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Possible Enhancing of Spraying Management by Evaluating Automated Control in Different Training Systems

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Abstract: This study explores the feasibility of an automated sensor system for precise plant protection product application in plum orchards, aiming to address issues related to inefficient spraying practices, environmental pollution, and reduced crop quality associated with traditional training systems. The research focuses on detecting tree canopy presence, evaluating electromagnetic valve actuation in different plum training systems, and optimizing plant protection product usage. Sensor-based spraying demonstrates its potential to improve operational efficiency, reduce product losses, and foster environmentally responsible agricultural practices, contributing to the broader field of precision agriculture. For the selected scene, the results show the possibility of a substantial savings of 71.37%, 47.17%, 58.59%, and 55.06% for the One-axis, Bi-axis, UFO, and Combine systems, respectively. Implementing this technology can potentially lead to significant improvements in plum orchard operations while minimizing the industry's ecological impact on the environment.

Keywords: sensors; spraying application control; target-oriented spray; plum orchard; training systems

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1. Introduction

The primary objective of fruit growers is to cultivate easily manageable trees that yield high-quality fruit and robust yields, optimizing labor utilization and ensuring an early return on investment [1,2]. Efforts to enhance orchard system efficiencies for improved profitability have been significant in recent years [2–5]. Integrating different training systems for production efficiency and orchard management has shown promising results in intensifying plum orchards [6,7]. In contrast to this progress, research on the application of automated chemical plant protection products (PPPs) in plum orchards is lacking, despite their potential advantages. Fruit production faces various challenges, including reducing chemical pesticide usage, adopting sustainable practices, and achieving precise and effective application while minimizing drift [3,8].

The European Union's target of a 50% reduction in chemical pesticide use and the adoption of safer alternatives by 2030 [9] emphasize the need to explore innovative and sustainable approaches in orchard management. Precision farming technologies, like real-time variable rate spraying through sensor systems, have been successfully applied in permanent crops such as apple orchards [10–12]. Integrating sensor technologies into spraying equipment enables data-driven decisions for more precise and efficient spraying [13,14]. One such technology, LiDAR (Light Detection and Ranging), has been effectively used for canopy characterization, allowing for target-oriented spraying [15,16]. In [17], it was shown that LiDAR can accurately measure the volume and shape of fruit tree canopies at short distances, enabling the adjustment of pesticide application rates based on canopy characteristics and significantly improving spraying precision. When mounted on sprayers, LiDAR sensors can create detailed maps of orchard canopies, facilitating the PPPs and minimizing waste. The advantages of LiDAR technology include high accuracy in canopy characterization, the ability to operate in various environmental conditions (e.g., day or night), and the provision of real-time data for immediate decision-making [18]. These benefits contribute to more efficient use of resources, reduced environmental impact, and potentially lower costs for farmers [19]. However, there are also some challenges associated with the use of this technology. For instance, the initial cost of LiDAR and, especially, RTK GPS systems used in localization [6] can potentially be very high, which may be a barrier for some farmers [7]. Additionally, the technology requires regular calibration and maintenance to ensure accuracy, and its performance can be affected by factors such as dust, fog, or heavy rain [20,21].

Targeted spraying based on canopy characterization represents a critical advancement in sustainable orchard management. The widespread reliance on continuous and undifferentiated applications of PPPs, which remain common practice [18], not only increases pesticide use and associated costs but also poses significant long-term environmental and public health risks. Excessive pesticide applications contribute to soil and water contamination, reduce biodiversity, and exacerbate ecological imbalances. Economically, these practices impose unnecessary financial burdens on farmers without delivering proportional benefits. Therefore, the adoption of advanced sensor systems, such as LiDAR-based systems, is essential for transitioning towards more sustainable, efficient, and environmentally responsible agricultural practices.

The integration of advanced sensor systems with spraying equipment has the potential to revolutionize PPP application in fruit orchards, particularly in plum orchards. The primary aim of this study is to assess the feasibility of utilizing an automated sensor system in plum orchards for precise plant protection product (PPP) application through mist blowing and to determine their potential savings. This innovative approach aims to enhance operational efficiency, reduce PPP losses, and promote environmentally responsible agricultural practices. The system employs a SLAM (simultaneous localization and mapping) algorithm [22] to synchronize the detection of the canopy with the precise activation of the sprayer, ensuring real-time adjustment to the tractor's speed.

The study addresses both the development and operational principles of the sensor system in detecting tree canopy presence and spacing, while also comparing the actuation of electromagnetic valves under various plum training systems, including the traditional system, Spindle (One-axis), Bi-axis, Upright Fruiting Offshoots (UFO), and a Combined system, with a random combination of all the aforementioned systems.

To address the challenges of sustainable orchard management, this study aims to evaluate the feasibility and performance of an automated sensor system integrated with a mist blower for precision application of plant protection products (PPPs) in plum orchards. Specifically, the system utilizes a SLAM-based localization algorithm and dual LiDAR sensors to synchronize canopy detection with real-time sprayer actuation, ensuring PPPs are applied only where necessary. The objectives include assessing the system's adaptability across different plum training systems—Spindle, Bi-axis, UFO, and Combined—and quantifying potential PPP savings. By achieving more precise spraying and reducing resource use, this research contributes to advancing sustainable practices in precision agriculture and demonstrates a scalable solution for orchard management challenges.

2. Materials and Methods

2.1. Mist Blower

The TURBO TEUTON P POLIPO mist blower (Campodarsego (PD), Italy) was selected for our experiment due to its advanced design and focus on environmental sustainability. Its localized diffusion system and ability to produce and atomize micro-drops enable high-efficiency treatments while minimizing the environmental impact of plant protection product (PPP) application. This state-of-the-art system is particularly effective for crops with irregular leaf walls or those requiring comprehensive coverage, making it an ideal baseline for our precision agriculture research.

In our study, we further enhanced the functionality of the TURBO TEUTON system by integrating a custom-developed Spraying Application Control System (SACS). Our solution uses dual LiDAR sensors (SICK TIM510, Waldkirch, Germany) and a SLAM-based localization algorithm [22] to synchronize canopy detection with the precise activation of the mist blower's electromagnetic valves. This ensures that spraying occurs only in areas where canopy presence is detected, significantly improving accuracy and reducing PPP waste. By combining the mist blower's inherent efficiency with our precision-oriented modifications, we transformed an already advanced system into a smarter, more sustainable solution tailored for precision agriculture in plum orchards. This enhancement maximizes resource efficiency, reduces environmental impact, and aligns with modern sustainability goals in orchard management.

2.2. Spraying Application Control System

The so-called SACS (Spraying Application Control System) used in the plum orchard test was upgraded and prepared as part of the Interreg Central Europe project Transfarm 4.0 in pilot action 2—remote and proximal sensing [23]. Its operation is quite straightforward and summarized by the two flowcharts in Figure 1. The SACS utilizes advanced sensor systems which enable the precise application of PPPs. The SACS aims to improve efficiency and automate spraying to make it more effective and responsible in terms of sustainable agricultural practices. The latter can be achieved by a system that detects the presence or absence of plant canopies in orchards or vineyards and enables an appropriate response according to the crop coverage. The principle is to spray where necessary and to stop spraying where there is no plant surface to be sprayed. The SACS uses multiple electromechanical components to carry out its tasks, including two TIM510 LiDAR sensors, 10 electro-magnetic valves (Tecomec, Reggio nell'Emilia RE, Italy), 16 relays (Controllino MEGA, Innsbruck, Austria) and a Raspberry PI 4 processing unit (Cambridge, England).

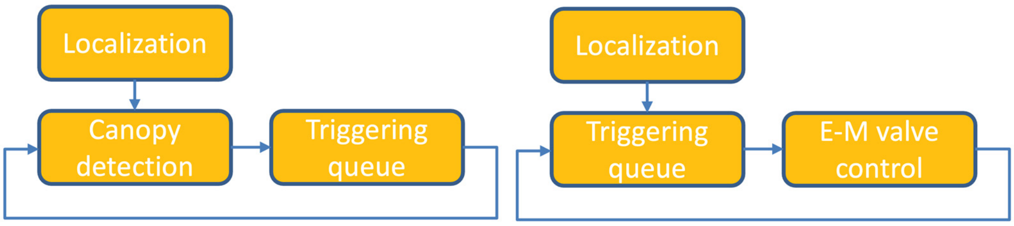
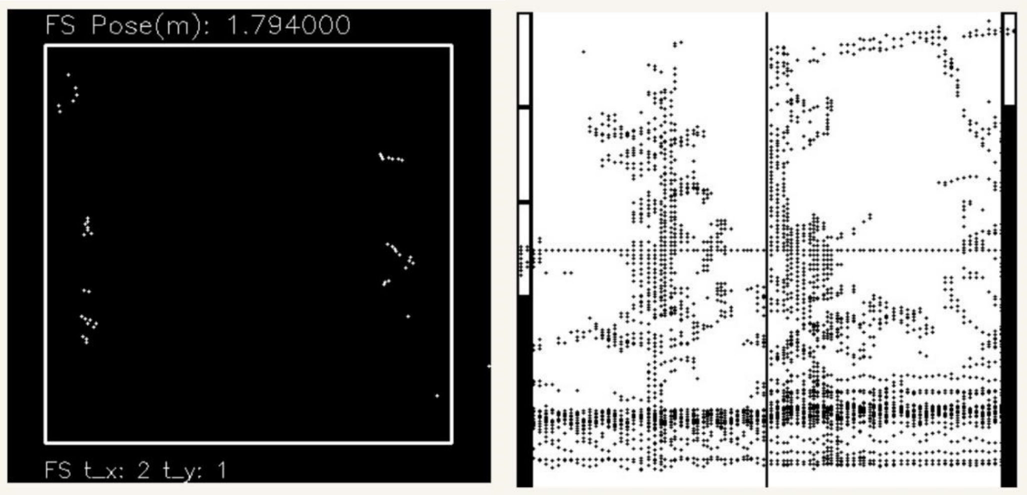


Figure 1. Two flowcharts explaining the capturing (**left**) and triggering (**right**) phases of the SACS.

The SACS incorporates the FieldSLAM algorithm, which was previously developed [11]. This provides an advantage to the system by allowing it to operate in a natural environment. As the nozzles and sensor cannot be placed side by side without the spraying affecting the LiDAR-supported canopy data capture, localization is of paramount importance to know where the readings of the plant canopy presence have been taken and which tasks have been stored at the current location of the nozzles. This way, the data capture and spraying are synchronized, even if the tractor is traveling at a variable speed. In the current setup, the SACS is on the front of the mist blower, while the nozzles are positioned at its back, approx. 1 m away from the SACS. An example of the localization and reconstruction of readings is shown in Figure 2.

The system relies on a SLAM algorithm to manage the precise timing of the opening and closing of the electromagnetic valves, which control the spraying mechanism. Detection of the target (e.g., canopy or open space) is processed in epochs. These epochs correspond to time intervals, during which the system analyses data and triggers appropriate actions (spraying or not spraying). By adjusting to the tractor's speed, which was kept at a consistent 3 km/h during the trials, the system ensures that the resolution of detection remains constant, whether detecting part of the canopy or open spaces. The SLAM-based quantization allows for real-time adjustments, maintaining high precision during the spraying process.

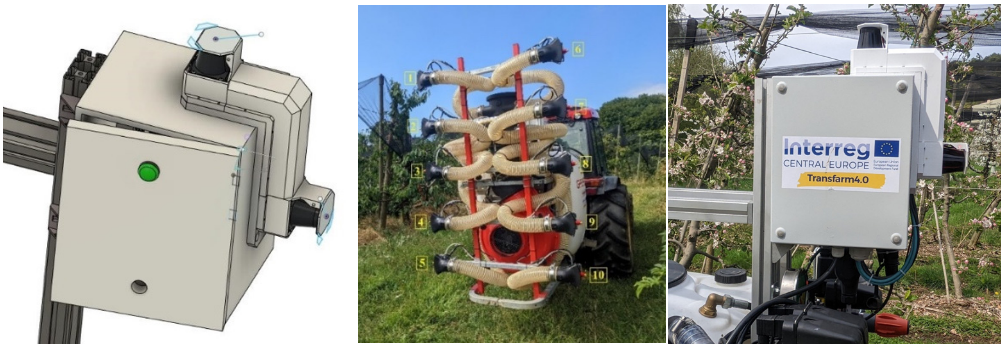


(**a**) (**b**)

Figure 2. (**a**) Visualization of the processing part, FieldSLAM processing picture; (**b**) reconstruction of canopy tree trunks and actuators (nozzles) on the sides (rectangles on the edges—5 left, 5 right), where white = nozzle off, black = nozzle on.

The enhanced SACS employs two LiDAR sensors (model TIM510 from SICK). The first sensor, mounted vertically, is responsible for capturing data necessary to identify the presence of plant canopies. The second sensor, positioned horizontally, assists in determining the overall position of the system. This dual-sensor configuration ensures comprehensive spatial awareness and accurate data collection, which are critical for the precise application of PPPs.

Potential system enhancements include the integration of multi-channel LiDAR sensors, which could significantly improve the accuracy and reliability of the system. However, the design philosophy prioritized affordability and accessibility for target users over the adoption of complex and expensive technologies such as RTK GPS. This approach aims to provide an effective yet cost-efficient solution for precision agriculture, ensuring broader applicability and adoption among various stakeholders. The system layout and its actual implementation on a state-of-the-art mist blower are shown in Figure 3.



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

Figure 3. (**a**) Render of the Spraying Application Control System (SACS), (**b**,**c**) actual implementation on the state-of-the-art mist blower, with numbers corresponding to each nozzle.

The distribution of nozzles, as illustrated in Figure 3, ranges from 1 to 5 on the left side and from 6 to 10 on the right side of the mist blower. The numbering begins with the lowest numbers at the top, 1 and 6, corresponding to the tops of the plant canopies, and progresses downwards, with numbers such as 5 and 10 placed at the lower parts, primarily corresponding to the tree trunks. On the SACS, we used ATR 80° Albuz nozzles (Évreux, France), which, in combination with electromagnetic valves (Tecomec, 12 V solenoid valves), enable precise and automated spraying of plant protection products (PPPs), ensuring an even distribution of the spraying liquid.

2.3. Plum Training Systems and Canopy Characteristics

Globally, there are still numerous extensive and semi-intensive plum orchards that are grown with minimal application of pomotechnical measures, characterized by a naturally shaped canopy without the use of a support system, commonly referred to as the traditional plum training system. However, like apple and pear trees, the cultivation of plums is undergoing a process of intensification, which is accompanied by changes in the canopy structure from a three-dimensional form to a flatter, semi-two-dimensional form.

There have been significant advancements in the improvement of training systems for apple and pear trees, leading to increased reproductive potential without affecting the leaf mass per fruit or the number of leaves needed for proper fruit development. However, in stone fruit trees such as plums, suppression of growth and increased differentiation of fruiting buds lead to a decrease in the number of vegetative buds on the tree, resulting in a reduction in leaf mass per fruit. The implementation of training systems such as UFO and Bi-axis can lead to a redistribution of canopy exuberance, resulting in the increased feasibility of automating labor operations, promoting moderate annual growth, and improving the utilization of solar energy [3,24]. To compare the performance of the Spraying Application Control System, the following training systems (Figure 4) were used in this study in a plum orchard: Spindle (One-axis), Bi-axis, Upright Fruiting Offshoots (UFO) and the Combined system.

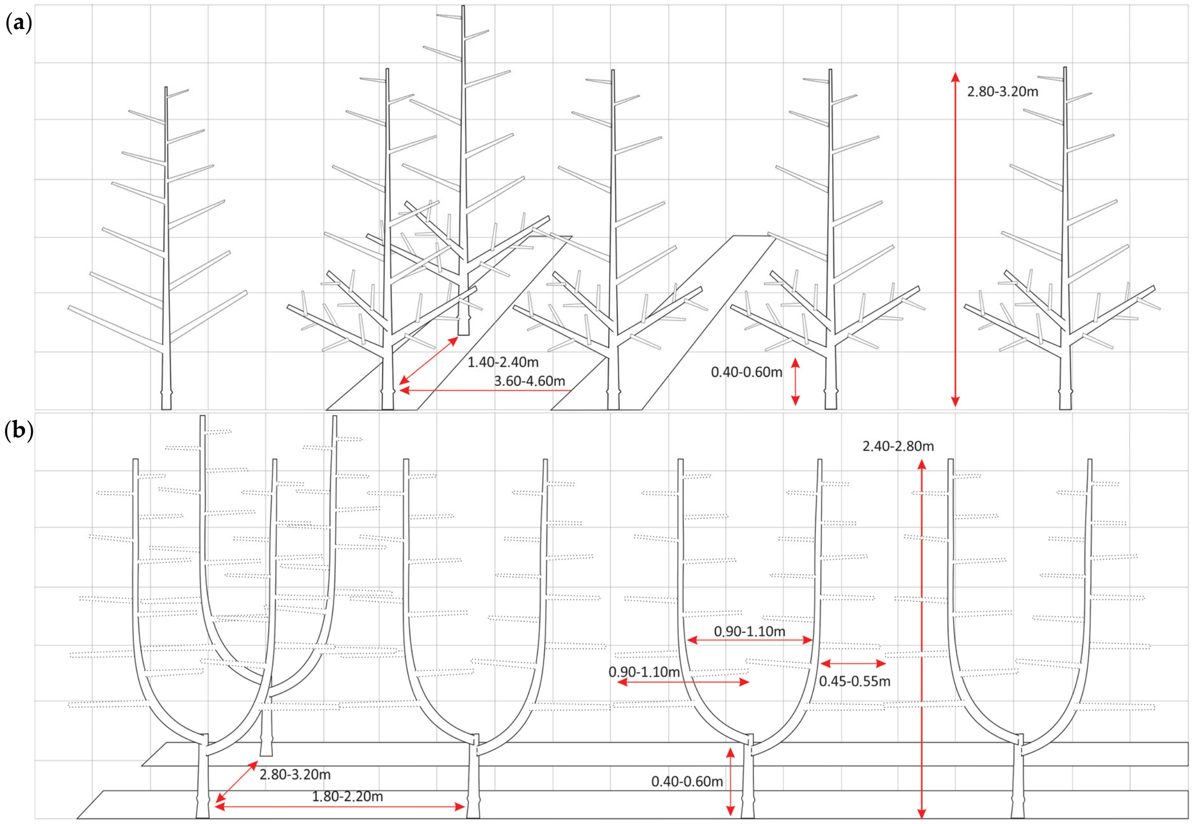


Figure 4. *Cont.*

(**c**)

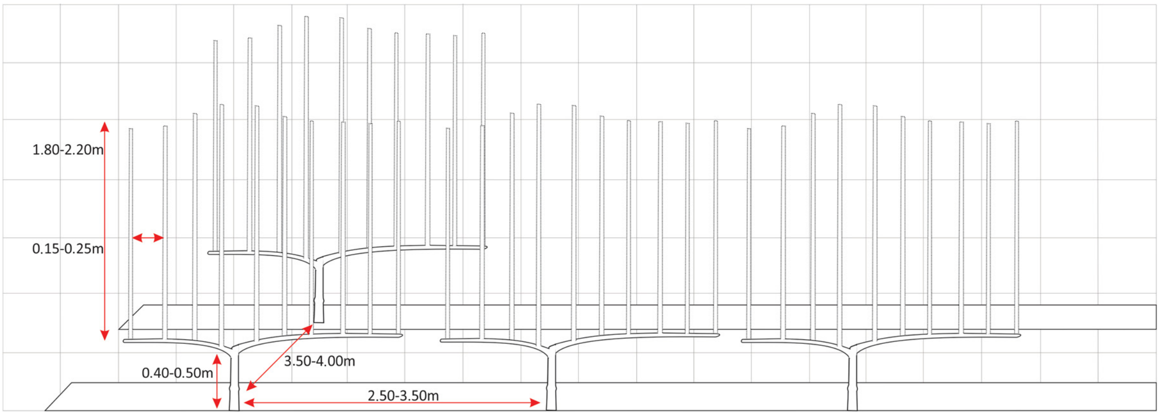


Figure 4. Graphical representation of the different training systems used in the experiment: (**a**) Spindle (One-*axis*), (**b**) *Bi-axis*, (**c**) Upright Fruiting Offshoots (UFO).

2.4. Field Experiment

The trial was conducted in May 2022, on a clear and sunny day, using data from a preliminary application in the experimental plum orchard (*Prunus domestica* L.) managed by the Experimental Educational Center of the Faculty of Agriculture, located in Aleksandrovac (elevation: 105 m), in the northwest region of the Republic of Srpska, Bosnia and Herzegovina. The orchard includes several plum varieties, such as 'Elena', 'Čačanska ljepotica', 'Čačanska rodna', and 'Hanita'. Nearby, the agricultural company "Agro-voće", situated in the village of Bakinci (elevation: 272 m), manages 72 hectares of plum plantations. So, there is a commercial interest in applying the researched technology to these larger orchards, as its successful implementation could significantly benefit the company by improving efficiency and sustainability in large-scale operations. This research is therefore not only academically relevant but also crucial for advancing practical applications in commercial plum production.

All the varieties were grafted on a cherry plum seedling rootstock (*Prunus cerasifera* Ehr.). The plant spacing for all varieties and training systems was 4.0 × 1.4 to 3.5 m, relative to the selected training system. The heights and maximum widths of the trees were approximately 2.5 m and 1.7 m. The distance from the automated advanced sensor system to the tree row plane was 2 m, so the working width was set between 2 m and 3 m. The installation height of the automated advanced sensor system was 1.7 m. Preliminary tests in apple orchards showed a maximum working height of 2.5 m to 3 m, so the height sensor settings remain the same. The vegetative state of the plants was at full vegetation. The majority of the trees were in the BBCH 50–59 stage, indicating fruit development, while some had already transitioned into the BBCH 70–79 stage, marking the early stages of fruit ripening. The working pressure range in the experiment ranged from 5 bar to 6 bar. In all four sets of experiments, the pressure and flow rate of the supply system were consistently maintained, ensuring that the control variable was uniform.

During field trials, the tractor maintained a consistent speed of approximately 3 km/h. This consistency ensured that the system's epoch-based quantization remained constant, resulting in a detection resolution of 5 cm per epoch, approx. ±2.5 cm from the sampling location, achieved with the help of a vertically positioned LiDAR sensor. The synchronization between detection and spraying was achieved effectively, with minimal delays due to the real-time adjustments facilitated by the SLAM algorithm.

2.5. Statistical Processing of Results

In addition to descriptive statistics for the interpretation of the results of the valve opening and closing in an individual training system, other statistical methods were also used in this study. The data were first entered and managed in Microsoft Excel (version 2301) and then transferred to IBM SPSS (version 29.0) for analysis. To assess the differences between the groups, we used the non-parametric Kruskal–Wallis test. In addition, we employed boxplots to visually display the distribution of the data for each group. The Kruskal–Wallis test was chosen because it does not assume a normal distribution of the data, making it appropriate for our non-normally distributed data. This test allowed us to determine if there were statistically significant differences between the groups. The boxplots were used to provide a clear visualization of the distribution of the data in each group, allowing us to identify any outliers or skewness in the data.

It is worth noting that the results presented in the graphs are subject to the limitations of the sensor system used and the specific conditions of the plum orchard rows. Nonetheless, the data provide valuable insights into the valve actuation for each training system and each valve.

3. Results and Discussion

The figures presented herein depict the percentages of the valve actuation openings for each training system and each valve. These results were generated using processed data acquired by the sensor system, which recorded valve actuation data (1 = open valve, 0 = closed valve) via sensing in the plum orchard row. The mean value of the sensor detections in each training system per plum plantation row was approximately 680 on both sides. The percentage of valve opening, alongside its associated training system, is provided to elucidate the potential savings of PPPs in each training system. The canopy shape characteristic for each training system is briefly described next to each graph. In Section 4 statistical analyses and tests were conducted to assess the relationships and correlations between individual training systems.

Figure 5 presents the valve actuation results for the One-axis (Spindle) training system (A treatment). In this training system, a single dominant trunk is trained to grow vertically with lateral branches evenly spaced. This results in a pyramidal shape with a wider fruiting wall. In our experiment, as depicted in Figure 5, 71.37% of the potential PPP savings were achieved.

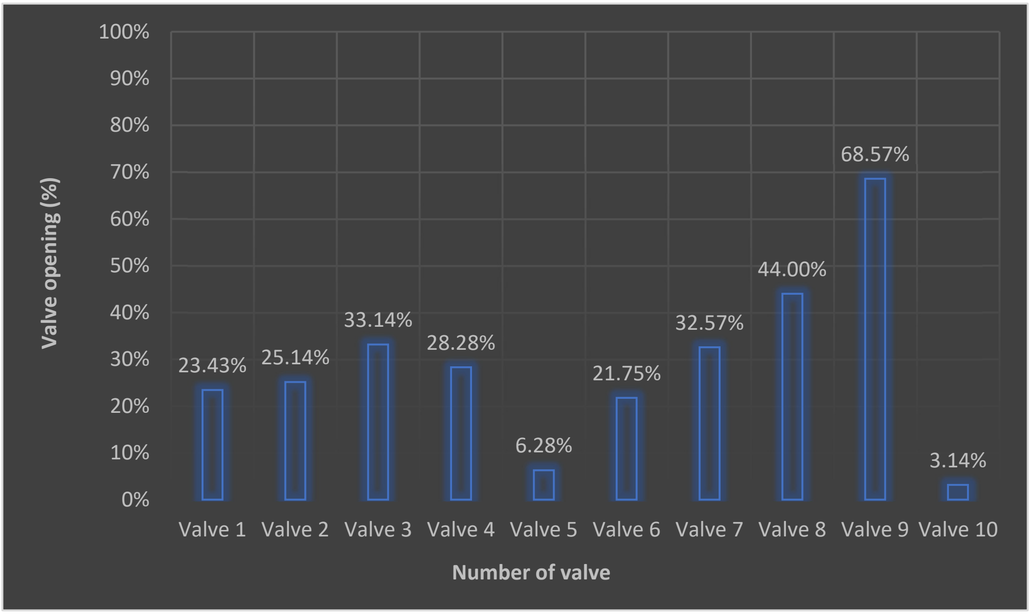


Figure 5. Valves opening (%) in One-axis (Spindle) training system (treatment "A").

The Bi-axis training system (treatment "B") shapes plum trees into a rectangular V-shape with a narrow fruiting wall by pruning the tree to have two primary axes or trunks. Unlike the palmette style, which develops multiple upright runners or scaffolds, the Bi-axis training system involves pruning double runners without large or long lateral branches, similar to a slender spindle system. This results in a compact, efficient tree that allows for good light penetration and optimal fruit production. Figure 6 shows the valve actuation results for the treatment "B". The calculated PPP savings for this system in our experiment are 47.17%.

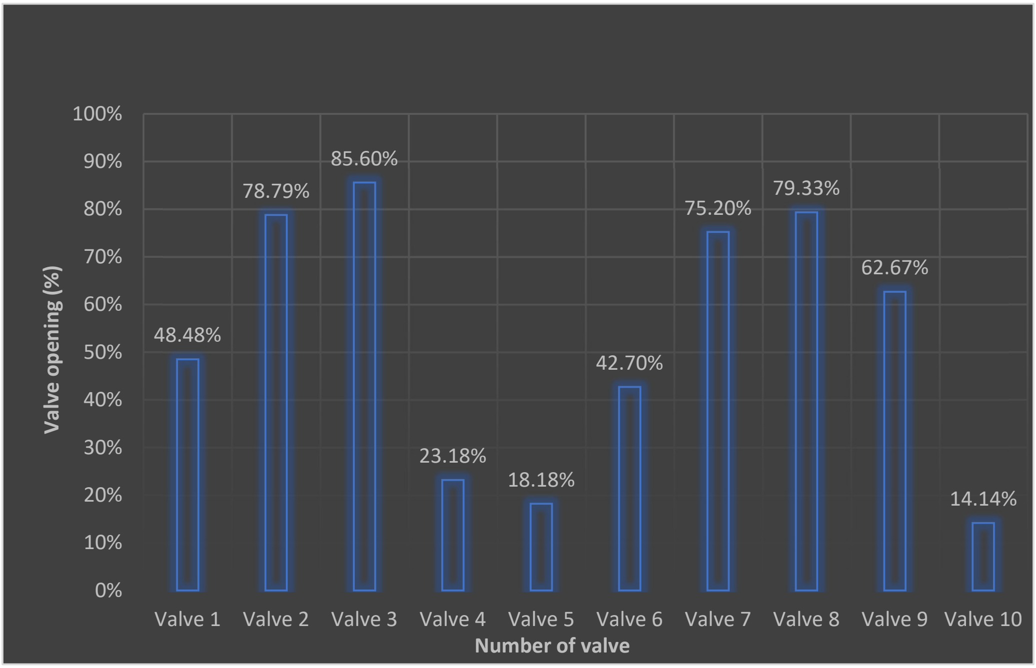


Figure 6. Valves opening (%) in Bi-axis training system (treatment "B").

Figure 7 presents the data on the percentage of valve opening in the UFO (Upright Fruiting Offshoots) training system (treatment "C"). The treatment "C" offers a simplified approach to training, pruning and maintaining fruit trees, leading to increased efficiency. It facilitates the growth of productive fruiting shoots vertically from a single horizontal trunk, forming a fruiting wall that can be renewed. The system exhibits early fruit-bearing capabilities and requires minimal pruning. It is well-suited for deployment in a single vertical plane with approximately five trellising wires. As a result, the treatment "C" shows great promise for improving fruit tree management and maximizing productivity.

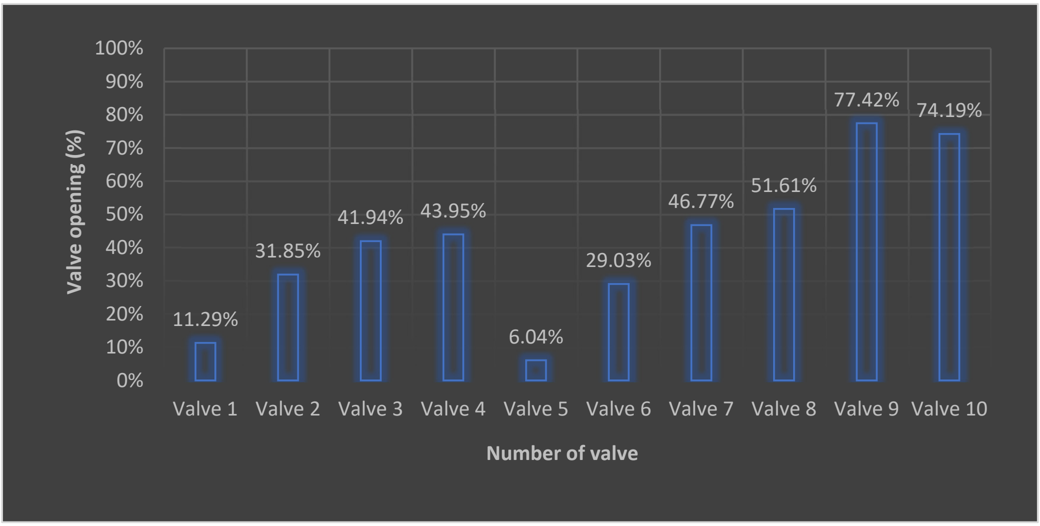


Figure 7. Valves opening (%) in one UFO training system (treatment "C").

Maximum canopy and trunk coverage with the treatment "C" occurs at a height of approximately 50 to 70 cm. The results show that nozzles 9 and 10 remained open the longest, consistent with the treatment "C" system's characteristics, indicating greater circulation in that specific area. Coverage decreased on the left side of the mist blower, where nozzle 5 was among the least open. Further analysis in the orchard revealed that nozzle 5 was obstructed by the taller trunks of the treatment "C" system, as those trees are older.

To provide a comprehensive analysis and comparison of different training systems for plum orchards, our experiment included a Combined training system (treatment "D") that combined all three previously mentioned systems in roughly equal proportions. The results, shown on Figure 8, revealed potential savings of 55.06% PPPs, which highlights the efficiency of the sensor system in optimizing PPP application across various training systems.

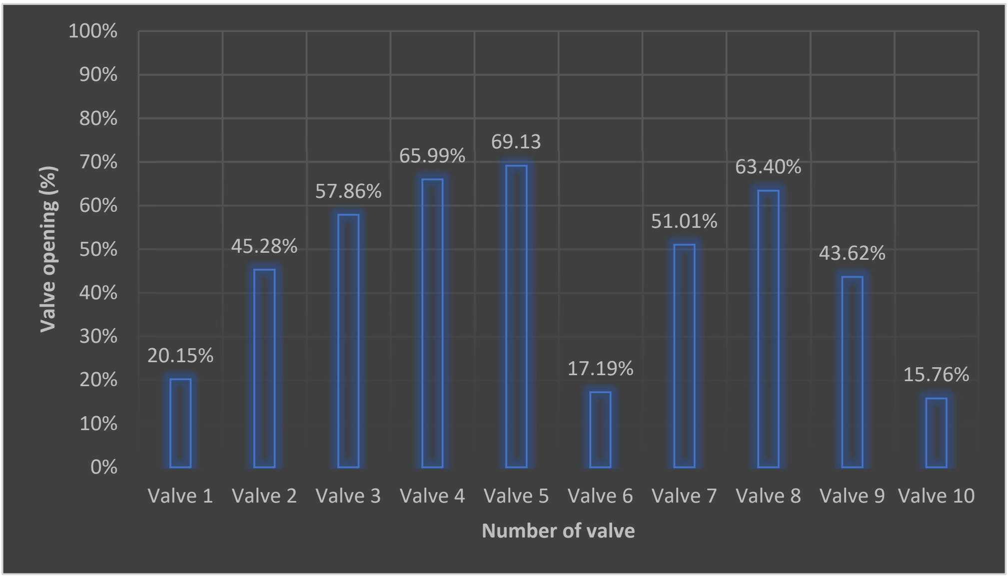


Figure 8. Valves opening (%) in Combined training system (treatment "D").

The graph in Figure 9 presents the average valve opening and the corresponding savings for each individual treatment, with the highest savings observed in Treatment "A" and the lowest in Treatment "B". The graph below presents the average valve opening and the corresponding savings for each individual treatment.

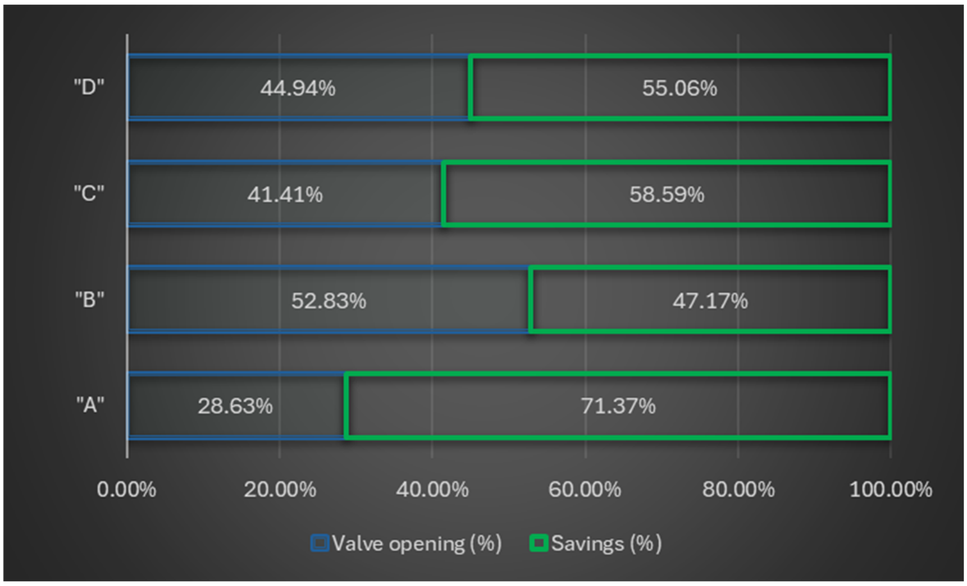


Figure 9. The average valve opening (%) and the corresponding savings (%) after each individual treatment.

One of the aims of our study was to examine differences in the number of electromagnetic valve actuations in different training systems. We used the Kruskal–Wallis test to test whether there were statistically significant differences in performance among four groups of training systems. The results of the Kruskal–Wallis H test showed that there is no statistically significant difference between the four training systems in a plum orchard, H(3) = 4.58, p = 0.206. As shown in Table 1, the median performance for all groups of training systems was similar, and the ranges of values were also similar.

Table 1. Results of the performed Kruskal–Wallis H test.

Kruskal–Wallis H	4.576
Df	3
Asymp. Sig.	0.206
a. Kruskal–Wallis Test	
b. Grouping Variable: Groupings	

In order to provide a more complete understanding of the data and to gain additional insight into the natural variation, we visualized four boxplots based on the data in Figure 10. The boxplots show the distribution of the data for four groups (training systems) based on the triggering of the electromagnetic valves. The boxplots display the median (bold black line), quartiles (bottom and top of the box), and the smallest and largest observed values that are not outside the range (whiskers). Based on the graph, it can be observed that the data in all four groups are relatively symmetrically distributed around the median, indicating a roughly equal distribution of values in each group. It also appears that all four groups have approximately the same range of values, as all boxes are of similar size. In order to present more accurate results, we performed pairwise comparisons of groupings with adjusted p-values (Bonferroni correction) for each comparison. According to the results of the pairwise comparisons, statistically significant differences are only found between the two groups (treatment "A"–treatment "B"). This means that there are differences in the percentage of valve openness between the treatment "A" and treatment "B" systems. Other comparisons showed no statistically significant differences at the 0.05 significance level after adjustment for multiple testing. From the obtained results, it can be deduced that variations in canopy shapes or distinct training systems may exert an influence on valve triggering or the distribution of PPPs. This assertion is based on the observed distinctions between the One-axis and Bi-axis training systems. The former features a single dominant trunk, while the latter possesses two primary axes (rectangular V-shape), leading to divergent orientations and branch distributions.

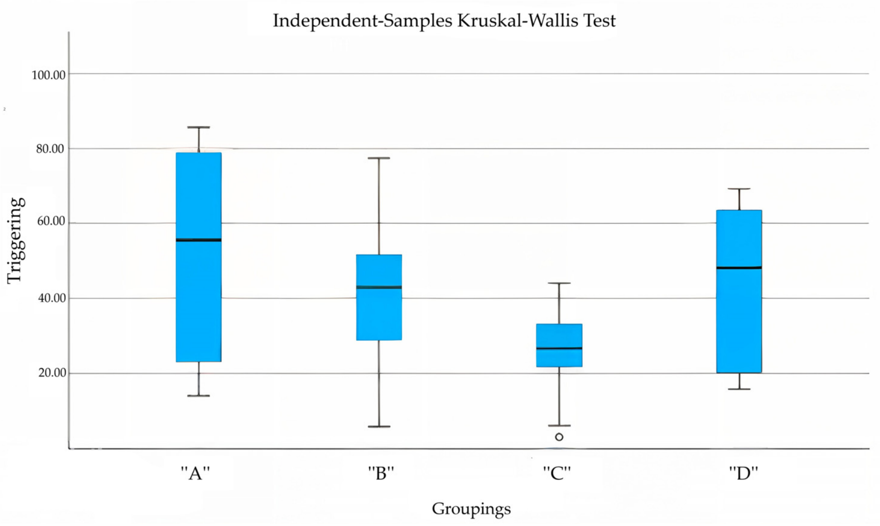


Figure 10. Boxplots of estimated correlation between the training systems.

Nevertheless, it is imperative to acknowledge that a comprehensive understanding of the precise disparities between the treatment "A" and treatment "B" training systems necessitates further in-depth analysis. This analysis could encompass considerations of additional factors, including but not limited to microclimatic conditions and soil characteristics.

4. Discussion

Plum orchards are notorious for their high labor requirements, and traditional training systems with uneven canopy distribution often lead to inefficient spraying, resulting in environmental and health concerns. However, implementing appropriate training systems and understanding the structural characteristics of orchards can optimize the application of PPPs. Upgrading to advanced spraying equipment, particularly sensor-based systems, can reduce costs, increase yield and crop quality, minimize labor, and most importantly, enhance application efficiency. Automating the spraying process with sensor technology enables precise control and adjustment, ensuring targeted application based on canopy characteristics.

This study assessed the feasibility and potential effectiveness of an automated sensor system for targeted PPP application in various training systems in plum orchards. By employing SLAM (simultaneous localization and mapping) technology, the system enables precise activation of electromagnetic valves in response to canopy features, aligning spray application with the orchard's actual needs. The results revealed significant PPP savings, ranging from 47.17% to 71.37% compared to traditional methods (100% open valves), underscoring the technology's potential to reduce environmental impact and lower costs for farmers.

By analyzing the spatial variability and dimensions of the canopy, the study identified opportunities to minimize PPP application and optimize the use of sensor systems. The inclusion of diverse training methods, such as One-axis, Bi-axis, Upright Fruiting Offshoots (UFO), and a Combined system, allowed for a comprehensive evaluation of their impact on sensor performance. For instance, the Bi-axis system, with its more uniform canopy distribution, demonstrated enhanced sensor efficiency, consistent with findings that canopy structure influences PPP application efficiency [16].

These findings align with prior research utilizing technologies like LiDAR for targeted spraying in orchards (e.g., [16–18]). As shown in these studies, accurate canopy characterization reduces PPP usage by aligning dosage with actual requirements. LiDAR's ability to measure canopy volume and shape is instrumental in optimizing spray application [17]. Our study extended these findings by demonstrating the value of SLAM algorithms, which synchronize sensors with tractor speed, further enhancing flexibility and precision.

The implications of this research are significant. First, integrating sensor-based systems with advanced mist-blowing equipment offers practical solutions for achieving environmental stewardship while maintaining high-quality fruit production. Second, the system supports the European Union's goal of reducing pesticide use by 50% by 2030 [9]. By optimizing resource utilization, this technology addresses critical sustainability goals, contributing to a shift toward eco-friendly orchard management practices.

However, the study's limitations should be noted. It was conducted on a single orchard, limiting the scope of generalizability. Additionally, direct analyses of spray deposition and long-term impacts on plant health were not included, though these would further substantiate the results. Challenges such as high initial equipment costs, the need for regular calibration, and environmental factors like dust, fog, and rain remain critical areas for further investigation [6,20].

While the current system demonstrates the feasibility of an on/off control mechanism for precision spraying, future improvements are essential. Incorporating pulse-width modulation (PWM) technology could enable dynamic spray intensity adjustments based on canopy features like Leaf Area Index (LAI) or tree density, enhancing chemical efficiency, particularly in areas with sparse foliage. Integrating LAI sensors or advanced algorithms for real-time canopy density assessment would further refine the system's targeting accuracy.

Enhancing computational power, such as upgrading from a Raspberry Pi 4 to a more robust processing unit, could facilitate faster data analysis and finer control, broadening the system's applicability to various orchard types and training systems.

In conclusion, the practical application of this sensor system in plum orchards demonstrates clear benefits, including significant PPP cost savings, improved sustainability, and reduced environmental impact. This technology represents a pivotal advancement in precision agriculture, offering scalable solutions for resource-efficient farming. Its adaptability also opens avenues for implementation in other permanent crops, underscoring its potential to shape the future of sustainable agriculture. By adopting innovative, sensor-driven spraying methods, fruit growers can realize early returns on investment while contributing to ecological preservation and advancing the goals of sustainable agricultural practices worldwide.

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