration

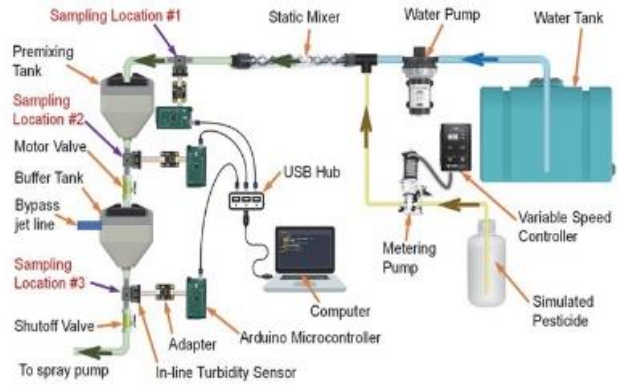


Figure 13. Schematic diagram of the in-line turbidity sensors for measuring spray mixture concentrations at three different locations in the premixing in-line injection system.

Precision-Spraying Technologies: (a) LiDAR-guided variable-rate sprayer (Fessler et al., 2020); (b) Machine vision sprayer (Samseemoung et al., 2017); (c) Prescription map variable-rate sprayer (Rovira-Más et al., 2024); (d) Multi-sen (c) Prescription map variable-rate sprayer (Rovira-Más et al., 2024); (d) Multi-sensor fusion sprayer (Liu et al, 2024).

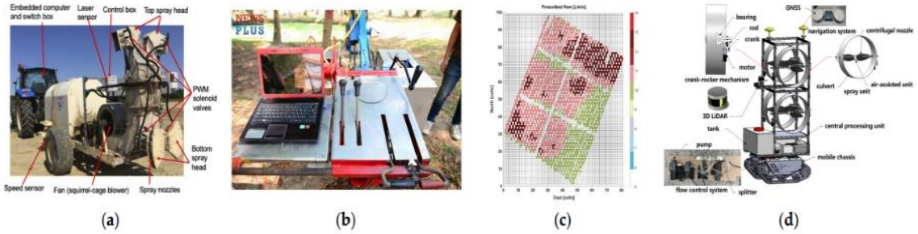


Figure 15. Various Orchard-Spraying Machines: (a) Mounted sprayer (Salas et al., 2023); (b) Self-propelled spray (Qiu et al., 2020]; (c) Electrostatic sprayer/Pneumatic atomization sprayer (Dai et al., 2023).

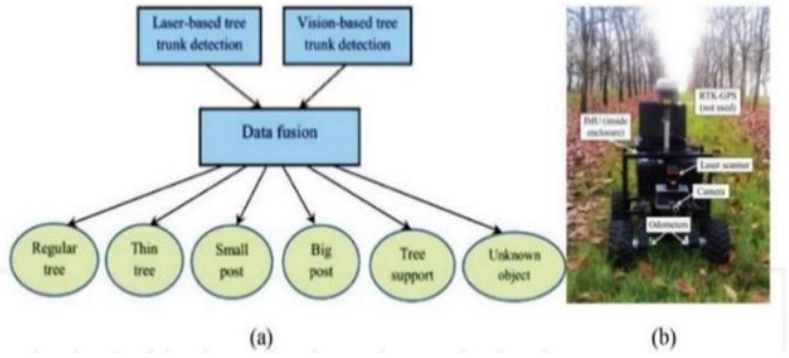


Figure 16. (a) The block diagram of the two-tree trunk detection algorithms, (b) explorer platform with orchard sensors.



Figure 17. Environmental sensing sensors: Visual, LiDAR, Multispectral



Figure 18. RGB-D visual sensor.

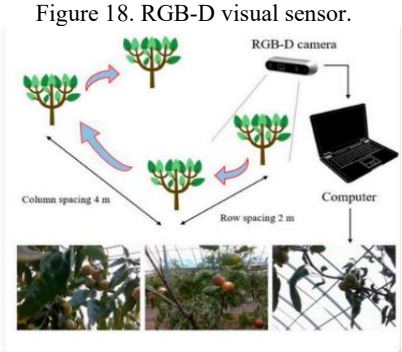


Figure 19. Winter Jujube RGB and Depth image acquisition system

Multispectral and Hyperspectral Imaging for Precision Orchard Management

Multispectral and hyperspectral imaging technologies provide high-resolution insights into crop health, canopy structure, and disease status, enabling precision spraying and targeted management. Multispectral sensors decompose incoming light into discrete spectral channels, capturing information in red, green, and near-infrared bands. These channels allow rapid assessment of leaf moisture, chlorophyll content, and visible disease symptoms, supporting early detection and intervention (Figure 20).

UAV-mounted systems, such as the Parrot Sequoia on a 3DR Solo, can acquire canopy metrics including height, width, and plant projection coverage at multiple altitudes, facilitating accurate structural analysis of orchards. LiDAR sensors, such as the VLP-16, provide 3D point clouds of tree canopies. By removing trunks, supports, and ground interference through point cloud processing, canopy density and volume can be quantified, enabling partitioned data for multi-nozzle variable-rate control and highly accurate targeted spraying (Figure 22). Combining multispectral imaging with 3D reconstruction and machine learning, including LDA and Backpropagation Neural Networks, allows precise detection of diseased trees and early-stage infections. For example, integration of NDVI, NIR, and structural features has achieved up to 100% accuracy in tree-level disease identification, supporting density-based zonal pesticide application (Figure 23).

Data-driven orchard management is increasingly platform-based, integrating heterogeneous sensors, UAVs, ground-based sprayers, and AI algorithms. Real-time sensor fusion enables dynamic adjustment of spray volume, flow rate, and path according to canopy density, pest presence, and disease severity. Commercial systems, including GUSS, Smartomizer H3O, and Smart Spray, illustrate the feasibility of combining automated sensing, intelligent control, and precision decision-making. UAVs offer flexibility in hard-to-access areas, although payload capacity and flight stability remain technical challenges for large-scale orchards. The future of precision spraying relies on fully integrated sensor and AI systems capable of real-time data acquisition, canopy mapping, pest and disease assessment, and environmental monitoring. Advances in multi-source fusion, high-resolution spectral imaging, and machine learning will enhance predictive accuracy, optimize chemical use, and reduce environmental impacts. Platform-based systems, leveraging cloud computing, edge processing, and standardized interfaces, promise scalable, autonomous orchard operations, enabling sustainable, efficient, and cost-effective crop protection. The relevant sensors are shown in Figure 20.



Figure 20. Multispectral camera



Figure 21. Multispectral data acquisition system for pest and disease detection: (a) Lychee canopy multispectral data acquisition.

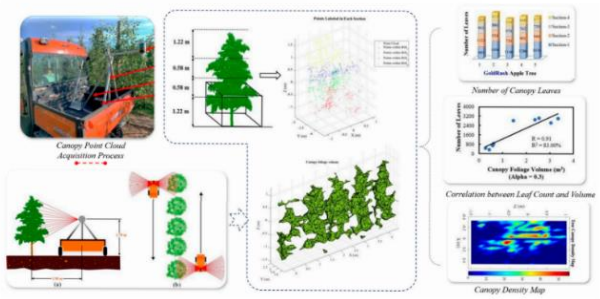


Figure 22. Three-dimensional canopy structure reconstruction based on VLP-16 LiDAR data.

Wang et al. (2025) emphasize that the future of orchard management lies in data-driven, platform-based systems that integrate heterogeneous sensors and equipment through standardized interfaces.

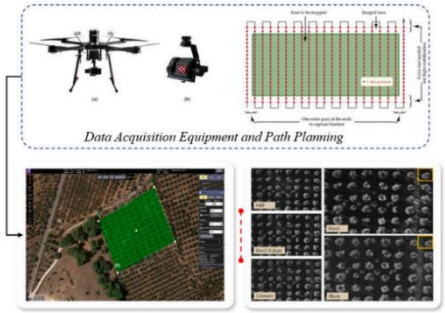


Figure 23. Application examples of pest and disease detection based on hyperspectral sensors: (a) Multispectral camera combined with 3D reconstruction and LDA algorithm achieves disease tree detection and localization (b) Hyperspectral imaging combined with multi-source fusion model enables early identification of anthracnose disease in pear leaves.

CONCLUSIONS

This review underscores the importance of advanced spraying technologies in tree fruit orchards, highlighting current limitations, key performance determinants, and gaps that must be addressed to develop next-Generation precision sprayers. Conventional air-blast systems, though widely employed, are inefficient, with only approximately 43% of applied pesticides reaching target foliage; substantial losses occur due to off-target deposition and drift. These inefficiencies not only elevate chemical costs but also pose serious environmental and human health risks. In response, global policies, such as the European Green Deal's Farm to Fork Strategy, aim to cut pesticide use and associated hazards by 50% by 2030. Precision and smart spraying technologies have emerged as effective solutions. By integrating real-time canopy sensing via ultrasonic, infrared, LiDAR, laser, depth, and multispectral sensors with computer vision and artificial intelligence, these systems dynamically adjust spray volume and coverage according to canopy size, shape, and density. Field trials in apples, grapes, olives, pears, and vineyards demonstrate pesticide reductions of 50–75%, spray drift decreases of up to 87%, and ground loss mitigation of up to 93%, without compromising pest control efficacy. Variable Rate Technology (VRT), often combined with Pulse Width Modulation (PWM) nozzle control, allows precise nozzle-by-nozzle adjustments without altering droplet spectra or spray pressure, ensuring uniform deposition during acceleration, deceleration, and operation on slopes while minimizing overlaps and under-dosing. Additional innovations include GPS-guided autosteering, drone-based spraying, and in-line chemical injection systems equipped with real-time sensors to maintain consistent mixture concentrations and minimize operator exposure. Despite persistent challenges, such as high upfront costs, sensor performance under variable environmental conditions, and integration complexity, ongoing advances in low-cost sensing, sensor fusion, deep learning, and autonomous robotics are improving the feasibility and adoption of these technologies. Overall, smart spraying represents a pivotal strategy for sustainable orchard management, enabling precise pesticide delivery, reduced environmental footprint, improved crop protection, and alignment with contemporary sustainability objectives.

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PREGLED PRIMENE PAMETNIH TEHNOLOGIJA UPRAVLJANJA PRSKANJEM U VOĆNJACIMA

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Apstrakt. U radu su prikazani savremeni trendovi u razvoju pametnih tehnologija prskanja za upravljanje proizvodnjom u voćnjacima i njihov značaj za unapređenje efikasnosti, održivosti i racionalnog korišćenja resursa u savremenoj poljoprivredi. Brz napredak u oblasti sistema za precizno prskanje, elektrostatičkih prskalica, primene bespilotnih letelica (UAV) i automatizovanih prskalica doveo je do unapređenja načina primene sredstava za zaštitu bilja. Ove tehnologije zasnivaju se na naprednim senzorskim i računarskim sistemima, koji omogućavaju veću preciznost aplikacije i optimizaciju utroška inputa.

Senzorske tehnologije koje podržavaju precizno prskanje obuhvataju vizuelne sisteme zasnovane na kamerama, ultrazvučne senzore i uređaje za lasersko skeniranje, koji se koriste za detekciju i karakterizaciju krošnje. U kombinaciji sa tehnologijom promenljive norme aplikacije (VRT), primena sredstva za zaštitu bilja može se prilagoditi karakteristikama krošnje voćke, kao što su visina, širina, gustina i zapremina. Ovakav ciljani pristup smanjuje potrošnju pesticida i vode, uz istovremeno održavanje efikasne kontrole štetnih organizama.

Sistemi za precizno prskanje mogu smanjiti utrošak tečnosti za prskanje za 34–88%, kao i smanjiti zanošenje kapljica (drift) za do 85% u poređenju sa konvencionalnim prskalicama.
Autonomne platforme, uključujući robotske prskalice, povećavaju bezbednost rada i smanjuju potrebe za angažovanje radnika u procesu. Sistemi promenljive norme aplikacije, integrisani sa tehnologijom modulacije širine impulsa (PWM), omogućavaju brz odziv sistema i stabilno formiranje kapljica pri promenljivim uslovima u krošnji voća. Ova dostignuća doprinose održivom upravljanju zaštitom bilja smanjenjem primene sredstava za zaštitu bilja za 15–44%.
Buduća istraživanja treba da obuhvate integraciju metoda mašinskog učenja i dubokog učenja radi povećanja preciznosti senzora i unapređenja detekcije štetnih organizama u voćnjacima.

Ključne reči: *Tehnologija prskanja, upravljanje stablima u voćnjaku, senzorske tehnologije*

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