INTELLIGENT SYSTEM FOR SPRAY MIXTURE MANAGEMENT IN TRADITIONAL GRAPE PRODUCTION

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Abstract: *Conventional application methods of plant protection products (PPPs) in viticulture lack the capability for automated dose regulation based on the morphological characteristics of individual grapevines. This often results in excessive use of PPPs and contributes to negative environmental impacts. By integrating Light Detection and Ranging (LiDAR) technology with advanced control algorithms for spray mixture management, the application process was optimized at the level of individual nozzles. Experimental implementation of the automated system in vineyard conditions demonstrated a significant reduction in PPP usage by a maximum average of 55.78% on specific nozzles compared to conventional application methods. These findings indicate a substantial improvement in dose precision and adaptability to canopy variability, leading to enhanced sustainability in grape production through reduced chemical input and lower environmental burden.*

Key words: *control, plant protection product, automation, LIDAR, vineyard*

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This Publication has to be referred as: Stajnko, D[enis]; Pausic, A[ndrej] & Berk, P[eter] (2025). Intelligent System for Spray Mixture Management in Traditional Grape Production, Chapter 07 in DAAAM International Scientific Book 2025, pp.089-102, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734-45-7, ISSN 1726-9687, Vienna, Austria
DOI: 10.2507/daaam.scibook.2025.07

1. Introduction

In recent decades, the use of plant protection products (PPPs) has significantly contributed to increased productivity in fruit and vegetable production, enabling farmers to minimize crop losses caused by pests, weeds, and diseases (Ghimire & Woodward, 2013). According to Sharma et al. (2019), global PPP usage amounts to approximately 2 million tonnes annually. Data from the Farm Accountancy Data Network (FADN) of the European Union indicate that PPPs constitute a substantial economic input in agriculture, accounting for up to 12.5% of total production costs in certain EU regions. In viticulture, the application of pesticides is essential for effective control of major fungal diseases such as downy mildew (*Plasmopara viticol*a), powdery mildew (*Erysiphe necator*), and grey mold (*Botrytis cinerea*), all of which can cause considerable yield reductions if not adequately managed. Conventional viticultural practices have traditionally relied on the preventive and routine application of chemical pesticides, resulting in a considerable ecological burden through the accumulation of active substance residues in soils, water bodies, and surrounding ecosystems. The excessive and repeated use of PPPs contributes to the development of resistance in target pathogenic organisms, thereby diminishing the long-term efficacy of crop protection strategies. Furthermore, in numerous wine-producing regions, soils exhibit elevated levels of heavy metals and fungicide residues particularly copper-based compounds which tend to accumulate in the pedosphere as a consequence of prolonged and intensive application. Confronted with the risks associated with conventional viticultural practices, modern viticulture increasingly adopts integrated plant protection strategies, which entail a coordinated combination of biological, agrotechnical, and mechanical control measures, alongside a reduced and more targeted application of plant protection products. Möth et al. (2021) demonstrated that vineyards employing integrated pesticide management exhibit higher densities of predatory mites and enhanced ecosystem services, attributable to reduced pesticide use and more diverse vegetative cover in inter-rows. Additionally, Grella et al. (2024) is developing disease-resistant grapevine cultivars and best practice guidelines aimed at reducing fungicide dependency by 50–80%, reinforcing the role of resistant varieties within a broader IPM framework. A critical component of sustainable viticultural systems is the deployment of advanced digital-modular technologies that facilitate the systematic acquisition, processing, and analysis of data concerning vine physiology, microclimatic variables, and the efficacy of protective interventions. Such technologies enable the controlled execution of operations in vineyards, particularly pesticide spraying where the dosage of PPPs is automatically adjusted in accordance with metrics such as leaf mass density or green wall dimensions. For example, in a field validation study in apple orchards, a variable rate application (VRA) sprayer equipped with ultrasonic sensors was able to reduce PPP usage by up to 35% compared to conventional constant-rate methods, by adapting spray rate to canopy width and density (Salas et al., 2025). The implementation of modular automated control systems for PPP application, integrating advanced technologies such as Global Positioning System (GPS), Light Detection and Ranging (LiDAR) sensors, intelligent dose-adjustment algorithms, and Internet of Things (IoT) frameworks, has been demonstrated to enable pesticide use reductions exceeding 30% (Salas et al., 2025).

This integrative approach confers multiple benefits, encompassing environmental sustainability and economic efficiency, by optimizing the spraying process, decreasing production costs, and enhancing crop quality through the reduction of pesticide residue levels (Balafoutis et al., 2017).

1.1 Empirically derived models characterizing pesticide dynamics in viticultural systems

Empirical models for determining the appropriate doses of PPPs in permanent crops such as vineyards and orchards are commonly based on observed correlations between the quantity of PPPs applied and the morphological characteristics of the plants within a given plantation structure. In Slovenia, for example, a traditional empirical approach referred to as the "hectare dose" is employed, wherein PPP consumption is expressed per unit of surface area, typically per hectare of vineyard (OIV, 2025).

This model is based largely on experiential knowledge, general observations, and average plantation attributes, without taking into account the precise morphological parameters of the crop, such as plant shape, canopy size, density, or specific protection requirements. In contrast, more developed EU countries increasingly rely on the Leaf Wall Area (LWA) model for determining PPP dosages in permanent crops, particularly vineyards and orchards (AGRIS, 2025). The LWA model is grounded in the premise that the required amount of PPP is proportional to the actual leaf surface area exposed for treatment, thus providing a more accurate and crop-specific measure than traditional hectare-based approaches, which are limited to surface area considerations alone.

Contemporary digital empirical models facilitate precise regulation of PPP dosages in permanent crops such as vineyards and orchards by leveraging advanced technologies for adaptive dosing. These models account for actual morphological and structural plant characteristics (e.g., canopy size, leaf area density, plant volume), plantation architecture, and prevailing environmental conditions. The principal objective of implementing such digital models is to optimize the quantity and spatial distribution of PPP applications, thereby enhancing application efficiency while mitigating environmental impacts associated with PPP usage (Rakun et al., 2024). Notable implementations of digital PPP dose management in permanent plantations include sensor-guided adaptations utilizing technologies such as LIDAR, ultrasound, and computer vision systems; GPS-enabled variable rate application; modular IoT platforms equipped with remote monitoring and data analytics; decision-support algorithms; and electronically controlled valves and nozzles (Partel et al., 2021, Pathmudi et al., 2023).

Collectively, these digital control strategies have demonstrated potential reductions in PPP consumption by 30–50%, improvements in spraying efficacy, diminished environmental contamination through reduced drift of PPP droplets into air, soil, and water, compliance with sustainable agriculture principles and European Union regulatory frameworks, and enhanced traceability and digitalization within agricultural practices.

1.2 Quantitative digital assessment of grapevine morphological and physiological traits

Accurate quantification of the geometric properties of the vine canopy (e.g., height, width, volume, and the extent of the leaf wall area) is critical for the spatially targeted application of PPP in vineyards. This precise characterization substantially facilitates the optimization of PPP dosage, leading to a reduction in overall chemical usage and mitigating adverse environmental effects on the surrounding ecosystem.

Recent advancements in sensor-based measurement technologies and computer vision have facilitated the development of three-dimensional analytical systems capable of accurately quantifying the morphological and structural characteristics of grapevines. The digitization of canopy traits in permanent vineyard systems enables the implementation of highly precise, objective, and reproducible methods for assessing both morphological and physiological parameters relevant to viticulture (Petrovič et al., 2022). Among the most widely adopted methodological approaches is the analysis of high-resolution imaging data, acquired via RGB, multispectral, or hyperspectral cameras and sensors.

These technologies allow for detailed and spatially explicit quantification of vegetation attributes. Furthermore, such systems may be integrated with continuous, non-destructive monitoring of auxiliary parameters, such as soil moisture content, thus enhancing the overall precision of vineyard management practices. Computer vision and image processing algorithms enable the automated extraction of key morphological parameters of grapevines, including leaf area estimation, canopy volume calculation, quantification of the vegetative-to-generative biomass ratio, and monitoring of phenological development stages (Petrovič et al., 2022).

These vision-based measurement systems provide non-invasive, reproducible, and temporally continuous observation of grapevine growth dynamics throughout the entire growing season, thereby supporting data-driven decision-making in precision viticulture. LIDAR technology is an optical measurement sensor based on the emission of light rays (most often laser) and the analysis of their reflection from various types of surfaces, which enables precise measurement of distances in polar coordinates and the creation of three-dimensional models of objects and surfaces.

Using laser LIDAR measurement systems, data on two-dimensional and three-dimensional geometric characteristics of objects is obtained, whereby, based on the analysis of the number of hits of laser pulses or the generated point cloud, the characteristic structure and density of the green wall of the leaf surface in the habitus of perennial plantations can be determined (Berk et al., 2021). The use of laser measurement sensors brings numerous advantages, as it allows measurements of the leaf surface of grapevine crowns in real time, while at the same time low costs of sensor integration into spraying sets of conventional sprayers and enables the capture of spatial data on larger areas of the plantation.

1.3 Advanced automated application systems enabling spatially variable dosing of plant protection products in perennial crop management

Accurate regulation of spray application rates constitutes a fundamental component of sustainable and technologically advanced plant protection strategies, as it significantly influences both the efficacy of treatments and the mitigation of environmental impact. Conventional spraying techniques typically rely on fixed or manually controlled flow rates, often lacking real-time responsiveness to field variability. This can result in the over-application of PPPs, leading to unnecessary input use and increased ecological burden. In contrast, contemporary automated application systems facilitate the dynamic modulation of spray volumes in response to critical operational and biological parameters, including sprayer travel speed, system pressure, working width, and the phenological stage of crop development (Berk et al., 2019). Such adaptive technologies are essential for advancing precision agriculture and minimizing off-target losses. In the early development of automated spraying systems, sprayers were commonly equipped with electromagnetic valves (EMVs) and ultrasonic sensors for canopy detection. The regulation of PPP dosages was typically governed by a binary ON/OFF control logic, representing a basic level of automation with limited adaptability to spatial or morphological variability in canopy structure. An example of such a system is the TeeJet 844-AB spray system, developed by TeeJet Technologies (USA), which is specifically designed for the precise control of PPP application in perennial cropping systems, particularly in orchards and vineyards. This system enables accurate regulation of spray application by allowing selective activation or deactivation of EMVs, facilitating targeted PPP delivery at different canopy heights. Moreover, the system supports segmented control of spray boom sections, which is especially beneficial when tree canopies do not extend to their full vertical development. This capability prevents unnecessary spraying in the upper zones, thereby reducing PPP usage and minimizing environmental contamination risks (Berk et al., 2022). Flow-based control represents one of the fundamental yet crucial approaches in automated dosing systems and is widely implemented in contemporary technologies for the precise application of PPP (Berk et al., 2022). This control strategy involves the real-time adjustment of spray output volume in accordance with the instantaneous travel speed of the sprayer, thereby ensuring a consistent application rate per unit area (e.g., L ha^{-1}). By dynamically regulating flow to match operational speed, flow-based control systems contribute significantly to the accuracy and efficiency of PPP applications, minimizing both over- and under-application across variable terrain and crop structures.

In recent years, Pulse-Width Modulation (PWM) technology has emerged as a highly advanced approach for the automated and precise regulation of PPP application rates. This system operates by electronically controlling the duty cycle of EMVs on individual spray nozzles, allowing them to open and close at high-frequency intervals (Berk et al., 2022). PWM facilitates precise regulation of spray flow rates without necessitating changes in system pressure, effectively decoupling droplet size from application volume.

This capability enhances dose uniformity, improves spray deposition accuracy, and minimizes off-target drift, particularly under variable canopy architectures and heterogeneous field conditions. Numerous practical applications have been developed addressing automated PPP spraying in vineyards. Recently, an automated dosing system was developed within the scope of a research project, which employs ultrasonic sensors for real-time detection of vineyard canopy depth. The modular automated system operates based on an advanced algorithm that digitally estimates the plant canopy volume quantified via the Tree Row Volume (TRV) method using measured parameters of the green wall (height and width) alongside the sprayer's instantaneous travel speed. Subsequently, the system dynamically adjusts the PPP application rate in accordance with the phenological development stage of the vine. Field trials demonstrated that the implementation of this automated application technology resulted in up to a 22% reduction in PPP consumption compared to conventional spraying methods, thereby substantiating its efficacy in optimizing plant protection product application processes (Moreno et al., 2020). This chapter aims to provide a comprehensive overview of: (i) the digital assessment of grapevine morphological and physiological characteristics, (ii) automated application methodologies for precise regulation of plant protection product (PPP) dosages in perennial cropping systems, and (iii) empirical evaluation of an automated spraying mixture control system.

2. Materials and methods

A practical evaluation of an automated spray mixture control system was conducted in an intensive vineyard planted with the *Sauvignon blanc* variety, aged six years. The experiment was conducted in a vineyard owned by the agricultural holding Puklavec Family Wines, located at Kolodvorska cesta 11, 2270 Ormož, Slovenia. The experimental plot covered an area of 1.40 hectares, comprising a total of 5,278 grapevines. The precise coordinates of the vineyard are 46°28'38.2"N, 16°13'53.0"E (Fig. 1).

Fig. 1. Overview of the experimental site (left) and the modified conventional sprayer equipped with a real-time spray mixture control system (right).

The vines were grafted onto the rootstock *SO4*, known for its excellent compatibility with *Sauvignon blanc*, and commonly used in various Slovenian wine-growing regions (Fig. 1). The vineyard was established with an inter-row spacing of 240 cm and an intra-row spacing of 90 cm between vines. The training system employed was a single-Guyot training system, consisting of a cane bearing up to ten buds and a spur with one to two buds, with the vine trunk height maintained at 90 cm. During the growing season, a total of seven spray treatments were applied using an intelligent spray mixture management system, integrated into a conventional sprayer (Fig. 1).

Intelligent automated systems for continuous control and monitoring of spray mixture dosage in real-time were installed on a conventional axial type of sprayer Dragone K2, V700, manufacturer (Dragone Macchine Agricole, Piemont, Italia) and tested it under real conditions in the vineyard. The system was used to control the optimal dosage of the spray mixture on three segments of the left and right halves of the vine canopy, according to the size of the density of the green leaf wall area, which is digitally defined using laser measurement technology (Petrovič et al., 2022).

Continuous monitoring and control of spray mixture dosage (ranging from 0% to 100%) was performed at the level of individual nozzles (*Albuz ATR 80 Orange*) using electromagnetic valves (*TeeJet 115880-2-12 Dynajet*), operating under a modern PWM system (Fig. 2). Compared to previous setups, the intelligent modular control system was upgraded with an integrated IoT module (Fig. 2b) and enclosed in a metal housing compliant with IP65 protection standards.

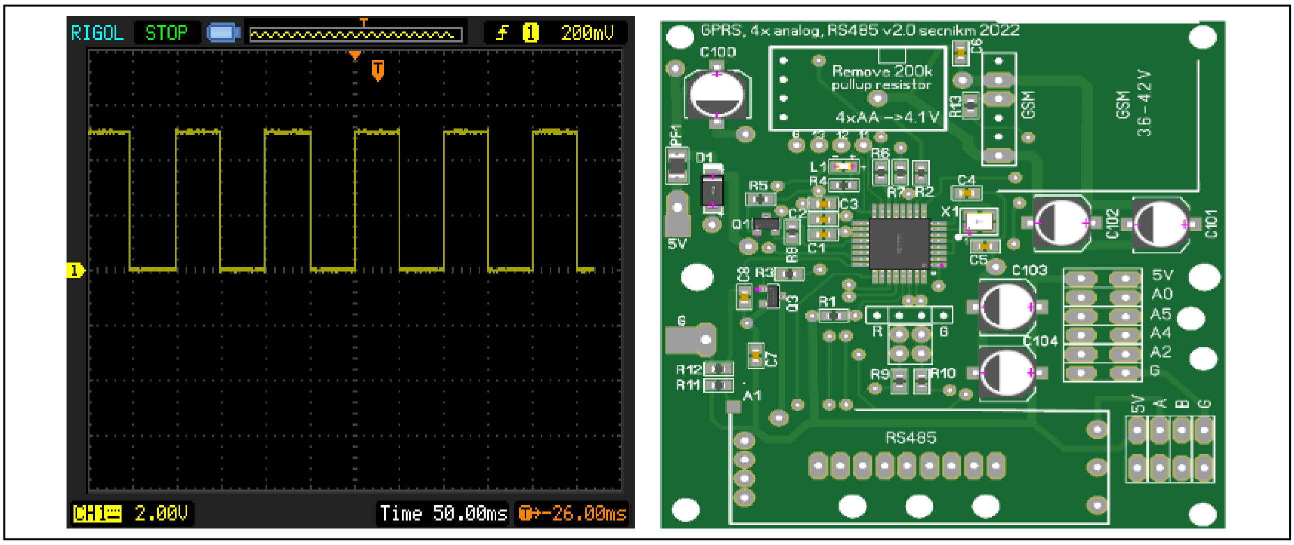

Fig. 2. PWM-based control of electromagnetic valves (left) and IoT electronic module for real-time monitoring of spray mixture dosage rates (right).

The IoT module enabled real-time acquisition and visualization of dosage rates per nozzle on both the left and right boom sections. These data were displayed in tabular format on a dedicated web interface for remote monitoring and analysis. An automated sprayer prototype was mounted on a fruit-growing tractor, operating at an average spraying speed of 8.0 km/h^{-1}.

The sprayer was equipped with Albuz ATR orange nozzles (80°) i.e. four left and four right, side, operating at a pressure of 8 bar, delivering a flow rate of 1.25 L min^{-1}. For automated control of the spray mixture dosage across three segments of the vine canopy, TeeJet 115880-2-12 DynaJet solenoid valves were employed. These valves are normally closed, solenoid-actuated shutoff valves, commonly used in agricultural spraying systems for individual nozzle control, including in pulse-width modulation (PWM) systems.

The typical electrical current draw for each valve is approximately 0.9 A (≈ 10 W) at 12 V. In the vineyard experiment, a LakiBeam 1S – 270° industrial-grade single-line 2D ToF LiDAR sensor (manufacturer: Richbeam (Beijing) Technology Co., Ltd., China) was utilized as a component for measuring two polar coordinates: distance and polar angle. The LakiBeam 1S is a single-line, two-dimensional LiDAR device based on the Time-of-Flight (ToF) measurement principle. It performs scanning via a rotating mirror across a 270° horizontal field of view, enabling wide-angle detection of the surrounding environment. Designed for industrial and robotics applications, the sensor is well-suited for short- to medium-range detection with high measurement precision. It supports two scanning modes, providing an angular resolution of 0.2° at a scan rate of 10 Hz, and 0.5° at 20 Hz. Using LiDAR-based measurement technology, it was possible to digitally reconstruct characteristic features of the vine canopy specifically, the size and density of the leaf wall area across different phenological stages of vine development, which in turn influence spray mixture dosage requirements (Berk et al., 2019)." The IoT module is composed of two primary components: the Atmega328P microcontroller and the SIM800L GSM/GPRS communication module. The Atmega328P is a high-performance, picoPower® 8-bit AVR® RISC-based microcontroller by Microchip, featuring 32 KB of in-system programmable Flash memory with read-while-write capabilities, 1 KB EEPROM, 2 KB SRAM, 23 general-purpose I/O lines, and 32 general-purpose working registers. The SIM800L is a compact GSM/GPRS module designed for integration into a wide range of IoT applications, providing mobile connectivity for data transmission.

In this application, the IoT module serves as an enhancement to the automated modular system for precision spray application in vineyards. It performs real-time monitoring of the average spray mixture dosage rate through individual nozzles and transmits this data every 5 seconds. The core function of the module is to capture dosage data and transmit it via the GSM network to an SQL database. This enables real-time visualization and monitoring of spray mixture dosage rates through a web-based interface.

3. Results

A key achievement in the development of the intelligent spray mixture management system for traditional grape production was the successful testing of an automated modular system, integrated with a conventional sprayer, specifically the Dragone K2, V700 model.

The modular system enabled real-time, in-field monitoring and continuous control of spray mixture dosage rates applied to the green leaf wall area, facilitated through IoT technology. The dosage control was performed via EMVs operating in PWM mode, allowing precise regulation of mixture delivery.

Date of application	PPP	PPP price (EUR per Kg or L)	PPP dosage (kg or L/Ha)	PPP price [$EURh^{-1}$]
2024_5_19	Reboot	104	0.35	36.40
	Karathane gold	43	0.50	21.50
2024_5_29	Valis F	34	1.20	40.80
	Kusabi	115	0.30	34.50
	Cosan	3	6.00	18.00
2024_6_10	Reboot	104	0.35	36.40
	REVYONA®	18.7	1.50	28.05
	Cosan	3	6.00	18.00
2024_6_21	Zorvec Vinabel	138	0.52	71.76
	Dynali	57.83	0.65	37.58
	Vosan	3	6.00	18.00
	Mospilan 20 SG	136	0.37	50.32
2024_7_3	Folpan Gold	27.3	1.61	43.95
	Luna experience	85	0.50	42.50
	Cosan	3	6.00	18.00
	Mavrik 240 EW	77.34	0.20	15.47
2024_7_15	Valis F	38.44	1.70	65.35
	Dynali	57.83	0.65	37.59
	Cosan	3	0.65	1.95
2024_7_28	Ampexio	25	0.47	11.75
	Tebusha 25 EW	24.8	0.4	9.92
	DECIS 100 EC	81.3	0.5	40.65

Tab. 1. Technological instructions, including the spraying schedule and prices of PPP, applied for disease management in the vineyard during the 2024 growing season.

Date of application	**Nozzle 1-left dosage savings [%]**	**Nozzle 2-left dosage savings [%]**	**Nozzle 3-left dosage savings [%]**	**Nozzle 4-left dosage savings [%]**	**Average dosage savings on the left side of the automated sprayer [%]**	**Average dosage savings on the left side of the automated sprayer [Lha^{-1}]**	**Conventional spray mixture dosage, left side [Lha^{-1}]**
2024_5_19	47.36	31.38	Not active	Not active	39.37	30.51	77.50
2024_5_29	33.34	24.08	55.78	Not active	37.73	43.86	116.25
2024_6_10	46.35	27.75	36.94	Not active	37.01	43.02	116.25
2024_6_21	36.59	23.43	26.52	24.59	27.78	43.06	155.00
2024_7_3	33.56	22.00	23.27	32.62	27.86	43.18	155.00
2024_7_15	35.97	24.66	25.59	33.66	29.97	46.45	155.00
2024_7_28	35.41	24.54	25.44	20.46	26.46	41.01	155.00
Date of application	**Nozzle 1-right dosage savings [%]**	**Nozzle 2-right dosage savings [%]**	**Nozzle 3-right dosage savings [%]**	**Nozzle 4-right dosage savings [%]**	**Average dosage savings on the right side of the automated sprayer [%]**	**Average dosage savings on the right side of the automated sprayer [Lha^{-1}]**	**Conventional spray mixture dosage, right side [Lha^{-1}]**
2024_5_19	46.97	30.31	Not active	Not active	38.64	29.95	77.50
2024_5_29	33.33	24.47	50.56	Not active	36.12	41.99	116.25
2024_6_10	50.44	28.49	33.35	Not active	37.43	43.51	116.25
2024_6_21	45.04	23.56	24.83	37.45	32.72	50.72	155.00
2024_7_3	43.05	22.03	21.84	28.48	28.85	44.72	155.00
2024_7_15	43.03	24.85	24.58	30.50	30.74	47.65	155.00
2024_7_28	42.77	24.54	24.26	29.86	30.36	47.06	155.00

Tab. 2. Comparative assessment of spray mixture consumption under automated versus conventional sprayer operation modes in the 2024 growing season.

Monitoring of the dosage rate consumption through individual nozzles, separately for the left and right sides of the sprayer is presented in Tab. 1. The table outlines the spraying program used during the experiment, which was aimed for controlling common vineyard diseases such as downy mildew (*Plasmopara viticola*) and powdery mildew (*Erysiphe necator*) under traditional grape production conditions.

In the vineyard experiment, spray mixture dosages were determined under two operational modes of the sprayer. In the first, conventional mode, dosages were applied to the green leaf wall area based on an empirical model corresponding to the standard hectare application rate. In the second, automated mode, dosage control was regulated according to the digitally assessed leaf wall density of the vine canopy, as described by Berk et al. (2022). Tab. 2 presents the percentage of spray savings achieved with automated operation. To optimize the application process, additional field experiments were carried out, varying the number of active nozzles on the automated sprayer prototype. The number of activated nozzles was adjusted according to the phenological growth stage of the vines.

Tab. 3 presents the analysis of PPP savings, expressed EUR, for both the left and right sides of the spray boom on the automated sprayer prototype. The analysis was conducted separately for each spray application event throughout the 2024 season. In evaluating dosage savings, the assessment was based on the predefined spraying program implemented during the regular seasonal protection schedule.

Aplication date	**Price for PPP / ha**	**Average dosage savings on the left side of the automated sprayer [%]**	**Savings (EUR), left side**	**Average dosage savings on the right side of the automated sprayer [%]**	**Savings (EUR), right side**
2024_5_19	57.9	39.37	11.39	38.64	11.18
2024_5_29	93.3	37.73	17.60	36.12	16.84
2024_6_10	82.45	37.01	15.25	37.43	15.43
2024_6_21	177.66	27.78	24.67	32.72	29.06
2024_7_3	119.92	27.86	16.70	28.85	17.29
2024_7_15	104.88	29.97	15.71	30.74	16.12
2024_7_28	62.32	26.46	8.24	30.36	9.46
TOTAL savings (EUR/ha)			109.59		115.41

Tab. 3. Evaluation of PPP savings [EUR] on left and right side of spraying boom.

The automated spraying process was conducted seven times during the growing season, with a variable number of active nozzles per application. During the first two spray events, four nozzles were activated two on each side of the automated sprayer prototype. For the second and third applications, six nozzles were used, while eight nozzles were activated for the final four treatments. The total spray mixture savings across all seven automated applications amounted to 291.09 $L \cdot ha^{-1}$ on the left side and 305.60 $L \cdot ha^{-1}$ on the right side of the sprayer.

The total PPP savings were estimated to 109.59 EUR·ha^{-1} for the left side and 115.41 EUR·ha^{-1} for the right side, as presented in Tab. 3. Spraying was done in two sprayer setting modes, with and without sensor-guided dosing of the amount of spray per hectare. Plots with the first or second sensor operation mode were divided into four sub-plots. Diseases infestation rate analysis was done according to EPPO (European Plant Protection Organisation) standards by direct visual scouting of % infestation area of leaves or grape clusters. 200 randomly chosen leaves or grape clusters were assessed per plot by several teams a season. The followed EPPO standards were used: PP1/4(4) *Uncinula necator*, PP1/17(3) - *Botryotinia fuckeliana* on grapevine and PP1/31(3) – *Plasmopara viticola*. The rate of fungal attack on leaves and grape clusters was assessed by visual scouting of % diseased area (Tab. 4). 200 leaves and 200 grape clusters were evaluated on each sub-plot. Leaves and grape clusters were randomly chosen in different parts of the grape-green wall.

Spraying method	**Plasmopara viticola**		**Erysiphe necator**		
	% infected surface area of leaf	% infected surface area of bunches	% infected surface area of leaf	% infected surface area of bunches	Yield (Kg/ha)
Without sensor-guided (100 % pesticide dose)	0,005 ± 0,005 a	3,92 ± 0,710 a	0,06 ± 0,024 a	0,02 ± 0,009 a	8552,63 ± 561,636 a
Sensor-guided dosing of spray (reduced pesticide dose)	0,0 ± 0,0 a	2,93 ± 0,637 a	0,05 ± 0,020 a	0,03 ± 0,014 a	10893,4 ± 1621,62 a

[a] means marked with the same letters do not differ significantly according to the Tukey HSD test at $p \leq 0.05$.

Tab. 4. Assessment of disease incidence caused by downy mildew (*Plasmopara viticola*) and powdery mildew (*Erysiphe necator*) was conducted on August 28.

4. Conclusion

Conventional application methods of plant protection products (PPPs) in viticulture do not allow running with automated dose regulation based on the morphological characteristics of individual grapevines. This often results in excessive use of PPPs and contributes to negative environmental impacts. Contrary, numerous studies have reported significant savings in PPP usage resulting from precision spraying techniques.

However, limited evidence is available regarding the impact of such reductions on the efficacy of disease control. By integrating Light Detection and Ranging (LiDAR) technology with advanced control algorithms for spray mixture management, the application process was optimized at the level of individual nozzles. Experimental implementation of the automated system in vineyard conditions demonstrated a significant reduction in PPP usage by a maximum average of 55.78% on specific nozzles compared to conventional application methods. These findings indicate a substantial improvement in dose precision and adaptability to canopy variability, leading to enhanced sustainability in grape production through reduced chemical input and lower environmental burden. We anticipate that further advancements are achievable through focused research, particularly in areas such as PWM valve control, the integration of IoT technologies, and the interaction between spray distribution and plant-pathogen dynamics. In the short term, IoT-based systems offer the potential for rapid and efficient evaluation of spray coverage on the green leaf wall area. Furthermore, novel analytical approaches may yield valuable insights into the relationships among PPP reduction levels, emerging plant diseases, disease control efficacy, and overall crop yield.

5. Acknowledgements

The authors acknowledge the Ministry of Agriculture, Forestry and Food for funding the EIP project No. 33121-6/2025/13. This paper was also prepared within the framework of the national CRP project No. V4-2428 (Fly4IPM), co-financed by the Ministry of Agriculture, Forestry and Food and the Slovenian Research Agency (ARIS).

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