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Assessment of Spray Deposit and Loss in Traditional and Intensive Olive Orchards with Conventional and Crop-Adapted Sprayers

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Abstract: Plant protection product (PPP) applications to isolated olive trees are commonly performed with regular air-assisted sprayers, which are not adapted to their particular characteristics. Whilst strong efforts have been undertaken over the last years to improve technical aspects like canopy detection and automated proportional dosing, nearly no efforts have been made regarding the sprayer adaption to the crop. For this reason, three prototype sprayers were developed for traditional and intensive olive cultivations systems (P1: centrifugal fan; P2: six small side axial fans; P3: two axial fans in tower structure) with the purpose to improve the application efficiency. The main goal of the present study was to check spray quality and efficiency in comparison with the conventional sprayer in both cultivation systems. The sprayers were tested in two different olive groves and properly calibrated according to the tree dimensions. The spray deposition, coverage, drift, and losses to the ground were measured in five trees per cultivation system by placing the appropriate collectors. The sprayers performed very differently in both cultivation systems. In the intensive system, the spray deposition did not present significant differences ($p = 0.105$). However, it did in the traditional system ($p = 0.003$), with P3 obtaining the best results. The spray coverage followed the same trend, with significant differences only in the traditional orchard ($p = 0.011$), with the prototypes leading. The conventional equipment generated the highest spray losses in both cultivation systems. Crop adapted spraying can significantly improve the spray quality and efficiency in difficult crops like olive. This topic may have a key importance to match the environmentally sustainable use of PPP.

Keywords: prototype development; canopy detection; applied innovation; spray drift; targeted spray application

1. Introduction

Plant protection product (PPP) application is one of the most controversial aspects of modern agriculture: on the one hand, it is completely necessary to achieve high yields to ensure the "zero hunger" objective of the 2030 Sustainable Development Agenda [1], but, on the other hand, when incorrectly applied, they can generate important environmental problems [2,3]. These problems are commonly focused on important agricultural areas, such as the Guadalquivir River basin, in Southern Spain, where the most important traditional olive area in Europe is found [4,5].

Olive is a difficult crop to manage for many reasons. First, it is usually placed in high slope areas, which hinders machinery movement. Second, it is an extensive crop with

very small farms, usually with a low number of isolated trees per unit of ground area. Indeed, the hedgerow cultivation system, known as super-intensive, only accounts for 3% in Spain [6]. Last, trees are generally old and big, with very irregular crown geometries [7]. This last feature makes it very difficult to spray the tree canopy homogeneously [8].

Most tree crops are currently sprayed with air-assisted sprayers. These mainly consist of hydraulic or pneumatic sprayers with axial or centrifugal fans to convey the sprayed droplets to the target leaves and gently move the foliage to increase the spray deposition in the innermost part of the canopy [9]. Regardless of its dimension, each fan type is characterized by a combination of its airflow rate and airspeed. In general, axial fans generate high airflow rates with low airspeed, and the opposite behavior is expected from centrifugal fans [10]. Most of the air-assisted sprayers commonly used for tree crops generate an airflow capacity between 10,000 and 100,000 $m^3 h^{-1}$, depending on the fan dimension, the number of blades and their pitch, the air outlet section, and the rotary speed [10–13]. Sprayer manufacturers should optimize fan dimensions and technical specifications for the crop for which the sprayer is developed. For this reason, manufacturers created specific sprayers for different crops like vineyards, pome and stone fruits, citrus, olives, coffee, and other 3D crops [14–17]. There are also important innovations aiming to improve traditional sprayers. For example, over the few last years, manufacturers have designed sprayers equipped with multiple fans mounted in different positions to improve spray penetration due to their combined action [18–20]. Additionally, researchers have developed automatic systems for real-time adjustment of the airflow characteristics according to the needs [9,21] and/or the canopy density variation [22]. Indeed, among the main factors determining the efficacy and efficiency of a spray application, the proper adjustment of the airflow plays a key role [23]. In fact, different studies have shown that, with the proper adjustment of this parameter, hydraulic and pneumatic sprayers achieve high-efficiency rates in crops like apples or vineyards [13,24,25].

Another important problem associated with tree crops is the adjustment of the application volume rate according to the canopy characteristics (e.g., geometry, density, development along the growing season, etc.). Well-known dosing systems are the Tree Row Volume (TRV, [26,27]) and the Leaf Wall Area (LWA, [28]). Nevertheless, these methods have been reported to lack accuracy because they do not consider pivotal parameters like the leaf density of plants [29–31]. This led to authors proposing different dosing systems to significantly reduce the applied volume rates without compromising the biological efficacy of the treatments. Some of these systems are designed for vineyards, pome fruits, stone fruits, greenhouse crops, citrus crops, and olives [29,30,32–35].

Recently, different solutions have been proposed to adapt spray doses to the canopy's geometrical and physiological characteristics [33,36,37]. This approach, known as variable rate application (VRA), needs to count with appropriate canopy characterization parameters, which highly depend on the crop. For example, hedgerow-trained olive trees can be conveniently characterized by measuring their canopy height [35]. In contrast, old large-sized isolated olive trees require a full volume characterization [38]. In the first case the ultrasonic [39,40] and laser sensors [41] proved to be effective for determining canopy characteristics such as leaf density. Contrarily, to accurately determine the canopy volume of isolated trees, where each one differs from the others, more complex sensors like the Light Detection and Ranging (LiDAR) scanner [42–46] and high-resolution cameras [47–49] are needed. In most cases, sensors are installed on the sprayer, providing data about canopy characteristics in real-time. This data needs to be analyzed by a microcontroller to translate the canopy parameter values into a spray volume based on the dosing systems. The spray parameters are then adjusted by the proper actuators to achieve proportional application. The most widespread solution for VRA is based on the modification of the spray pressure to vary the liquid volume emitted by the nozzle, affecting the droplet size spectra. More recent systems work with the PWM (pulse width modulation) method [50]. The PWM method is based on modifying the spray volume by quickly opening and closing the spray nozzle several times per second. Each time the nozzle opens, its duty cycle starts. The

more time the nozzle is open with respect to the duty cycle duration, the higher the emitted volume. This system presents the advantage of keeping a constant pressure and therefore, not affecting the droplet size.

Even if VRA focuses great attention among researchers, the interaction between the airflow characteristics and the tractor's forward speed showed a major impact on both canopy deposition and off-target losses [51,52]. Some studies revealed that the sprayer air-propelling system's design caused major differences in both spray distribution and off-target losses [53–55]. In particular, the main disadvantage of centrifugal propellers lies in the fact that the airspeed cannot be adapted to the canopy width and density at every target height [54]. Therefore, to properly cover the top of the tree, the fan rotary speed needs to be increased. This leads to a significant fraction of the spray volume being delivered into the open atmosphere above the crop [56,57], resulting in spray drift in windy conditions [58,59]. Currently, there are few possibilities for reducing the distance between the spray emitters and the target canopy to minimize the spray losses. Reducing distance also allows for the reduction of the airflow rate and the airspeed, increasing the spray deposition on leaves and reducing off-target losses. To solve this problem, three air-assisted sprayer prototypes especially conceived for intensive and traditional olive orchards were developed [60]. Their main characteristic consisted of adapting the spraying elements to the tree shape to keep a constant distance between the nozzles and the target canopy. This aspect solves the main difficulty present in the traditional and intensive orchards, where trees are isolated, and the conventional sprayers importantly reduce their efficiency [61].

Immediately after their construction, the preliminary tests showed very promising results. However, it was stated that more research was necessary to determine their advantages in comparison with commercial equipment [60]. In the present study, the main goal was to test the developed sprayers to check their spray quality and efficiency against a commercial air blast sprayer in the two most common olive cultivation systems: traditional and intensive.

2. Materials and Methods

2.1. Experimental Fields and Canopy Characterization

Two experimental sections were set on a commercial olive farm in Córdoba, Andalusia, Spain (37.712 N; −4.813 W). They comprised two orchards with very different characteristics, as their trees were planted in different cultivation systems (Table 1, Figure 1). These two are the most usual systems in Southern Spain, and, importantly, differ in tree size, plantation density, and olive variety. As a result, the distance between adjacent trees is also very different; while in the intensive orchard, it is 7 m, in the traditional one, it raises to 10 m (Table 1).

Table 1. Main characteristics of the two orchards selected for the field tests of the sprayers.

Field	Cultivation System	Plantation Density	Plantation Pattern	Row Distance (rd)	Tree Distance (td)	Tree Variety
		(trees ha^{-1})		(m)	(m)	
F1	Intensive	204	Rectangular	7	7	Picual
F2	Traditional	107	Quincux	12	10	Hojiblanca

Figure 1. Sprayers treating the two studied olive orchards: (**a**) Intensive; (**b**) Traditional.

The canopy characterization was crucial to rationally adjusting the spraying parameters, and it was performed by using the Mean Vector method [42]. The Mean Vector method consists of measuring the horizontal distance from the tree trunk to the eight outermost points of the canopy profile in eight different directions (Figure 2). The MV parameter obtained with this method showed to have a strong correlation with the tree crown volume, measured with a 2D-LiDAR scanner, and it showed to be the best manual estimation for traditional trees [42].
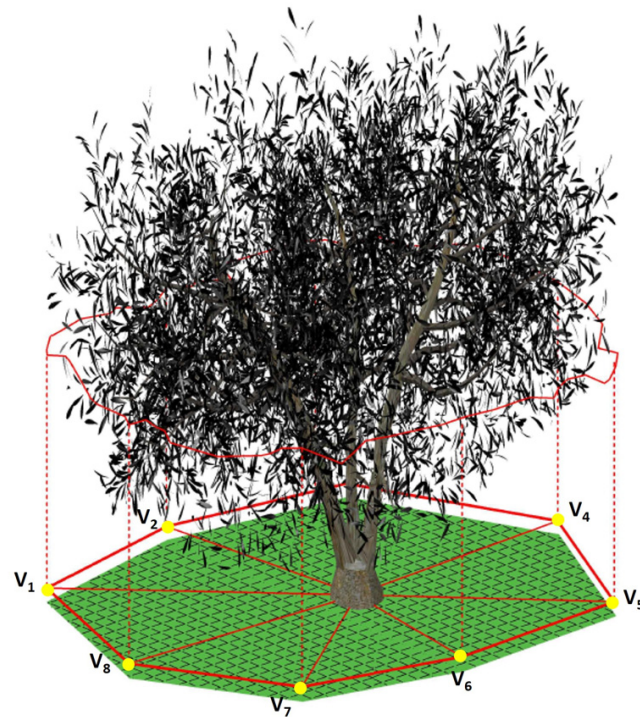
Figure 2. Mean vector (MV) measurements: vectors 1–8 are measured from the trunk to the outermost part of the tree crown in 8 fixed directions.

2.2. Spraying Equipment

Four air-assisted sprayers were compared: a conventional airblast sprayer and the three developed prototypes. The conventional equipment was equipped with a 1-m diameter axial fan (Eolojet 2200, Osuna-Sevillano, Jauja, Córdoba, Spain), hollow cone nozzles (Albuz ATR [®], Solcera Advanced Materials, Evreux, France), and ON/OFF ultrasonic sensors to only spray when the canopy was detected (Figure 3a). The first prototype (henceforth Prototype 1, P1) (Figure 3b) had a double-propeller centrifugal fan with six independent application units mounted on six mobile carrying structures. Each one of those consisted of an analogical ultrasonic sensor (mic + 600/IU/TC, Intertronic Internacional S.L., Paterna, Valencia, Spain) to control the arm movement and to enable the spray of its unit, an air outlet, and three hollow cone nozzles (Albuz ATR). The system was controlled by a specially designed microcontroller meant to remain at a 0.8 m constant distance from the outermost leaves. This prototype was specifically designed for intensive trees. Therefore, it was the only one not tested in the traditional orchard. The rest of the sprayers were tested in both cultivation systems.

The second prototype sprayer (Prototype 2, P2) (Figure 3c) presented six hydraulically-driven small-sized axial fans, three per side, with six perimetral hollow cone nozzles (Albuz ATR) each. The fans on each side of the sprayer were mounted on a mobile structure controlled by an analogical ultrasonic sensor (UC6000-30GM-IUR2-V15, Pepperl + Fuchs, Mannheim, Germany), placed at the same height as the central fan. Two digital sensors (3RG6014-3AD00-PF, Pepperl + Fuchs) were placed to control the spray of the other two spray units. A Programmable Automation Controller (PAC) controlled the whole system. The central fan was programmed to remain at a distance of 1 m from leaves.

The third prototype (Prototype 3, P3) (Figure 3d) consisted of two axial fans mounted on a tower-like structure. The propelled air was conducted through four mobile air outlets, two per fan, able to approach the target canopy by the action of linear actuators. Unlike the other two prototypes, the purpose of the outlets' movement was not to keep a constant distance from the canopy, but to funnel the air more markedly when the distance to the target increased. The goal was to achieve more horizontal air movement to reach further distances. This sprayer is also controlled by an electronic regulation system that

automatically adjusts the spraying pressure according to the desired volume rate indicated by the operator.

Figure 3. Sprayers used in the trial: (**a**) Conventional air blast sprayer; (**b**) P1 prototype; (**c**) P2 prototype and (**d**) P3 prototype.

2.3. Sprayer Calibration and Operational Parameters

The sprayers were appropriately calibrated in laboratory conditions, to assess their airflow rate for every rotary speed of the PTO, as explained in Miranda-Fuentes et al. [60]

As to the operational parameter values selected for every machine, they are all summarized in Table 2.

Table 2. Operational parameter values selected for every sprayer.

| | Cultivation System | | | | | | | |
| | Intensive | | | | Traditional | | | |
Parameter	P1	P2	P3	Conventional	P1	P2	P3	Conventional
Nozzle colour	Red	Yellow	Yellow	Green	-	Red	Red	Blue
Number of open nozzles	18 (2 × 9)	36 (2 × 18)	34 (2 × 17)	14 (2 × 7)	-	36 (2 × 18)	34 (2 × 17)	14 (2 × 7)
Pressure (MPa)	1.3	1.1	1.3	1.3	-	0.7	0.8	1.4
Liquid flow rate (L min^{-1})	39.06	38.52	39.78	39.06	-	58.32	58.82	55.86
Spray volume (L ha^{-1})	1052.2	1063.8	1055.8	1060.0	-	1170.3	1164.8	1151.8
Forward speed (km h^{-1})	4.05	3.95	4.11	4.02	-	2.99	3.03	2.91
PTO speed (rpm)	540	270	370	460	-	300	420	520
Fan gear	-	-	I	II	-	-	I	II
Air volumetric flow rate (m^3 s^{-1})	2.8	10.8	10.8	10.9	-	12.3	12.3	12.3

The specific spray volume (sprayed volume per m^3 canopy volume) was used to adapt the spray volume to the tree volume. A value of 0.12 L m^{-3} was used as the optimal value for isolated olive trees [38]. The air volumetric flow rate was adjusted in each case to apply the same air volume rate. As to the forward speed, it was adjusted to 3 and 4 km h^{-1} in the traditional and intensive orchards, respectively (Table 2).

2.4. Field Experimental Design and Sampling System

Five trees per plantation system were sprayed (Table 1). The trees were consecutively set along a crop row and covered with artificial collectors to assess the spray deposition and coverage. Thus, a total of 16 sampling positions were set and organized in three sampling heights and four sampling sectors, with two sampling depths in those corresponding to the intermediate sampling height (Figure 4).
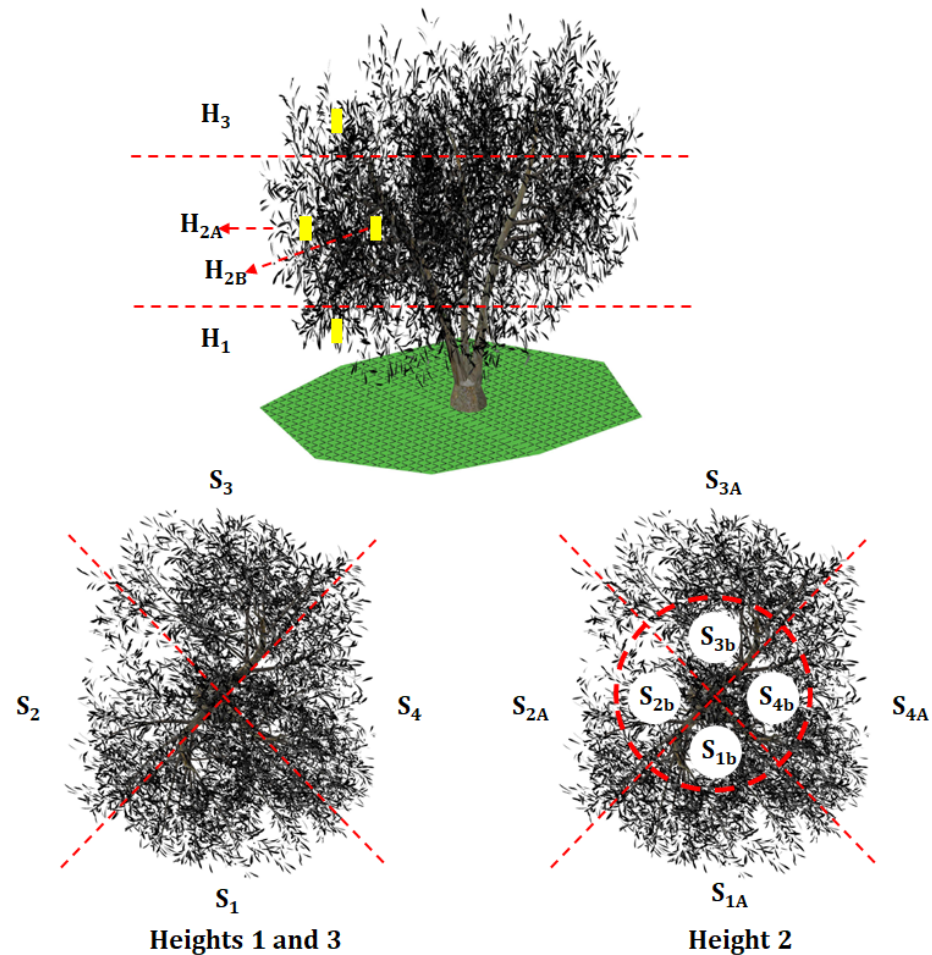
Figure 4. Sampling positions to measure spray deposit and coverage. A total of four sectors (S_1–S_4), with three sampling heights (H_1–H_3) and two sampling depths in the intermediate height (H_{2A} and H_{2B}) made a total of 16 sampling positions.

The collectors were 100×100 mm filter paper pieces for the deposition and 76×26 mm water-sensitive paper (WSP) pieces for the spray coverage. Each sampling position included one deposition and two coverage collectors, one on each side of a leaf, to which they were clipped.

The field sampling for the spray losses is explained in the paragraphs below.

2.4.1. Spray Drift Sampling

When considering spray drift characterization, it is important to point out that this study does not aim to quantify the total spray drift emitted by the evaluated sprayers but only to characterize the absolute spray portion that lands on the subsequent tree row. The actual drift can reach distances much longer than the ones sampled in this experimental work [62]. A short spray drift distance was noticed using different spray application techniques aimed at under-row weed control and suckering [63]. Spray drift is commonly sampled by following the ISO 22,866 methodology [64]. Nevertheless, different studies reported difficulties in applying this methodology in commercial olive plantations, mainly

due to the slope and low repeatability of the results [57,65]. In addition, the first approach to develop drift curves in olive crops suggested that 95% of the spray drift is in the first 10 m after the sprayed area [65]. Therefore, as the study aimed to compare different spray methodologies and not to assess the absolute drift values or to represent the drift curve, an alternative simplified methodology was proposed, as successfully applied in previous ones [55]. Thus, the spray drift was assessed by placing on the ground 15-mm-in diameter Petri dishes next to the spray area (Figure 5a). Each sampling position (3 in total) consisted of 2 sampled areas between the sprayed row and the next one (Figure 5a). The sampled distance ranged from 6 to 18 m away from the sprayer.
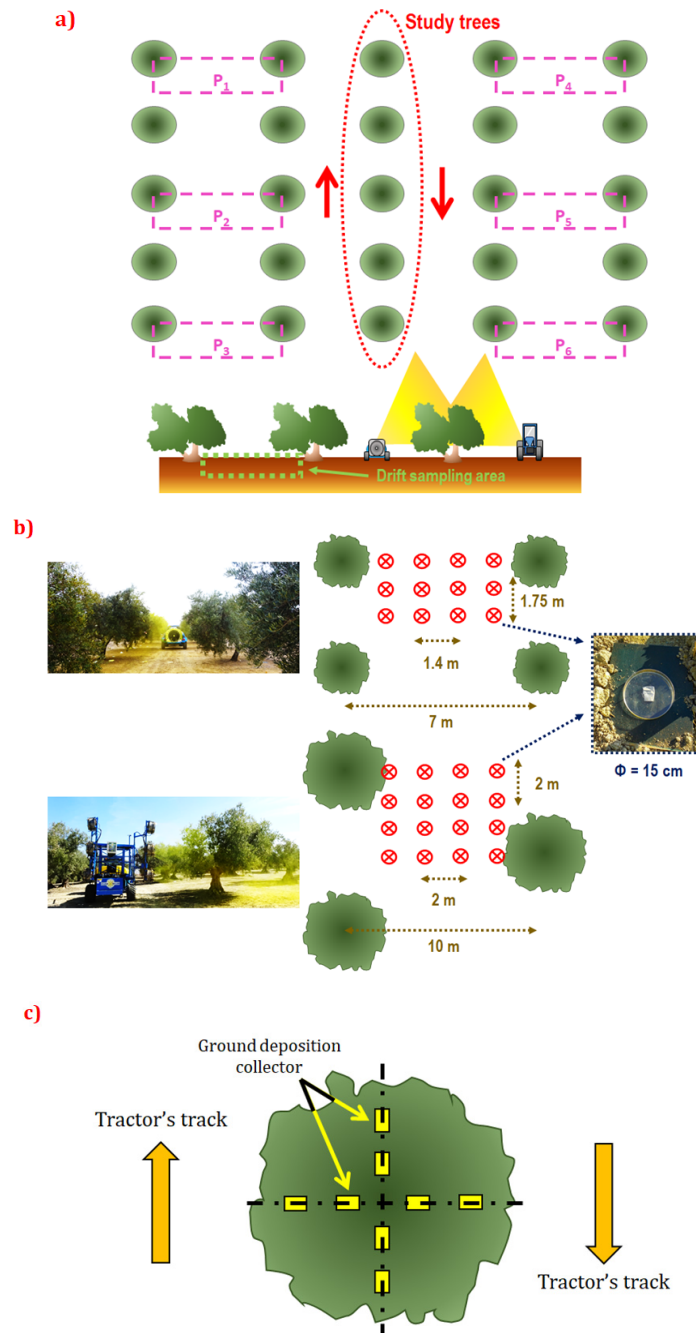
Figure 5. (**a**) Spray drift sampling area placement in relation to the sprayed trees; (**b**) Spray drift sampling grid in a sampling area for the intensive and traditional orchards; (**c**) Sampling of the direct losses to the ground.

Each sampling area, or plot, consisted of a grid of sampling positions for the dishes. There were 12 and 16 dishes per plot in the intensive and traditional systems, respectively (Figure 5b). In both cases there were four sampling distances, with three sampling profiles in the intensive and four in the traditional orchard to homogeneously cover the sampling area.

2.4.2. Losses to the Ground Sampling

To assess the direct losses to the ground, 20 × 10 cm filter paper pieces were attached to wooden boards under the trees. More specifically, a total of eight samples were placed under each sprayed tree, in four different profiles around the crown (Figure 5c). Each profile was sampled in two different depths.

2.5. Trial Performance and Weather Condition Characterization

The trial took two consecutive days: one for each cultivation system. The order of the crop was randomized, beginning with the traditional one. The order of the treatments with the four sprayers was also randomized, following the order: P1–P3—Conventional–P2.

The sprayers' tanks were completely filled with clean water, and the operational parameters were adjusted to test the real liquid and air flow rate values. When these preliminary calibrations were finished, the food dye E102, Tartrazine, was added to a target concentration of 8 g L^{-1}. Before each treatment, the sprayer was left mixing the tank content for 5 min to achieve perfect homogeneity in the spray mix. Then, two 100 mL samples were collected and taken to the laboratory to analyze the real dye concentration in the mix.

During the test, the real forward speed of the tractor was measured by placing a 100-m-measuring tape on the ground and timing. This was especially important as the different sprayers significantly differed in size and weight, affecting the tractor speed. The differences found in the tractor speed need to be considered in the data analysis as they significantly affect the applied water volume to the trees.

Once the sprayer finished its work, samples were left to dry for 10 min, collected and stored in dark conditions. Then, the sprayer was changed, the tank samples were collected, and the treatment was started. The intention was to accelerate the trial as much as possible to get similar wind conditions to make drift results comparable among sprayers.

The wind speed/direction monitoring was pivotal to ensure data comparability and interpretation. A dedicated weather station (CR800, Campbell Scientific Inc., Logan, UT, USA) was used to monitor the wind speed and direction, as well as the temperature and relative humidity. The anemometer, a 2D ultrasonic anemometer WindSonic 232 (Campbell Scientific Inc., Logan, UT, USA) able to measure the wind speed and direction, has a measurement range of up to 60 m s^{-1} and a resolution of 0.01 m s^{-1} and 1° for the wind direction measurement. The sensor presents up to four outputs per second when connected using an RS-232 communication port. However, for this study, only one was collected. Measurements of the temperature and the relative humidity were performed by using a CS215 temperature and relative humidity probe (Campbell Scientific Inc.), with a measurement range from 0 to 100% relative humidity and a temperature of −40 to +70 °C. A special control software was programmed into the application PC200W Datalogger Starter Software® (Campbell Scientific Inc., Logan, UT, USA) to perform the measurements and the data transfer. The measurements were taken with a frequency of 0.1 Hz, stored in the data logger's internal memory, and monitored in real-time using a laptop computer.

2.6. Sample and Data Analysis

2.6.1. Deposition on Absorbent Paper

The absorbent paper samples were taken to the laboratory and washed off by introducing 100 mL of distilled water inside the storage bags, then shaken for 1 min. Three aliquots were extracted from each one and put into a 96-well plate to be analyzed in a spectrophotometer (Synergy HTX, BioTek Instruments, Inc., Winooski, VT, USA). Each plate contained three blank wells to correct the values of the rest of the samples. All the

concentration values were corrected with the extractability factor obtained in previous studies for this combination of tracer-collector [38].

The calculation of the spray deposit per unit area, expressed in the terminology published by Pergher and Gubiani [66], was performed according to Equation (1).

$$d = \frac{T_{cl} \cdot w}{L_a} \tag{1}$$

where d is the deposit per unit area (μg cm^{-2}), T_{cl} is the tartrazine concentration in the washing solution (ppm), w is the volume of extractant used (mL), and L_a is the area of the absorbent paper (100 cm^2 in the case of the canopy collectors and 200 cm^2 in the case of the ground collectors). The deposit needed to be corrected as the tracer concentration in the sprayer tank suffered small variations across treatments.

The variation of spray deposit in the canopy was expressed by the coefficient of variation, CV (%), of the different deposition values obtained in each tree.

2.6.2. Deposition on Petri Dishes and Ground Filter Paper Samples

The washing process for the Petri dishes was very similar to that used in the absorbent paper, except for the water volume and the agitation time. In this case, a much lower tracer mass was expected; therefore, a lower water volume was required. After different tests, a 10 mL volume was selected, resulting in absorbance values well inside the optimal range of the spectrophotometer. However, there were few samples for which this volume needed to be increased up to 20 mL or even 50 mL in punctual cases.

As to the agitation time, it was set at 5 min to ensure the tracer's complete extraction.

As to the ground filter paper pieces, they were washed similarly to the ones clipped to the leaves, except for the water volume, which needed to be reduced in punctual cases to 50 mL or even 20 mL. The agitation time suffered no change.

2.6.3. Water Sensitive Paper Samples Analysis

WSP samples were scanned at 600 ppi resolution and analyzed with a specific ImageJ macro (ImageJ ®, National Institutes of Health, Bethesda, MD, USA) used in previous studies [67]. The considered coverage parameters were calculated for both sides of the leaf, and they were the percentage coverage, SC (%), and the number of impacts, Ni (cm^{-2}).

2.6.4. Statistical Analysis

Analysis of variance (ANOVA) was used to determine the effects of the factors on the dependent variables: corrected deposit per unit area (μg cm^{-2}), normalized deposit (μg cm^{-2}), percentage coverage in upper and underside of leaves, SCup and SClo (%), mean percentage coverage (%), impact number in the upper and lower side, Ni up and Ni lo (cm^{-2}) and mean impact number, Ni (cm^{-2}). The normalized deposit on the Petri dishes, d_P (μg cm^{-2}), the normalized deposit on the last row of Petri dishes (maximum sampling distance according to Figure 5b), d_P' (μg cm^{-2}), and the normalized deposit on the ground collectors, d_G (μg cm^{-2}), were also analyzed. The sphericity hypothesis of the model was checked by using the Mauchly W statistic (1940).

To check the null hypothesis for the within-subject factors and for their interaction, a univariate test based on the Greenhouse-Geisser correction (1959) was used. Prior to analysis, percentage data were subjected to an arcsin $[(Y/100)^{0.5}]$ transformation. The means were compared by using a Bonferroni post-hoc test ($\alpha = 0.05$). Analyses were performed by using SPSS v. 22 (IBM, Armonk, NY, USA).

3. Results and Discussion

The main results of the study are presented.

3.1. Canopy Measurements

The full characterization of the 10 sprayed trees is shown in Table 3.

Table 3. Geometric characteristics of the sprayed trees. MV is the mean vector parameter for the MV method, as described in Section 2.1, and V_L is the estimated tree crown volume. The 0° direction was the geographic North, and the rest of angular positions were placed clockwise. H_T was the total tree height, TD is the trunk diameter, and L_D is the leaf density (expressed in m^2 leaf surface $\cdot$ m^{-3} canopy volume).

|													
					INTENSIVE								
Tree	**0°**	**45°**	**90°**	**135°**	**180°**	**225°**	**270°**	**315°**	**MV**	**V_L**	**H_T**	**TD**	**L_D**
#	m	m	m	m	m	m	m	m	MV	m^3	m	m	m^{-1}
1	2.10	2.20	2.30	2.00	2.10	2.40	2.50	2.35	2.24	36.88	4.1	0.24	6.47
2	2.70	2.60	2.80	2.10	2.00	2.50	2.30	2.20	2.40	45.69	4.0	0.21	6.56
3	2.00	2.60	2.50	2.10	2.10	2.20	1.90	2.50	2.24	36.53	3.8	0.20	7.02
4	3.00	3.20	2.60	2.80	1.90	1.80	1.80	2.20	2.41	46.39	4.3	0.23	7.92
5	2.10	2.00	2.40	3.00	2.30	2.50	2.30	2.90	2.44	47.80	3.9	0.27	7.59
					TRADITIONAL								
Tree	**0°**	**45°**	**90°**	**135°**	**180°**	**225°**	**270°**	**315°**	**MV**	**V_L**	**H_T**	**TD**	**L_D**
#	m	m	m	m	m	m	m	m	MV	m^3	m	m	m^{-1}
1	4.60	3.40	3.00	3.60	2.90	2.40	3.10	4.40	3.43	105.56	4.5	0.49	4.51
2	3.40	3.60	3.00	2.70	2.60	4.40	5.50	4.20	3.68	117.40	4.7	0.56	5.33
3	2.40	1.90	2.50	2.50	2.10	2.50	2.50	2.70	2.39	56.42	5.0	0.53	5.50
4	3.70	3.50	3.00	3.10	3.80	3.50	2.50	3.70	3.35	102.00	4.4	0.60	5.34
5	2.80	3.90	3.70	3.80	3.50	4.70	4.40	3.90	3.84	125.09	4.6	0.51	5.10

As can be observed in Table 3, both cultivation systems presented a significant variation in the crown volumes. Thus, whilst the intensive trees resulted in a mean volume value of 42.66 m^3, the traditional ones reached a mean value of 101.29 m^3, meaning that, in general figures, traditional trees were 137% bigger than intensive ones.

The intensive trees were relatively big in comparison with the normal ranges in the area. In fact, normal volumes for these trees are in the range of 24.60 $\pm$ 2.19 m^3 [42], way smaller than the ones in the present study. This bigger size can bring consequences to the performance of the sprayers, as reported in the preliminary trials [60].

The case of the traditional trees is more typical, as their mean volume of 101.29 m^3 is within the range of 98.08 $\pm$ 5.21 m^3 reported in the aforementioned study.

This difference in estimated volume values is caused by the difference in the length of the measured radii (Figure 2). The difference in the projection of the trees can be easily observed in Figure 6. This picture shows that the trees were slightly asymmetrical, being bigger than the intensive ones on their North-East side and the traditional ones in the North-West. This fact made it necessary to spray them from both sides.

The tree height also was higher than the traditional trees, and the same happened with the trunk diameter. The leaf density, nonetheless, was higher in the intensive orchard.
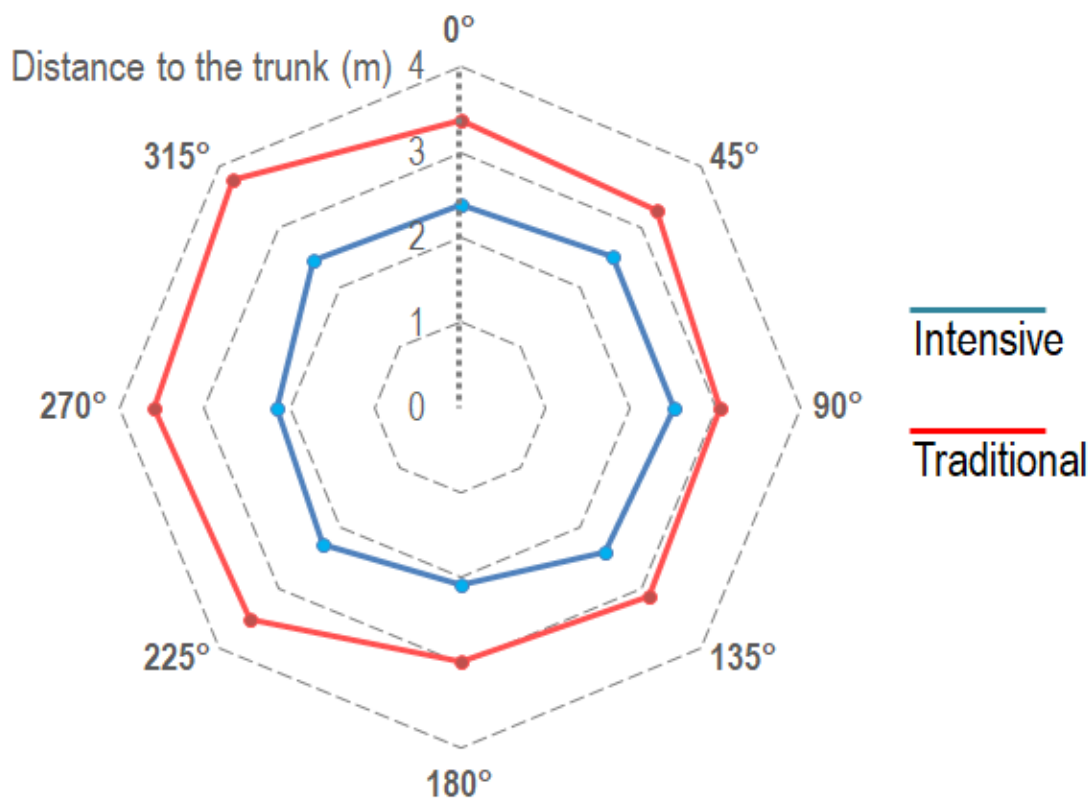
Figure 6. Mean value for the 8 radii of the tree crown in the two cultivation systems studied.

3.2. Weather Conditions

The weather conditions during the trial are resumed in Table 4. As shown, weather conditions were very favorable for the treatments, with wind speed values under $1 \ \text{m s}^{-1}$ in every case. Nonetheless, this factor was slightly higher in the case of the traditional trees, except for the conventional sprayer.

Table 4. Weather conditions during the trials.

		Intensive				Traditional			
		P1	**P2**	**P3**	**Conv.**	**P1**	**P2**	**P3**	**Conv.**
Air mean speed	$m \ s^{-1}$	0.0	0.2	0.0	0.1	-	0.7	0.6	0.2
Air mean direction	° *	-	225	-	245	-	243	220	222
Temperature	$°C$	21	20	25	20	-	21	24	24
Relative humidity	%	35	36	34	37	-	36	34	34

* 0° corresponds to the geographic North.

The wind direction was similar in every case, with values between 220° and 245°. These values had very small variations during the treatments (<5% in every case) and were nearly perpendicular to the tree row. Of course, this circumstance had an important effect on the results of the study, with nearly no deposit collection on the opposite side of the wind direction.

The temperature and relative humidity values were standard and not significantly affected the results.

3.3. Spray Deposit and Coverage

The main results for the deposition and coverage parameters of the spray application are listed in Table 5.

Table 5. Spray deposition and coverage parameters for the different sprayers in the two cultivation systems. Letters after figures indicate the post-hoc test homogeneous group in the case statistically significant differences were found.

| Parameter		Intensive				Traditional			
		P1	P2	P3	Conv	P1	P2	P3	Conv
Mean deposition	d (μg cm^{-2})	25.4	19.0	16.3	18.8	-	28.2 b	33.7 a	22.6 c
Deposition variability	CV (%)	150 a	68 b	68 b	73 b	-	65	72	87
Mean coverage	SC (%)	35.7	33.5	31.3	27.4	-	41 ab	46 a	26. b
Coverage upper side	SC up (%)	44 a	36 c	38 b	36 c	-	50 a	47 a	33 b
Coverage lower side	SC lo (%)	31 a	31 a	31 a	20 b	-	46 a	46 ab	26 b
Impact number	N_i (cm^{-2})	72 a	103 b	134 c	123 c	-	106a	70b	146c
Impacts upper side	N_i up (cm^{-2})	74 b	102 a	123 a	123 a	-	86 a	67 a	131 b
Impacts lower side	N_i lo (cm^{-2})	70 a	103 b	144 c	124 bc	-	126 c	72 b	155 a
Impacts variability	CV (%)	62 a	45 b	42 b	39 b	-	39 a	55 b	35 a

3.3.1. Intensive Cultivation System

In the intensive cultivation system, P1 achieved a higher mean deposition value (25.40 μg cm^{-2}) than the rest of the prototypes (19.01 and 16.31 μg cm^{-2} for P2 and P3, which accounts for reductions of 25.16% and 39.79%, respectively) and the conventional sprayer (18.75 μg cm^{-2}, a reduction of 26.18%) (Table 5). Nevertheless, this parameter did not present significant statistical differences ($p = 0.105$). The response of the different sprayers, even if not significantly different statistically, follows the same trend observed in previous studies, where the P1 prototype achieved great results in this cultivation system [60].

The homogeneity of the deposit presented statistically significant differences ($p = 0.01$). In this case, P1 showed a much higher CV (150%) than the other prototypes (both 68%) and the conventional sprayer (73%). This means P1 nearly doubled the variability of the rest of the sprayers. This circumstance can negatively affect the application quality, even if it has the highest mean deposit (Table 5).

In fact, Figure 7a shows the deposit distribution in height for the different sprayers in the intensive orchard. The heterogeneity that Table 5 depicts for P1 is clearly reflected in Figure 7a, where it presents a very high mean deposit of 42 μg cm^{-2} in the H3 sampling height. In fact, this feature could be helpful when aiming to the top of the trees for a specific treatment. However, it could be considered inconvenient from the homogeneity point of view. Nevertheless, a higher deposit in the top part of the tree is not necessarily negative if it does not compromise the deposit in the lower parts, given a certain applied liquid flow rate. The conventional sprayer showed a very homogeneous deposit in height (Figure 7a). This result was not expected as this sprayer, even with the proper calibration, achieved lower deposits in the top parts of the crown in previous trials [8]. P2 also showed a high homogeneity in the three tested heights. However, it followed a similar trend to P1, with high deposit values at the top height of the tree. Last, P3 showed a similar behavior than the conventional sprayer. The lower deposit in the intermediate height can be explained by the higher leaf density and volume in this particular part of the tree.

The dissection of the deposit per sample height showed that the three sprayers could work properly with the height of the intensive trees. The prototypes tend to work even better at higher heights, and this fact is due to their design purpose: to properly reach the top parts of big-sized olive trees.

Figure 7c shows the spray deposit per sampling depth for the different sprayers in the intensive orchard. There is a generalized decrease of the collected deposit in depth. This result is expected as it is much easier for any sprayer to reach the outermost leaves than the inner ones, especially in a cultivation system in which the leaf density is very high in comparison with others (Table 2).
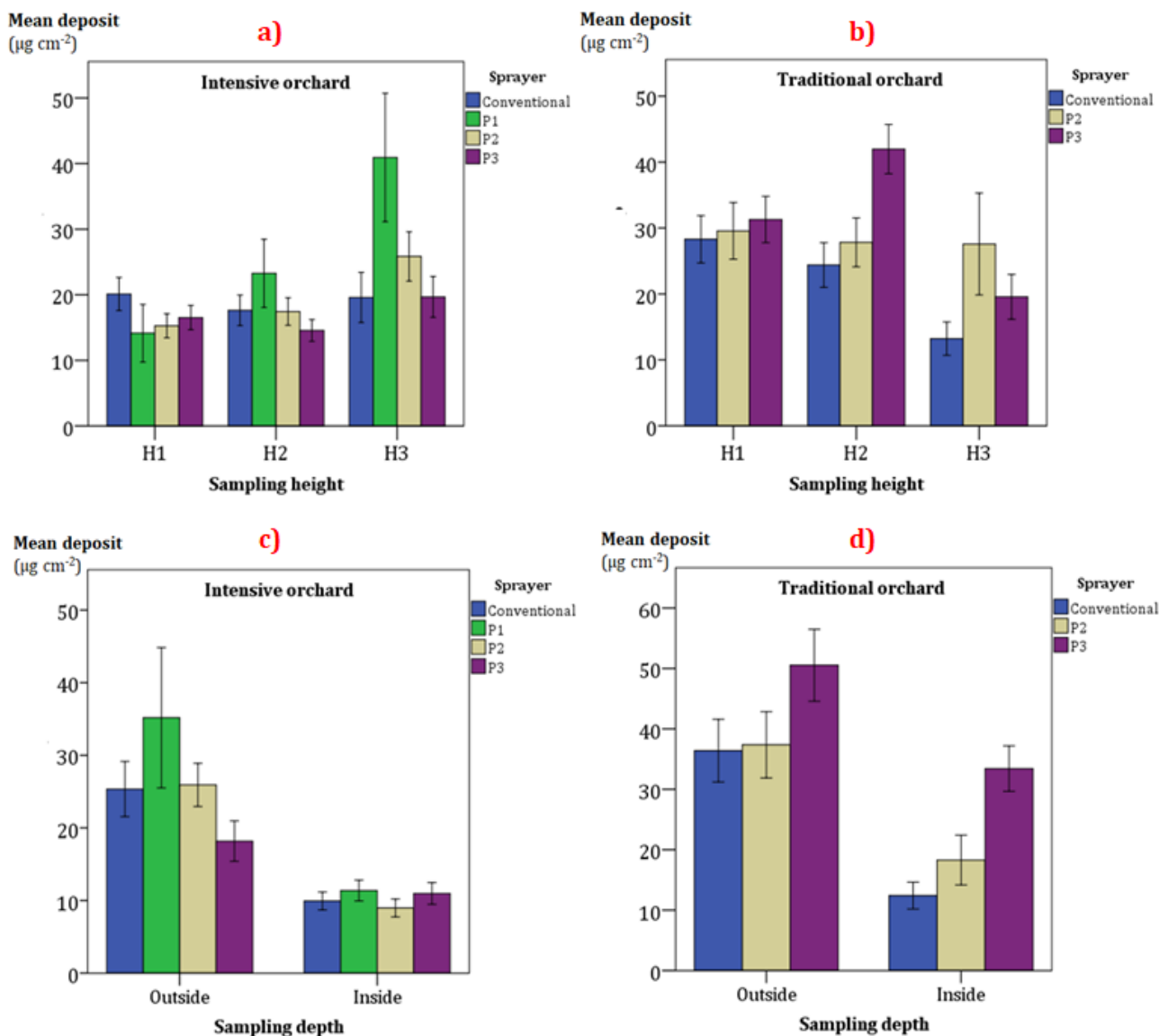
Figure 7. Mean deposit per sampling height for the tested sprayers in (**a**) the intensive orchard and (**b**) for the traditional orchard. Mean deposit per sampling depth for the tested sprayers (**c**) the intensive orchard and (**d**) for the traditional orchard. Whiskers represent the standard error.

Although every sprayer had different deposition values in the outermost parts of the trees, they all yielded results around 10 μg cm^{-2} in the inner ones (Figure 7c).

When looking at the results, it can be thought that the inner deposit in this cultivation system presents a ceiling around 10 μg cm^{-2} that cannot be surpassed by any of the spraying technologies tested. The differences found among the sprayers could be due to the sampling method and the different errors. However, they do not have a statistical meaning.

The spray coverage did not present statistically significant differences among sprayers for the 95% confidence level ($p = 0.056$). Nevertheless, the results can be grouped into two categories: the conventional sprayer with a mean cover of 27.4% and the prototypes with values of 35.7%, 33.5%, and 31.3% for P1, P2, and P3, respectively. If considering the criterion of Chen et al. [68] as a general prospect of the coverage quality, the conventional sprayer would result in general undercover of the leaf surface whilst the three prototypes would achieve an appropriate coverage level. The mentioned criterion establishes the optimum coverage value in any spray application. The results under this value are considered under coverage and the ones above it as over coverage. The proximity of the mean coverage values to this threshold indicates that the sprayer calibration was very accurate. This result

reinforces those obtained in Miranda-Fuentes et al. [38], where the 0.12 L m^{-2} application-specific volume was set as the optimum for the isolated olive trees.

The coverage on both sides of the leaf suffered statistically significant differences (*p*-values of 0.026 and 0.044 for the upper and lower side of leaves). In both cases, the conventional sprayer yielded the lowest results, with P1 leading and the other prototypes resulting in intermediate values (Table 5). A remarkable fact is the low coverage value achieved by the conventional sprayer on the lower side of the leaves (20%), which could lead to disease problems with contact pesticides like copper.

As to the number of impacts, N_i, there were statistically significant differences among the sprayers (*p* = 0.001). In this case, the highest number of impacts was achieved by P3 and the lowest by P1 (Table 5). N_i up and N_i lo also showed significant differences in both cases. The same trend of P1 giving the lowest coverage was obtained. The rest of the prototypes and the conventional sprayer gave different values (Table 5).

Taking into account that the droplet size was adjusted to be similar in every sprayer configuration, the low impact number generated by P1 compared with the rest of the sprayers could have been caused by the differences in the air current characteristics generated by the fan type. P1 mounts two centrifugal propellers, which deploy a lower air flow rate with higher airspeed than the rest of the sprayers, which mount axial fans [60]. This increased speed might have blown away the finest droplets making them pass through the canopy and leaving the coarsest ones on the leaves. On the other hand, the axial fans move at greater air flow rates with lower speed, leaving part of the finest droplets on the target canopy.

The impact variability showed significant differences as well (*p* = 0.039), with P1 resulting in the highest heterogeneity in this parameter (Table 5).

3.3.2. Traditional Cultivation System

For the reasons described in Section 2.2, P1 was not tested on the traditional olive orchard. Therefore, Table 5 does not include any results for this sprayer. The spray mean deposition, d, presented statistically significant differences in this cultivation system (*p* = 0.003). There were two homogeneous groups according to the Bonferroni test (α = 0.05): P3, which achieved the maximum mean deposit with 33.7 µg cm^{-2}, and the group composed of P2 and the conventional sprayer, with mean values of 28.2 and 22.6 µg cm^{-2}. Even if statistically homogeneous, P2 and the conventional sprayer differed in mean values, registering the first a 24.8% mean increase with respect to the second.

Contrarily, the coefficient of variation for d did not present statistically significant differences. The CVs for P2, P3, and the conventional sprayer were 65%, 72%, and 87%, respectively. Again, the variability of the spray deposits, even without any statistical difference, presented an increase of 33.8% between P2 and the conventional sprayer. Nevertheless, the study of the distribution of the deposition throughout the crown gives an interesting insight into this variability. As seen in Figure 7b, there are important variations in the spray deposit in height among the different sprayers. In fact, they present completely different trends. The conventional sprayer showed a clear decrease of the spray deposit in height, with mean deposition values of 28 and 13 µg cm^{-2} for H1 and H3, respectively (Figure 7b). This means a reduction of 53.6% from the base of the tree to its top, being one of the most important problems of commercial air blast sprayers in traditional olive canopies, as demonstrated in previous studies [8]. This fact generally leads the farmer to increase the spray volume to reach the top with the required spray deposit, generating an important overdose in the medium and lower parts of the tree.

P2 kept constant the spray deposit in height (Figure 7b). In this case, the mean reduction between the base and the top of the tree is only 10.3%. This low reduction in height is possible by the placement of the spray units, which cover the whole height of the tree (Figure 3c). In fact, this prototype yielded a 100% increased deposit in the top height compared with the conventional sprayer (26 vs. 13 µg cm^{-2}, Figure 7b), which can lead to

effectively reducing the applied pesticide dose without compromising the spray deposit in the top of the crown.

P3 showed a strong increase in the deposition from H1 to H2 and then an abrupt decrease from H2 to H3 (Figure 7b). The reduction from the base to the top of the tree was 40.6% in this case, but the deposit in P3 is still 46% higher than that achieved by the conventional sprayer. The explanation for this decrease at the top lies in the fact that this sprayer encapsulates the air current within the top and the bottom of its delivering structure (Figure 3d). This height is 3.20 m, plus the effect of the superior deflector [60]. This is significantly lower than the olive height in any case (4.4 to 5.0 m; Table 3), which affects the deposit collected in the top. Further improvements should be made in this prototype to properly reach the top of the high trees like the ones present in this study. The shape of the spray plume, very prominent in the intermediate sampling height, can also be accountable for the high deposit collected in the H2 sampling height.

Figure 7d shows the spray distribution per sampling depth for the three tested sprayers in the traditional orchard. The penetration is higher in this system than in the intensive one (Figure 7c). This result is not surprising, as traditional trees are usually much bigger and less dense than the intensive ones (Table 3). In fact, their canopy is very open in the middle and grows around the tree, which generally presents several trunks in a crown shape. Therefore, it is much easier to access the inner parts, provided that the spray system is adequate to this particular case.

P3 prototype generated a mean outer deposit of 51 μg cm^{-2} and an inner one of 34 μg cm^{-2} (Figure 7d).

The P2 prototype achieved a lower deposit in both sampling depths in comparison with P3, and the conventional sprayer yielded the lowest values (Figure 7d). Therefore, another important problem is presented regarding the conventional sprayer in this cultivation system: it lacks penetration compared to other spraying systems like the ones evaluated in the present study. In fact, it reaches very similar values to those obtained in the intensive cultivation system (Figure 7c), with way more dense and compact crowns. This fact is explained by the sprayer's design for compact trees sprayed from short distances. However, when this distance increases, the spray plume expands and losses penetration capacity.

Speaking about the mean spray coverage, SC, in the traditional orchard, statistically significant differences were found (p = 0.011). In this case, the Bonferroni test gave two homogeneous groups: on the one hand, P3 achieved the top SC, with a mean value of 46% (Table 5). On the other hand, the conventional sprayer yielded the lowest value, with 26%. P2 is included in both groups, with a mean SC of 41%. According to the previously discussed criterion to evaluate the coverage of leaves [68], both prototypes would over-cover the leaf surface, and the conventional sprayer would achieve an appropriate result. Nevertheless, the high mean deposition of the prototypes along with this coverage result could make it possible to reduce the applied water volumes, with the consequent pesticide saving and environmental benefits. However, this statement needs to be corroborated through the appropriate research.

SC up and SC lo also presented significant differences (p = 0.001 in both cases). As to the upper side of leaves, SC up was much higher in the prototypes than in the conventional equipment (Table 5). The same trend was found in SC lo. As can be observed, the results on both sides of the leaves were very similar in this cultivation system, but the conventional sprayer slightly under covered the lowest side of the leaves (Table 5).

N_i also presented significant differences (p = 0.002), with the top value achieved by the commercial sprayer and the lowest one by P3. There also were statistically significant differences in the upper and lower parts of the leaves (p = 0.003 and 0.002; Table 5). In this case, the lower side of the leaves received less impacts than the upper part, even if the spray coverage was slightly lower (Table 5). The impact variability was higher in P3 than in the other two sprayers (Table 5).

3.4. Drift and Ground Losses

The spray losses parameters are comprised in Table 6.

Table 6. Mean results and homogeneous groups according to Bonferroni's test for the parameters related to the spray losses. Letters after figures indicate the post-hoc test homogeneous group in the case statistically significant differences were found.

Parameter		Intensive				Traditional			
		P1	P2	P3	Conv	P1	P2	P3	Conv
Mean deposition on Petri dishes	d_P (μg cm^{-2})	0.39 a	0.68 ab	1.13 bc	1.56 c	-	0.36 a	0.81 b	0.75 b
Mean deposition on the last Petri dishes row	d_P' (μg cm^{-2})	0.17 a	0.31 a	0.46 ab	1.20 b	-	0.15	0.31	0.37
Mean deposition on ground collectors	d_G (μg cm^{-2})	8.72 a	13.33 b	21.74 c	16.31 b	-	26.18	28.62	23.91

3.4.1. Intensive Orchard

The mean deposition on the Petri dishes, d_P, suffered significant differences in the intensive orchard ($p < 10^{-3}$). As can be seen in Table 6, the deposition values present four homogeneous groups according to Bonferroni's test. The lowest value was produced by P1, with 0.39 μg cm^{-2}, and the highest one was yielded by the conventional sprayer, with 1.56 μg cm^{-2} (four times greater). Every prototype resulted in a significantly lower d_P value than the conventional sprayer, except for P3, which was statistically similar. If looking at the mean values reflected in Table 6, P1, P2 and P3 generated d_P reductions of 75%, 56%, and 28%, respectively.

Figure 8a shows the spray drift reduction per sampling depth in the intensive orchard. As can be seen, deposition values in the first sampling depth were almost identical in the conventional sprayer and P3, with lower values in P2 and, especially, in P1. The in-depth drift patterns sensibly differed among sprayers. While some presented minor reductions along the consecutive sampling positions, like P1 and the conventional sprayer, others resulted in abrupt reductions, like P2 and P3. Therefore, even if the collected deposit for P3 and the conventional sprayer in position 1 was similar, the deposit in position 4 was very different, being the conventional sprayer's nearly three times that of P3 (Figure 8a).
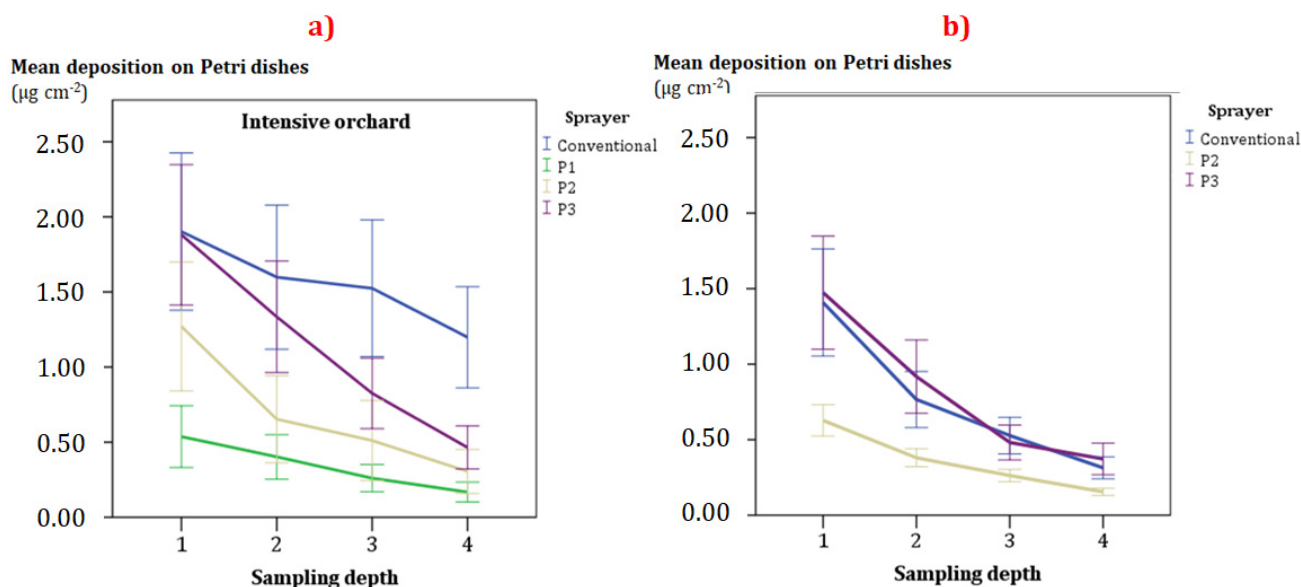
Figure 8. Mean deposition values on the Petri dishes per sampling depth (according to the scheme in Figure 5b, 1 is the minimum distance to the sprayed trees and 4 is the maximum one) in (**a**) the intensive orchard and (**b**) the traditional orchard. Whiskers represent the standard error.

When comparing the mean deposition on the last row of Petri dishes, d_P' (Table 5 and position 4 in Figure 8a), there were significant differences ($p = 0.002$) among the sprayers. In this case, there were only two homogeneous groups: P1 and P2 yielded significantly lower d_P' values than the conventional sprayer. P3 resulted in an intermediate value ($0.46\ \mu g\ cm^{-2}$) and was significantly like the other two groups. When comparing the results of the different sprayers, P1 achieved a d_P' reduction of 606% in comparison with the conventional sprayer. This circumstance has crucial importance when spraying near a sensible area, like a water mass

The mean deposition on the ground collectors, d_G, presented significant differences between sprayers ($p < 10^{-3}$, Table 6). The Bonferroni's test resulted in 3 homogeneous groups: the minimum d_G was achieved by P1, with $8.72\ \mu g\ cm^{-2}$, the intermediate group included P2 and the conventional sprayer, with 13.33 and $16.31\ \mu g\ cm^{-2}$, and the maximum d_G was yielded by P3, with $21.74\ \mu g\ cm^{-2}$ (Table 6). This means P1 reduced 87% of the direct losses of the conventional sprayer.

3.4.2. Traditional Orchard

The mean deposition on Petri dishes, d_P, presented significant differences in the traditional cultivation system ($p = 0.002$, Table 6). There were two homogeneous groups: on the one hand, the P2 prototype yielded a mean deposit of $0.36\ \mu g\ cm^{-2}$. On the other hand, the rest of the sprayers, with d_P values of 0.81 and $0.75\ \mu g\ cm^{-2}$ for P3 and the conventional sprayer, respectively (Table 6). From the mentioned values, it can be said that, in mean terms, P2 reduced the mean deposit on the Petri dishes by 52%. This result, along with the higher mean deposition produced by this sprayer in this cultivation system, makes it very convenient for its conditions.

When looking at the spray deposit reduction per sampling distance (Figure 8b), a very similar response between P3 and the conventional sprayer can be observed. In fact, their deposit values in the first and last sampling positions were almost identical. P2 yielded much lower values in every sampling position, keeping a 50% lower deposit along the full curve (Figure 8b).

In this case, the mean deposition on the last row of Petri dishes showed no significant differences, despite P2 yielding a much lower d_P' value than the other sprayers tested ($0.15\ \mu g\ cm^{-2}$ vs. 0.31 and $0.37\ \mu g\ cm^{-2}$, Table 6).

The mean deposition on the ground collectors was statistically similar in the three sprayers tested ($p = 0.248$), with mean values of 26.18, 28.62, and $23.91\ \mu g\ cm^{-2}$ (Table 6).

4. Conclusions

Three air-assisted sprayer prototypes were compared with a conventional one in the two most common olive cultivation systems in terms of spray quality and efficiency by considering the spray deposition, coverage, drift, and direct losses to the ground.

The results showed that crop-adapted spraying tends to yield positive results in comparison with conventional equipment used in a wide range of 3D crops. In this sense, the available spraying systems should be mounted on appropriate structures to fit the needs of very particular crops, like olives. In addition, different cultivation systems may need different technical solutions to optimize treatments, as shown in the present study. While the centrifugal propeller was well-fitted for the intensive system, the tower-like structure generated the highest spray deposition in the traditional one. Additionally, the small-sized fans importantly reduced the spray drift losses in this second system. Though many efforts are being undertaken to implement the newest technology in the spraying machinery, the focus should also be spotted on improving the machinery itself. In this sense, the combined experience of sprayer manufacturers and research groups in innovation projects like the one in which these prototypes were developed may have an important synergy at improving the efficiency of treatments in difficult crops. This step is completely necessary to match the environmental requirements of the public administration without compromising the biological efficacy of treatments.

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