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Automated Fixed System Specifically Designed for Agrochemical Applications in Protected Crops

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Abstract: Protected crops are intensive production systems characterized by high vegetation density, high temperatures, and high moisture, making them favorable environments for the development of pests and diseases. Consequently, these systems often require several interventions with agrochemicals to maintain profitable yields and high produce quality. However, the application of plant protection products (PPPs) in such systems is not efficient and poses environmental concerns. This study aims at analysing spray behaviour, particularly in terms of foliar deposition and losses to the ground according to spraying equipment and foliage height, focusing on a specifically designed and developed system for agrochemical application in protected crops, and comparing it with a commonly used spraying system, namely, the cannon sprayer. Such a system consists in a fixed net of tubing and anti-drip nozzles positioned at the top of the greenhouse's apex, connected to a pneumatic sprayer 'Special Serre 2000' outside the greenhouse. Findings revealed a significant effect of the spraying system (Kruskal–Wallis χ^2 = 12.239, df = 1, and p-value = 0.0004681) on normalized foliar deposition, with higher values obtained using the fixed spraying system. In addition, a simulation of the spatial distribution based on the principle of inverse distance weighting (IDW) was performed for qualitative spray assessment, confirming the heterogeneity of foliar deposition over the greenhouse with both of the used equipment. In addition, losses to the ground were affected by both spraying equipment and captor position.

Keywords: automated fixed system; crop protection equipment; foliar deposit; greenhouse; ground losses; spray behavior

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1. Introduction

In Italy, protected crops extend over 42,347 ha, representing 10% of the total herbaceous horticultural crops and producing more than 2.80 million tons, which corresponds to more than 19% of the fruit and vegetable production [1]. Protected crops are intensive production systems characterized by high vegetation density, high temperatures, and high moisture, making them favorable environments for the development of pests and diseases [2]. Consequently, several interventions with agrochemicals are required to control these undesirable biological agents and maintain profitable yields and high produce quality.

For an extended period, farmers' concerns and plant protection product (PPP) producers' objectives were to maximize the biological efficacy of the active principles until bio-formulations were developed to contrast the negative effects of synthetic pesticides on health and environment [3,4]. However, treatment efficiency depends on several factors, and equipment is a notable consideration. Frequently, the application of PPPs is not efficient because of obsolete or not properly calibrated equipment, which results in an uneven distribution of agrochemicals and raises environmental concerns, including soil pollution, water pollution, air pollution, food contamination [5], and potential exposure of laborers and bystanders.

Current trends and policies—particularly after the issue of directive 2009/127/CE [6], which establishes the 'essential requirements with which machinery for pesticide application must comply before being placed on the market and/or put into service', and directive 2009/128/CE [7], which 'establishes a framework to achieve a sustainable use of pesticides'—lead operators to seek more efficient and sustainable production methods. This includes the use of machinery for PPP applications to ensure treatment efficiency, worker safety, and environmental protection. Moreover, in addition to the aforementioned concerns, we must also consider the high risks of laborers to be exposed to chemicals in enclosed environments such as greenhouses, the scarcity of manpower, and the necessity for the timely implementation of crop protection measures.

There have been several studies on the machinery and equipment used for PPP application in greenhouses. For instance, Cerruto et al. [8] evaluated spray behavior, including operator exposure [9], in tomato greenhouses using hand-held spray lances. Failla and Romano [10] compared the performances of a horizontal boom sprayer and a spray gun under different pressure and forward speeds, considering different tomato seedling growth stages. More recently, Rincón et al. [11] tested a remote-controlled sprayer prototype for pesticide application in greenhouse tomato crops, obtaining better penetration and coverage on the underside of leaves within the canopy. Additionally, Mosalanejad et al. [12] explored the potential of a four-wheel sprayer robot for spraying greenhouses. Notably, because of the use of ultrasonic sensors, robot movement was uniform, and spraying was better than that obtained by conventional equipment, considering vegetation depth.

Considering that the use of robots is still at an experimental stage, not least because of the costs and management issues involved, this study aims at analysing spray behaviour—particularly in terms of foliar deposition and losses to the ground, according to spraying equipment and foliage height, focusing on a specifically designed and developed system for agrochemical application in protected crops, and comparing it with a commonly used spraying system, namely, the cannon sprayer. The methodological approach and findings are presented in the following section.

2. Materials and Methods

This section provides details on the experimental trials performed in the field and laboratory, along with details on data analyses.

2.1. Equipment Description

Two distinct systems for the application of PPPs in greenhouses were tested to compare their technical performances. The first system involved an automatic spraying mechanism specifically designed and manufactured for greenhouses. The system comprised a fixed net of tubing and anti-drip nozzles positioned at the top of the greenhouse's apex (Figure 1), connected to a pneumatic sprayer 'Special Serre 2000' outside the greenhouse, and pulled by a New Holland TN95F tractor (Figure 2).

The system described enables the application of PPPs in an enclosed environment and over the entire area of the protected crop simultaneously, regardless of its extension, without the intervention inside the greenhouse of the operator, whose tasks are limited to mixture preparation, sprayer connection to the distribution net, and sprayer activation. In addition, this system is equipped with a digital flowmeter, which allows the operator to adjust spray volume in real time, according to intervention requirements. The tank is equipped with a washing circuit and mixer, a membrane pump that operates at 15 bar, and a second membrane pump used only for product mixing, which operates at 50 bar.

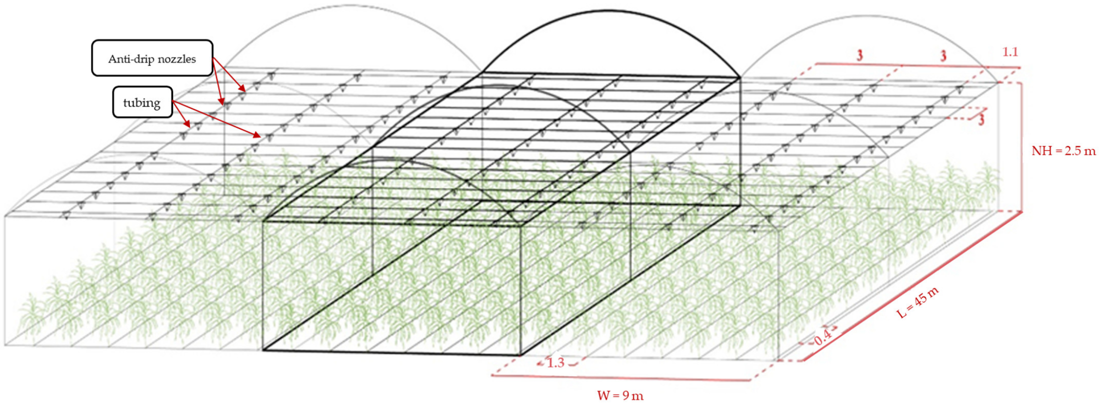

Figure 1. Representative scheme of the fixed net of tubes and nozzles of the Special Serre 2000 system inside the greenhouse. Numbers in the figure indicate the distances expressed in metre (m). Particularly: greenhouse span width W = 9 m; greenhouse span length L = 45 m; distance between pepper rows = 1.3 m; distance between pepper plants in the row = 0.4 m; layout of the net of nuzzles = 3 m × 3 m; distance between the edge of the greenhouse span and the first tubing line = 1.1 m; height of the fixed net of tubing and anti-drip nozzles NH = 2.5 m.

Figure 2. The first spraying system 'Special Serre 2000' used in experimental trials on a protected pepper crop.

The technical features of the above-described sprayer are listed in Table 1.

Table 1. Technical features of the Special Serre 2000.

Item	Unit	Value
Pump	L	560
Gearbox		2 speeds
Hydraulic pressure regulator	/	1–2
Digital flow counter	/	2
Compressor head	/	1
Exercise pressure	Bar	15
Air tank	/	2
Air tank capacity	L.	540
Air safety valve	/	2
Air circuit beaker	/	1
PTO speed	rpm	540
Premixing plant	/	NO
Power	kW	41.11
horsepower	Hp	60

The second system consists of a conventional cannon sprayer, which is commonly used by greenhouse farmers. In particular, the Tifone Storm 2000 80S model, towed by a Lamborghini RF100 tractor, was evaluated (Figure 3). Table 2 summarises the main technical features of this sprayer.

Figure 3. The second spraying system 'Tifone Storm 2000 80S model' used in experimental trials on a protected pepper crop.

Table 2. Technical features of the Tifone Storm 2000 80S model.

Item	Unit	Value
Main tank	L	2250
Machine washing tank	L	65
Hand washing tank	L	15
Power	kW	37
Horsepower	Hp	49.62
	CV	50.31
Fan	/	Centrifugal
Fan diameter	mm	410
Weight (empty)	kg	711
Dimensions (l × w × h)	cm	320 × 138 × 165
Flow	m	45–50

2.2. Field Tests

Field trials were performed on a privately owned farm that specialises in the production of fruits and vegetables (38°48′37.26″ N, 16°13′27.28″ E) in Southern Italy. The utilised agricultural area is extended over 63 ha, of which 30 ha are dedicated to protected crops. For the experimental trials, a green pepper protected crop at its final stage was selected (Figure 4) to ensure maximum foliar coverage. For each spraying system, a span of 9 m width, 45 m length, and 3 m height were considered. To avoid a deposit contamination phenomena between the two trials, a buffer area of 18 m (two spans) was implemented. Both experiments were performed in the same day, under the same conditions, to lower, as much as possible, the effect of greenhouse environmental factors on the spray behaviour.

Figure 4. Green pepper crop considered for experimental trials.

Spraying was performed using the above-described systems. A dye solution, specifically tartrazine yellow (E102 85%) solution (Figure 5), was prepared as described in previous works [13,14]. Two hundred litres were sprayed in each designated span.

Figure 5. Application of the tartrazine yellow (E102 85%) solution on protected pepper crop using the two spraying systems.

The operating parameters used in the trials were those usually implemented on a farm (Table 3).

Table 3. Spraying equipment operating parameters used in the trials.

Parameter	Unit	SpecialSerre2000	Cannon
Engine speed	rpm	1500	1800
Exercise pressure	bar	2	1.2
Distributed volume	L	200	200
Liquid flowrate	$L{\cdot}m^{-1}$	805	140
Advancement speed	$km{\cdot}h^{-1}$	-	1.5
Nozzle type		Dynamic nozzles 35 $L{\cdot}h^{-1}$	1.2 mm Ø
Operating nozzle number		3 m × 3 m	12
Nozzle network height	m	2.5	-
Pipe properties		Low density polyethylene pn 10, 20 mm Ø	-

2.3. Sample Collection and Laboratory Analysis

The samples, which included sprayed leaves as natural targets for foliar deposition and Petri dishes as artificial targets for ground losses, were then collected. Each sample was placed in a sealed container and stored away from sunlight until laboratory analyses.

In both experiments, leaf sampling was performed randomly in different plots across and along each span of the greenhouse, to cover the entire sprayed surface. Also, sampling concerned two levels of height: the basal (<0.5 m of plant height) and apical levels (>0.5 m), as shown in Figure 6. The total number of samples, determined according to the equation (Equation (1)), per greenhouse and distribution system, was 48 leaves.

$$\text{Samples number} = \text{n}^\circ \text{ height levels } (2) \times \text{n}^\circ \text{ plants } (12) \times \text{number of replicates } (2) \quad (1)$$

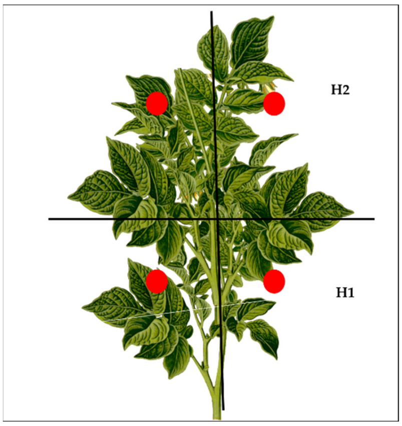

Figure 6. Natural target (leaves) sampling points at plant level (in red).

To evaluate ground losses, Petri dishes were placed in the inter-rows and under the vegetation.

The collected samples, stored as mentioned above, were transported to the laboratory for subsequent colorimetric analysis to determine the intercepted volume by each target. The methodology comprises washing the sample with a specified volume of distilled water (25 mL in this study), and analysing the obtained solution using a bench UV-visible spectrophotometer, model UV-1800 (SHIMADZU CORPORATION Analytical & Measuring Instruments Division, Kyoto, Japan) at a wavelength of 426 nm, which corresponds to the absorbency peak of the tartrazine yellow (E102 85%) solution.

The colorimetric analysis was performed subsequently to spectrophotometer calibration, according to a calibration curve that determines the absorbance of E102 solutions with known concentrations (Figure 7).

Afterwards, leaf sample areas were measured using an area meter, model LI-3100 Area Meter (LI-COR, inc., Lincoln, NE, USA), to calculate the intercepted volume by the targets to their surface, and express it in $\mu L \cdot cm^{-2}$.

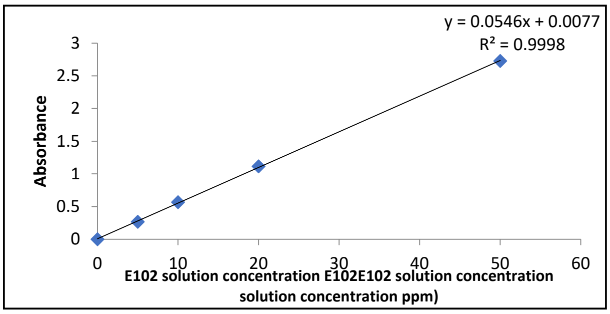

Figure 7. Calibration curve used for spectrophotometer calibration and retrieval of E102 concentration intercepted by targets.

2.4. Data Analysis

Data related to foliar deposition and ground losses were initially standardised to 1000 $L \cdot ha^{-1}$, according to the equation (Equation (2)) reported by Cerruto et al. [8], to enable cross-comparison between the tested equipment and to make them comparable to those reported in the scientific literature:

$$d_n = \frac{d}{V} \times V_n \tag{2}$$

where

d_n represents the normal deposition in $\mu L \cdot cm^{-2}$
d represents the effective deposition in $\mu L \cdot cm^{-2}$
V is the mixture volume distributed during trials in $L \cdot ha^{-1}$
V_n is the normalised volume equal to 1000 $L \cdot ha^{-1}$

The data normal distribution was then checked by performing the Shapiro–Wilk normality test. Analysis of Variance (ANOVA) was applied when normality was verified. In cases in which normality was not met, the non-parametric Kruskal–Wallis rank sum test was used. All statistical tests were performed using the free software environment for statistical computing and graphics R v.3.4.3 (2017-11-30), implementing the Rcmdr package version 2.4–4.

Furthermore, the simulation of the spatial distribution was conducted by interpolating the data obtained according to the principle of inverse distance weighting (IDW) performed with the software ArcGis Pro 3.03. A similar approach was used by Olivet et al. [15] to evaluate leaf droplet density and tracer deposition distribution in a pepper greenhouse.

3. Results

3.1. Foliar Deposition Quantitative Assessment in Function of Spraying System

The normal distribution of the data related to normalised foliar deposition was checked by performing the Shapiro–Wilk normality test by group, as previously stated. Normality was not verified for both tested systems (Table 4).

Consequently, the non-parametric Kruskal–Wallis test was applied, revealing a significant effect of the spraying system (Kruskal–Wallis χ^2 = 12.239, df = 1, and p-value = 0.0004681) on normalised foliar deposition. The mean values correspond to 0.030 $\pm$ 0.021 $\mu L \cdot cm^{-2}$ for the cannon and 0.051 $\pm$ 0.028 $\mu L \cdot cm^{-2}$ for the SS2000 (Figure 8), with a coefficient of variation (CV) equal to 68% for the cannon and 56% for the SS2000.

Table 4. Results of normality tests on normalized foliar deposition.

	Cannon	**SS2000**
W	0.94675	0.9339
p-value	0.04172	0.00952
Median	0.030	0.045

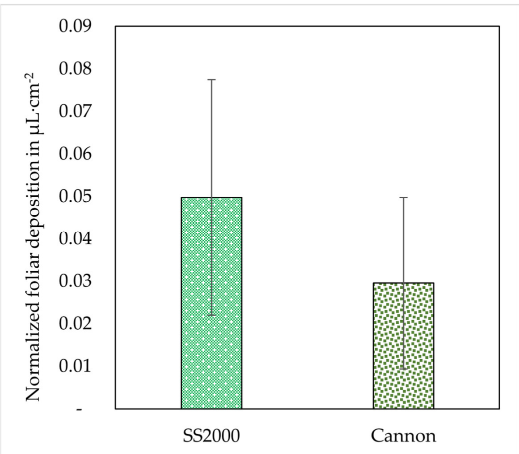

Figure 8. Normalized foliar deposition mean values ($\pm$Dev. St.) expressed in $\mu L \cdot cm^{-2}$.

The analysis of the spraying systems separately shows that data inherent to upper and lower foliage deposition generated by each system were not normally distributed (Figure 9).

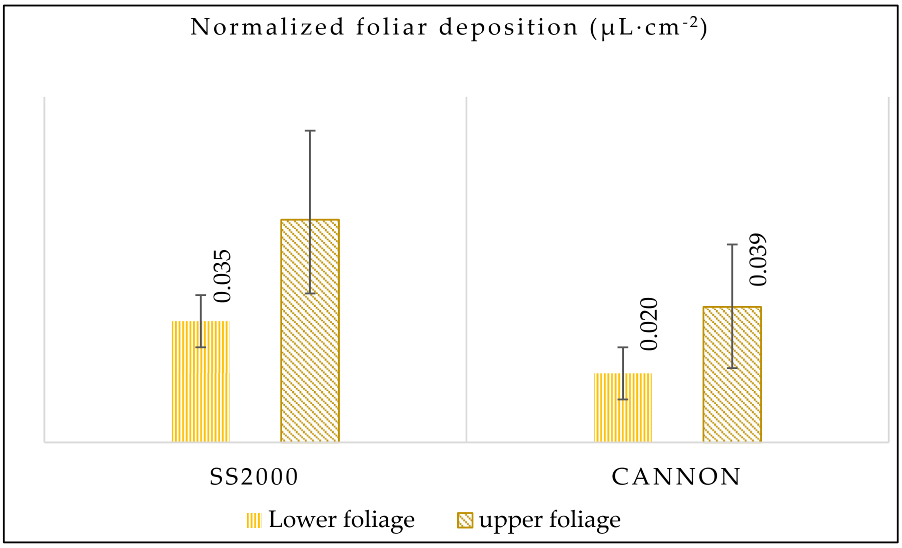

Figure 9. Normalized foliar deposition mean values (±Dev. St.) expressed in μL·cm^{-2} in function of foliage sampling height for each spraying system.

The mean spray deposition values, according to foliage height and spraying system, are listed in Table 5. The results showed that for both systems, the upper foliage received more solutions than the lower foliage (Figure 9). A lower dispersion was observed for the SS2000; indeed, CV values corresponded to 40% and 61% for upper and lower foliage, respectively, while CV values corresponded to 46% and 89%, respectively, for the cannon sprayer.

Table 5. Results of normality tests on normalized foliar deposition according to foliage height.

	Cannon		SS 2000	
	Upper Foliage	**Lower Foliage**	**Upper Foliage**	**Lower Foliage**
W	0.95718	0.88008	0.88914	0.89401
p-value	0.4346	0.01212	0.01276	0.0161
Median	0.04	0.02	0.06	0.03
Mean ± St Dev. (μL·cm^{-2})	0.040 ± 0.019	0.020 ± 0.018	0.065 ± 0.026	0.036 ± 0.021
CV (%)	46	89	40	61

The Kruskal–Wallis test showed that normalised foliar deposition was also affected by foliage sampling height in both situations (Table 6).

Table 6. Results of the non-parametric Kruskal-Wallis test related to the effect of foliage height on spray deposition for each of the analyzed systems.

	χ^2	df	*p*-Value
Cannon	9.4742	1	0.002084
SS2000	14.222	1	0.0001624

Considering foliar deposition data, a two-dimensional (2D) model was developed to simulate spray behaviour using an interpolation algorithm based on the IDW. Such a deterministic, non-linear technique is widely used to estimate the value for an unmeasured point from the neighbouring measured sample points, giving much more impact to the closest neighbours compared to the farthest ones [16,17]. Hence, the IDW model was developed using real deposition measurements to estimate the value for unmeasured points and assess spray behaviour in the whole span of the greenhouse.

Therefore, the upper and lower levels were analysed separately, and the interpolations obtained for each level and each spraying system confirmed the previously described results. Specifically, Figures 10 and 11 show a certain gradation in grey scale, indicating that spray deposition was not homogenous in both tests. A higher amount of solution was obtained when using the SS2000, particularly on the left side, rather than the cannon sprayer, for which we observed darker areas (corresponding to higher volumes) towards the lower left and upper right corners. In addition, in both cases, the upper crop levels received significantly more solution than the lower ones.

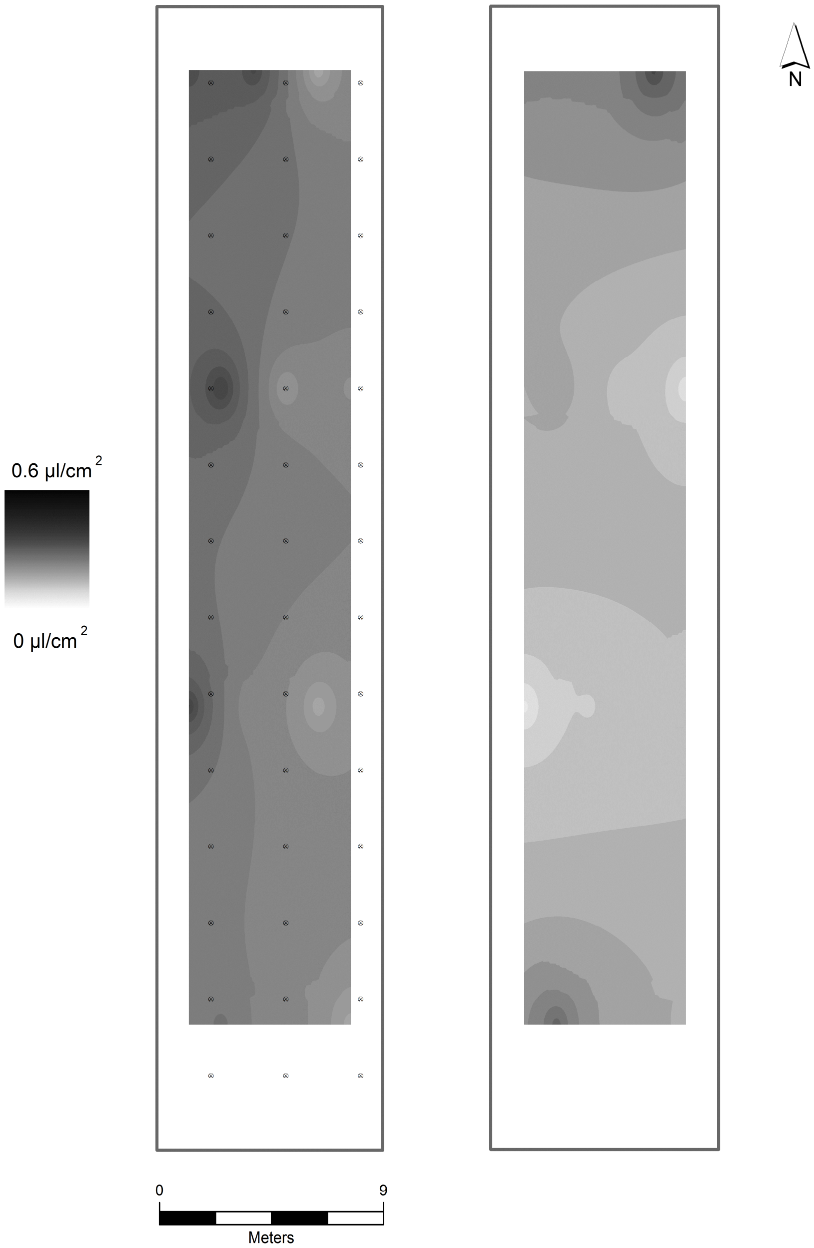

Figure 10. Interpolation of spray deposition over the upper foliage level. (**Left**): SS2000, dots represent nozzles position; (**Right**): cannon.

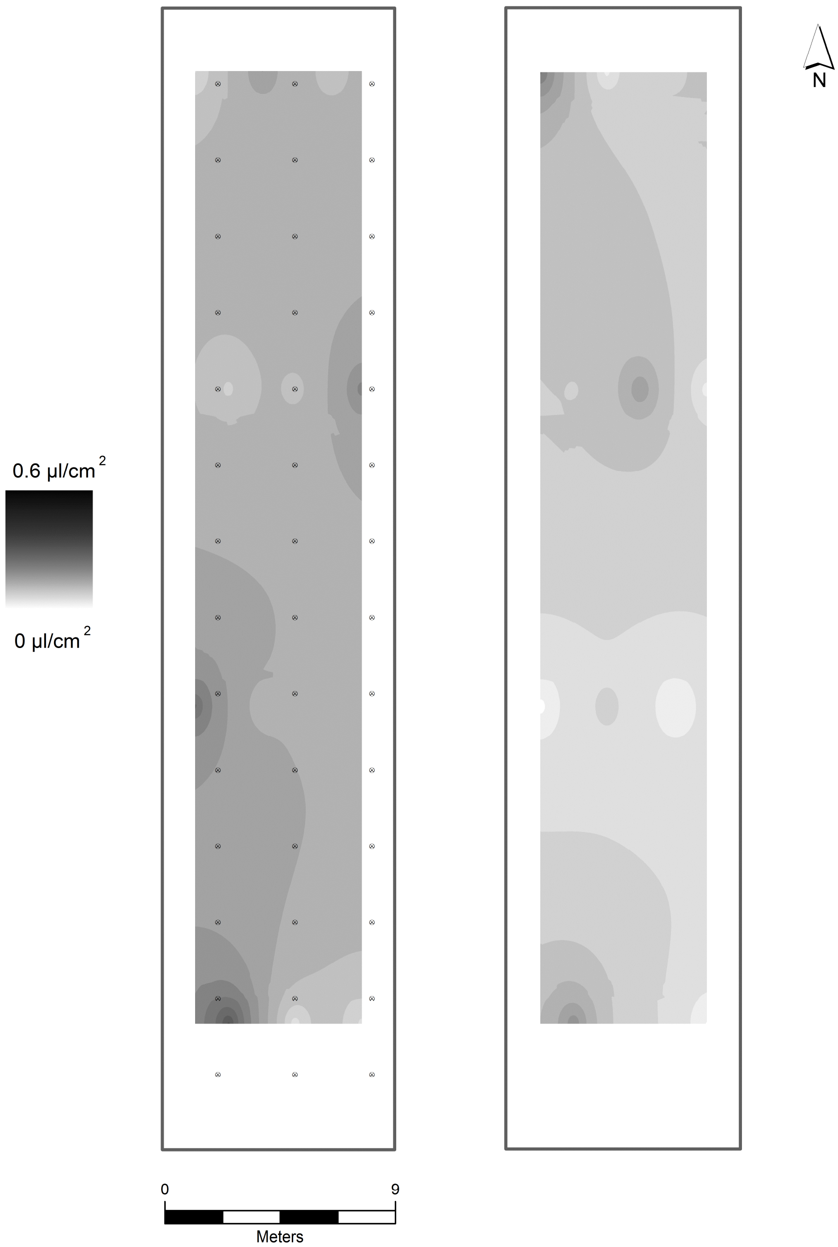

Figure 11. Interpolation of spray deposition over the lower foliage level. (**Left**): SS2000, dots represent nozzles position; (**Right**): cannon.

3.2. Evaluation of Ground Losses According to Spraying Equipment

Data analyses showed that spray losses to the ground followed the same trend as foliar deposition. Specifically, higher losses were observed with the fixed automatic spraying system SS2000 (Figure 12), with values equal to 0.13 ± 0.09 µL·cm^{-2} against 0.07 ± 0.06 µL·cm^{-2} for the cannon sprayer. Normality test results and mean values of normalised losses to the ground (Figure 13), categorised by spraying system and sampling position, are presented in Table 7 and Figure 13. Because data were normally distributed for all groups (Table 7), a two-way ANOVA was performed. This analysis revealed significant differences based on the spraying system and sampling position (Table 8).

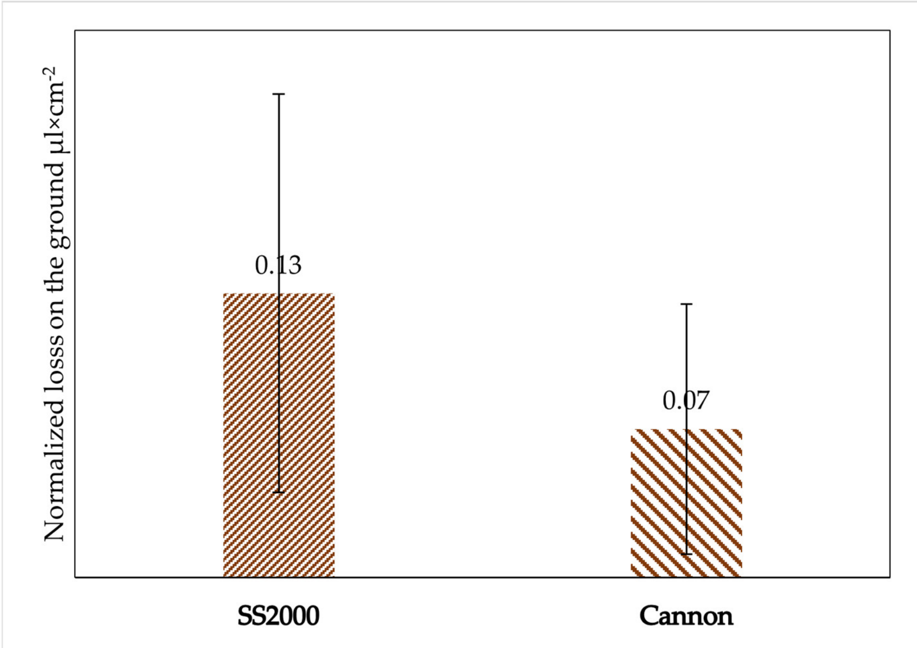

Figure 12. Normalized losses to the ground mean values (±Dev. St.) expressed in μL·cm^{-2}.

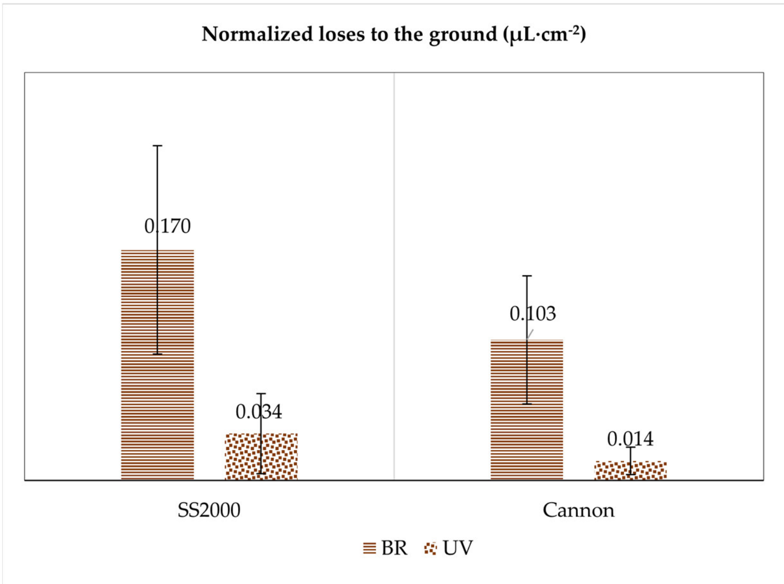

Figure 13. Normalized losses to the ground mean values (±Dev. St.) expressed in μL·cm^{-2} according to sampling position for each spraying system. BR: between rows; UV: under vegetation.

Table 7. Results of normality tests on normalized losses to the ground.

	Cannon		**SS 2000**	
	Between Rows	**Under Vegetation**	**Between Rows**	**Under Vegetation**
W	0.86866	0.9445	0.9565	0.95579
p-value	0.06284	0.6558	0.733	0.7784
Mean ± St Dev. (μL·cm^{-2})	0.103 ± 0.05	0.014 ± 0.01	0.170 ± 0.08	0.034 ± 0.03

Table 8. Results of the two-way analysis of variance (ANOVA) related to ground losses according to spraying system and sampling position. Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

	Sum Sq	Df	F Value	Pr (>F)
Sampling position	0.098030	1	34.6883	1.335×10^{-6} ***
Spraying system	0.023082	1	8.1678	0.00733 **
Sampl. Pos. × Spray. Syst.	0.004338	1	1.5350	0.22410
Residuals	0.093259	33		

4. Discussion

Normalised foliar deposition mean values were higher with the SS2000, which produces mist inside the greenhouse, compared with the conventional cannon. Although both systems generated uneven distributions, the SS2000 showed better results, as demonstrated by the CV values. The unevenness observed with the SS2000 was primarily due to the configuration of the pipe and nozzle network (3 m × 3 m, see Figure 1 and Table 3), which did not fit the plantation layout, thus representing one of the limitations of such a system. In the case of the cannon sprayer, as illustrated in Figures 10 and 11, darker points correspond to the lower left and upper right corners. The operator performed the application from each side of the span, spraying from right to left on one side, and vice-versa on the other. The darker zones correspond to the end of the application; hence, further product was sprayed even when the sprayer was turned off.

Furthermore, in both systems, the upper foliage received a significant amount of the product compared with the lower foliage, indicating that the vertical distribution was not homogeneous. Notably, the trials were performed during the final development stage, with plants characterised by several layers of large foliage, making it difficult for lower layers to receive the product, even when applied with a fine mist using the SS2000, suggesting further improvements of such a system for a better spray distribution and, consequently, a better treatment efficiency.

The values obtained in this study were significantly lower compared with those obtained in other studies. Sánchez-Hermosilla et al. [18] tested a manually-pulled trolley, equipped with two vertical spray booms, and compared it with a manual spray gun. They observed a foliar deposition greater than 40.6% (≥4.1 μL·cm^{-2}) and lower losses to the ground when the trolley was operated at 1630 L·ha^{-1}, a pressure of 12 bar, and using the standard flat fan nozzle. In another study, Sánchez-Hermosilla et al. [19] tested the performance of a fog cooling system for pesticide application on a tomato protected crop, and compared it with that of a conventional spray gun. The researchers obtained a spray foliar deposition of 3.52 μg·cm^{-2} equivalent to 0.37 μL·cm^{-2}, with the fog cooling system operating at 2.5 and 3 bar, respectively, for air and liquid pressure, and spraying 994 L·ha^{-1}, against the 0.051 ± 0.028 μL·cm^{-2} obtained in this study, using a quite similar system. Failla and Romano [10] observed a foliar deposition for the second development stage (formation of side shoots/tillering) of tomato seedlings ranging from 0.52 to 1.77 μL·cm^{-2} using a horizontal boom and varying the forward speed, exercise pressure, flow rate, and distributed volume. Notably, highly significant differences were observed between the tests performed, against the 0.91 μL·cm^{-2} using the spray gun. The authors also reported ground losses with mean values of 1.24 μL·cm^{-2}. Rincón et al. [11] identified highly significant differences when three-way ANOVA was applied to canopy deposition data, considering spray application parameters, foliage height, and depth.

In the context of pepper protected crops, Sánchez-Hermosilla et al. [20] tested three hand-held sprayers—specifically, one hand-held spray gun and two hand-held spray lances. The researchers reported values ranging between 0.84 ± 0.68 and 1.09 ± 0.65 μL·cm^{-2} for foliar deposition, and values ranging between 3.76 ± 1.36 and 11.77 ± 6.61 μL·cm^{-2}

for ground losses. Sánchez-Hermosilla et al. [21] observed higher canopy deposition when using electrostatic spraying on a pepper protected crop, and recorded deposition values of 0.86 ± 0.51, 0.54 ± 0.32, and 0.58 ± 0.34 μL·cm^{-2} for the electrostatic spray gun, the electrostatic spray gun without charge, and the hand-held spray gun, respectively. These values are much higher than those obtained in our study for both systems, i.e., 0.030 ± 0.021 μL·cm^{-2} for the cannon and 0.051 ± 0.028 μL·cm$^{-2.}$ for the SS2000. However, the same authors [21] also obtained high CV values (up to 59.35%), almost similar to the values we obtained in this study corresponding to 68% for the cannon and 56% for the SS2000, indicating that the spatial distribution was not homogenous.

When this system was tested on a chrysanthemum crop [22], with different features in terms of crop layout as well as spraying network configuration, a better and homogeneous distribution was found horizontally for both apical and basal levels, while differences were found according to foliage height, due to the high vegetation density and leaf area index that characterize such kinds of crop.

5. Conclusions

This study reports the evaluation of spray deposits and ground losses using a specifically designed and manufactured fixed system for the application of PPPs in protected crops. The technical efficacy of this system was compared with that of a common sprayer, namely a cannon sprayer. The findings of this study are noteworthy because both systems generated uneven distributions in the vertical and horizontal planes; however, the fixed system exhibited better performances. The results highlighted improvement margins for the fixed system to improve spraying in greenhouses, especially in terms of vertical distribution. Nonetheless, its first users are satisfied with the several advantages it has. Indeed, the analysed fixed automatic guarantees timeliness, as it enables the treatment of an extended area to be performed simultaneously in a very short time (a few minutes), which is very important to ensure the sanitary status of a crop, particularly if primary symptoms appear, considering also the environmental factors of a protected crops. Moreover, it guarantees the safety of labourers who are used to applying PPP's inside the greenhouse, in an enclosed environment which increases their exposal to chemicals, and consequently to respiratory and dermatological issues. In this regard, Cerruto et al. [9] investigated operator dermal exposure to pesticides in tomato and strawberry greenhouses, considering the most-used hand-held equipment operating at high pressure. Their findings highlighted the effect of crop features, particularly height and walking direction while using the previously mentioned equipment, on the operator's bodily exposure to chemicals. Whereas with the fixed system, there is no need for laborer intervention and involvement inside the greenhouse. Another aspect regards the environment. Indeed, with the studied system, the PPPs application is performed in an enclosed environment, impeding, therefore, drift risks. Hence, even though the system presents some resolvable limitations, it brings concrete and sustainable solutions to agrichemical application in protected crops, and its use may also be extended to plant nurseries and soilless crops.

Finally, saving time and labour, guaranteed by the fixed system, forcefully turns in lowering production costs.

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