Relative efficiencies of experimental and conventional foliar sprayers and assessment of optimal LWA spray volumes in trellised wine grapes

Journal:	*Pest Management Science*
Manuscript ID	PM-20-1302.R1
Wiley - Manuscript type:	Research Article
Date Submitted by the Author:	n/a
Complete List of Authors:	Gil, Emilio; Universitat Politecnica de Catalunya, Agri Food Engineering and Biotehcnology Salcedo-Cidoncha, Ramon; Ohio State University Foundation, Department of Food, Agricultural and Biological Engineering Soler, Agusti; BayerCropScience SA-NV, Field Solutions Ortega, Paula; Universitat Politecnica de Catalunya, Agri Food Engineering and Biotehcnology Llop, Jordi; Universitat Politecnica de Catalunya, Agri Food Engineering and Biotehcnology Campos, Javier; Universitat Politecnica de Catalunya, Agri Food Engineering and Biotehcnology Oliva, Jordi; BayerCropScience SA-NV, Field Solutions
Key Words:	Plant protection, dose expression, LWA, foliar spray volume, wine grapes, leaf deposit

Relative efficiencies of experimental and conventional foliar sprayers and assessment of optimal LWA spray volumes in trellised wine grapes

Short title: Evaluation of spraying technologies in vineyards

Emilio Gil [a, 1], Ramón Salcedo [b, c], Agustí Soler [d], Paula Ortega [a], Jordi Llop [a],

Javier Campos [a] and Jordi Oliva[e]

[a] Department of Agri-Food Engineering and Biotechnology, Universitat Politècnica de Catalunya, Esteve Terradas 8, Campus del Baix Llobregat D4, 08860 Castelldefels, Barcelona (Spain).

[b] Department of Food, Agricultural and Biological Engineering, Ohio State University, Agricultural Engineering Building 590 Woody Hayes Drive, Columbus, OH 43210 (USA).

[c] Application Technology Research Unit (ATRU), Agricultural Research Service of the United States Department of Agriculture (USDA-ARS), 1680 Madison Avenue, Wooster, OH 44691 (USA).

[d] Market Development EMEA, Bayer CropScience, S.L., Avinguda Baix LLobregat 3-5, 08970 Sant Joan Despí, Barcelona (Spain).

[e] Field Solutions, Bayer CropScience, S.L., Avinguda Baix LLobregat 3-5, 08970 Sant Joan Despí, Barcelona (Spain).

[1] Corresponding author: Emilio Gil (Emilio.gil@upc.edu)

Authorship: Ramón Salcedo (RS) (salcedocidoncha.1@osu.edu), Paula Ortega (PO) (paula.ortega@upc.edu), Jordi Llop (JL) (jordi.llop-casamada@upc.edu), Javier Campos (JC) (javier.campos@upc.edu), Agustí Soler (AS) (agusti.soler@bayer.com), Jordi Oliva (jordi.oliva@bayer.com) and Emilio Gil (EG) (emilio.gil@upc.edu).

Author's contribution: Conceived and designed the experiments: RS, JL, AS and EG. Performed the experiments: RS, JC, JO, PO and JL. Analysis and interpretation of data: PO and EG. Wrote the paper: EG, RS and AS.

Location: Work was done at the Laboratory of Agricultural Mechanization belonging to the facilities of Agropolis Research Campus of the Universitat Politècnica de Catalunya in Viladecans (Barcelona, Spain) (41°17'18.44"N/2°2'43.39"W).

Corresponding Author

Emilio Gil, DEAB, Universitat Politècnica de Catalunya, Esteve Terradas 8, Campus del Baix Llobregat D4, 08860 Castelldefels, (Barcelona, Spain).

Tel: +34 93 552 10 99

E-mail: emilio.gil@upc.edu

Website: https://uma.deab.upc.edu/en.

ABSTRACT

Background: Leaf wall area (LWA) has been proposed as an appropriate dose expression for field testing of plant protection products (PPPs) applied via foliar spray in trellised grapes. But its efficiency could change depending on the characteristics of the crop or the pesticide application equipment (PAE). Herein, three spray technologies were evaluated. A traditional air-assisted tractor-mounted sprayer was compared with two portable knapsack sprayers: a backpack mistblower and a backpack hydraulic sprayer. Trials were conducted in trellised wine grapes at three selected crop stages (BBCH 55, 65, 75) covering the main period of canopy development. In each canopy stage, leaf deposition and coverage were sampled for each technology. The tractor-mounted sprayer was working at 200 L ha^{-1} of LWA spray volume for the earliest stage and 370 L ha^{-1} for the other two. Three higher volume rates were used for backpack sprayers up to 800 and 1250 L ha^{-1} for the mistblower and the hydraulic system, respectively.

Results: Optimal LWA spray volumes differed among application devices in terms of efficiency and uniformity of deposition on the canopy,. The efficiency of each spray application was not only conditioned by the spray volume but also by the presence of gaps in the canopy or the air assistance.

Conclusion: LWA is useful for defining optimal spray volumes in trellised grapes. However, both canopy density and spray technology should be considered to assist this process. Field testing of PPPs and subsequent label recommendations should take into account the relative efficiencies of corresponding experimental and conventional spray technologies.

Keywords: Plant protection, dose expression; LWA; foliar spray volume; wine grapes; leaf deposit.

1. INTRODUCTION

Dose expression for plant protection products (PPPs) applied via foliar spray on orchards, vineyards and other high growing crops (often referred to as three-dimensional or 3D crops) has generated extensive and controversial discussions. [1-10] Given the obvious structural differences between 3D crops and field (row) crops, [11, 12] there is ample consensus in recognizing that kg (or L) ha^{-1}, a dose expression well suited for field crops, is not appropriate for 3D crops and that Leaf Wall Area (LWA) is an appropriate dose expression for plant protection products applied via foliar spray on pome fruit, grapes, and high-growing vegetables. [7] Traditionally, use recommendations for PPPs in 3D crops have been mostly based on product concentration in the spray water (g or cm^3 hL^{-1}). This approach generates a direct relationship between PPP dose rate and spray volume and thus requires thorough scrutiny of water rates and spray quality, in order to limit human and environmental risks. [13] Improving spray efficiency allows limiting unintended risks by diminishing losses to non-target compartments and consequently reducing the absolute amounts of PPPs applied per ground area. [14-16] In turn, investigating and subsequently communicating the appropriate amount to be applied in a given 3D crop scenario, i.e. clearly stating the *amount of PPP per unit canopy* in corresponding labels, requires the use of an unambiguous and practicable dose expression. [3, 8] Different dose expressions have been proposed for development of PPPs in 3D crops and for their eventual insertion in corresponding labels. These methods make various claims regarding improved efficiency of PPP use, linked to the consideration of one or several canopy characteristics. [1, 17-22] Attempts to identify appropriate dose expressions have included recommendations based on either two- or three-dimensional factors related to the canopy structure. [22-25] However, the lack of a harmonized approach in Europe has resulted in remarkable differences in dose expressions, as reveals the comparison of label instructions for PPPs authorized in different European countries. [21]

The process of harmonization of the information contained in European labels, especially for uses in three-dimensional (3D) crops, is still in progress. [10, 26] Concerning the southern regulatory zone (including Bulgaria, Cyprus, France, Greece, Italy, Malta, Portugal, and Spain), in most cases label recommendations are based on PPP concentration in the sprayed volume (%; rate hL^{-1}), accompanied by the maximum amount of product per unit of ground surface, and a range of recommended water volumes. [13, 27, 28] It is widely accepted that both the amount of PPP and the spray volume should be adapted to canopy structure and dimension. [9, 29-33] Therefore, several research groups have developed models for adequately adjusting the spray volumes to the canopy characteristics [13, 23]. In practice, these models allow converting the traditional dosing system, based on PPP concentration, into an appropriate dosing system for 3D crops, via adjustment of the spray volume to the treated canopy. This is because provided the optimum amounts of both PPP and spray water refer to the same *canopy unit*, a constant concentration will invariably arise. [21]

The practical information available in many PPP labels in southern Europe, in particular that concerning uses in grapes, has traditionally referred to a standard spray volume of 1000 L ha^{-1}. This should be considered a remnant from past times, when high spray volumes were required at full vegetation, to compensate for the low efficiencies achieved at that time by field sprayers. After years of continuous improvement of application technologies, at present growers of wine grapes in southern Europe seldom apply such a high water-volume, except when dealing with very large and dense canopies. In recent years, the value of significantly reduced spray volumes, in terms of quality of distribution and reduction of losses, has been widely demonstrated. [34-37] Nevertheless, the extent to which such reductions in spray volumes can be attained, without compromising spray efficiency, is clearly linked to spray technology. [38]

The current regulatory frame for authorization of PPPs in Europe requires the previous conduct of numerous and diverse field trials which, for practical reasons, are executed using portable experimental spraying equipment. Small-plot field trials involving several replicated treatments, as required by corresponding European guidelines, can’t be conducted using conventional tractor-mounted sprayers. Therefore, backpack spraying devices (typically, motorized hand-held mistblower and hydraulic sprayers) are commonly accepted as surrogate spraying devices in field experimentation. In order to appropriately reproduce commercial-scale, conventional spraying of PPPs, the use of hand-held devices in field trials should result in deposition rates reasonably comparable to that provided by conventional field sprayers. [39, 40]

The objective of this research was to define the optimal spray volumes in trellised grapes, based on the leaf wall area (LWA) dose expression, for conventional and experimental spraying devices, as well as quantifying the corresponding efficiencies of each spray application technique.

2. MATERIAL AND METHODS

2.1 Spray application equipment.

For representing devices used in field experimentation, two different hand-held sprayers were selected, respectively based on two key technical characteristics: height of the spray band and air assistance. These hand-held sprayers were compared with a tractor-mounted mistblower, representative of conventional field spray technology (Fig. 1). The main technical characteristics of the three selected sprayers were as follows:

a) Tractor-mounted sprayer (TMS): An air-assisted sprayer fitted with a 400-L lifted tank, a centrifugal turbine fan, and 5 individual orientable spouts per side, was used as a reference sprayer (Hardi SPV, Ilemo-Hardi, S.A.U., Lleida, Spain). [38]

b) Hydraulic backpack sprayer (HBS): A manually activated, continuous-pressure sprayer, with a 16-L tank (MATABI Evolu 16, Goizper group, Anzuola, Spain), connected to a vertical boom fitted with 2, 3 and 4 nozzles spaced 0.5 m. This experimental device was included to ascertain the influence of spray swath on spray efficiency.

c) Pneumatic backpack sprayer (PBS): A motorized mistblower with a 12-L tank fitted with a centrifugal fan and a single air-assisted output (Solo Port 423, Solo Kleinmotoren GmbH, Sindelfingen, Germany), adjusted out of specification (4.0 - 4.5

L/min), to attain delivery of high-volume rates. This experimental device was included to provide insights into the influence of air assistance and high-volume rates on spray efficiency.

2.2 Arrangement of the field tests

Tests were performed on a vineyard parcel located at the UPC research facilities of Agropolis Research Campus at Viladecans (Barcelona, Spain) (41°17’18.44”N/2°2’43.39”W). The vineyard had a surface of 1500 m^2 (30 m × 50 m) planted with 15 rows of Cabernet Sauvignon variety of wine grape (*Vitis vinifera* L.) with a planting scheme of 3.0 m × 1.2 m. and trellised following a Double Royat, with two wires in each row.

Three different tests were conducted along the crop season, covering the most representative canopy stages: BBCH 55, 65, and 75 (Table 2) [41] Previous to each spray event at the chosen crop stages, a complete canopy characterization of the whole experimental area was carried out, by taking a total of 35 individual measurements of canopy height equally distributed among plots, to obtain the corresponding LWA values per each plot (m^2 canopy ha^{-1}).

Based on the actual LWA values measured, estimated volume rates *i-LWA* (L ha^{-1} LWA or L 10000 m^{-2} canopy) were calculated for each plot and timing (Table 3). Accordingly, the main working parameters (total volume rate, forward speed, pressure, and nozzles) for every sprayer were defined, to convert the previously obtained *i-LWA* values into nominal volume rates per ground ha V_T (L ha^{-1}). For each sprayer, the time needed for the operator to spray the corresponding plot was measured, to calculate the actual forward speed and actual volume rates per ground ha V_R (L ha^{-1}). For each backpack sprayer, HBS, and PBS, three different volume rates *i-LWA* (low, intermediate and high) were initially established. Based on previous research work on vineyard crops, [25, 42] for HBS the low *i-LWA* rates matched the single rate selected for the conventional sprayer TMS, i.e. 200 L ha^{-1} LWA for the first spray timing and 370 L ha^{-1} LWA for the second and third timings. Two higher volume rates were used, increasing 200 L ha^{-1} LWA approximately every time until 800 L ha^{-1} LWA. Because of the specific characteristics of the manually activated HBS, a comfortable forward speed from 3.5 to 4.5 km h^{-1} was chosen, constantly maintaining the working pressure. Consequently, increases in volume rates were achieved by changing the spray nozzles. Conventional hollow cone and flat fan nozzles following ISO codes were utilized for TMS and HBS, respectively, [43] except for the first spray timing, in which TMS was fitted with hollow cone ATR nozzles (Albuz Saint-Gobain Solcera, Evreux, France). Finally, for PBS the low volume rate was set at 750 L ha^{-1} LWA, representing a rate commonly used in field experimentation with PPPs. This reference rate was increased stepwise in 250 L ha^{-1}, making the high-volume rate 1250 L ha^{-1} LWA. Since PBS was powered by an engine, larger volume rates could be tested, maintaining comfortable forward speeds for the operator. The selected nozzle in this case was a conical diffuser integrated into the pneumatic sprayer.

2.3 Experimental setup

Individual experimental plots were distributed over the 15 rows of the parcel (Figure 2). One entire row line was assigned for each spray device. For HBS and PBS, each row was divided into three segments of identical length, corresponding to each of the three volume rates tested. Buffer areas within- and between rows were established, to avoid cross contamination between experimental plots.

Leaf deposit *d* (μg cm^{-2}) was measured for each plot and spray timing, using leaves as natural collectors, following the protocol established in previous research work. [38, 44, 45] To evaluate the spray distribution uniformity, the canopy was divided into several sampling sections. Treated canopy height was divided into two equal parts (bottom and top) for BBCH 55 and 65, and in three parts (bottom, central, and top) for BBCH 75. In turn, canopy width was divided into three zones (external left, center, and external right). From each sampling zone, a variable number of leaves (between 2 and 4, depending on size) were carefully collected randomly after each application, placed into tagged plastic bags, and stored in a dark recipient. For HBS and PBS, fifteen leaf samples were collected from the corresponding rows at each timing, i.e. five samples per each of the three volume rates tested per sprayer. For TMS, five samples were taken along the corresponding row. Yellow tartrazine (E-102 yellow) at a concentration of 2.0 g L^{-1} was selected to determine deposition on leaves, due to its high recovery rate, non-toxic properties, and reasonable stability. [46]

In addition, following the same division of the canopy used to determine deposition on leaves, a total of six (BBCH 55 and 65) or nine (BBCH 75) water-sensitive papers (WSP) were placed to determine the spray coverage. For HBS and PBS, nine WSP strips were placed in each corresponding row, i.e. three per each volume rate. After spraying, each WPS strip was collected, placed on a template sheet of paper, allowed to dry completely, and stored in a closed plastic bag. Data on coverage (%) and average impacts cm^{-2} were obtained after analyzing WSP strips using a specific macro developed [46] for Image J free software (LOCI, University of Wisconsin, USA).

Before and after each spray event, samples of spray liquid were collected from the corresponding outputs of each spraying device, to determine the actual tracer concentrations.

At each spray timing, applications were initiated with the conventional TMS, followed by HBS and finally by PBS. All applications were conducted following the recommendations for Best Management Practices to Reduce Spray Drift. [47] This involved wind speed values below 3.0 m s^{-1} during spraying. [48] An automatic weather station (WatchDog Weather Station Model 2550, Spectrum Technologies, Inc., USA) was used to register wind speed during applications. The weather station was located at a 25-m distance downwind from the experimental area, at a height of 2 m, and without any obstacles in-between. Across all spray events, wind speeds ranged from 0.9 m s^{-1} to 2.9 m s^{-1}, with directions of 65 - 134°, considering 0° when wind flows from West to East.

2.4 Data analysis

Tracer concentrations T_{cl} (mg L^{-1}) in the liquid samples, obtained after rinsing the leaves, were calculated based on the methodology proposed by Gil *et al*. [42] For dislodging the dye, a volume *w* of 20 mL of deionized water was poured into each plastic containing the leaf samples and, after 60 s of shaking, a liquid sample was collected and subsequently analyzed using a spectrophotometer (Thermo Scientific Genesys 20, Thermo Fisher Scientific Inc., Waltham, USA) at a wavelength of 427 nm. The individual leaf area for all leaf samples (cm^2) was calculated considering the area: weight ratio determined previously, [42, 44,50] after measuring the weight and surface area of 50 samples collected from the bottom, middle, and top parts of the vine. Leaf surface area was measured with a LI-COR LI 3100C electronic planimeter (LI-COR Inc., Lincoln, USA). Leaf deposition per unit leaf area *d* (µg cm^{-2}) was determined according to Equation 1:

$$d = (T_{cl} \times w)/S_a, \qquad (1)$$

where *d* is the absolute deposit on leaves (µg cm^{-2} leaf), T_{cl} is the tracer concentration in the liquid sample (mg L^{-1}), *w* is the volume of washing water (mL), and S_a is the sample leaf area (cm^2).

Subsequently, three different normalized indexes were calculated: normalized deposit (d_N), normalized deposit per amount of tracer applied per unit surface (d_G), and normalized deposit per 100 L water (d_{100}).

a) Normalized deposit (d_N)

The normalized deposit d_N (µg cm^{-2} leaf) was calculated (Equation 2) by considering the values of tracer concentration for each timing, sprayer, and volume rate (Table 4). This methodology has been successfully applied in previous studies to directly compare different spray technologies and working conditions for PPP applications. [39, 44, 45, 50, 51]:

$$d_N = d \times f_{Tc} \times f_{VR}, \qquad (2)$$

where d_N is the normalized tracer deposit (µg cm^{-2} leaf), f_{Tc} is a factor that compensates for fluctuations in actual spray concentrations, and f_{VR} is a factor that compensates for the different spray volumes applied.

b) Normalized deposit per amount of tracer applied per unit of ground surface (d_G)

An additional normalization process was performed to obtain the normalized deposit per kg of tracer applied per hectare (µg cm^{-2}/kg tracer ha^{-1}). This new parameter d_G represents the relative deposition on leaves considering the same amount of tracer per unit of ground area, and was determined using Equation 3:

$$d_G = (d_N \times 10^6)/(T_{cs} \times V_R), \qquad (3)$$

where d_G is the deposit per unit of tracer applied per hectare (µg cm^{-2}/kg tracer ha^{-1}), d_N is the normalized tracer deposit (µg cm^{-2}), T_{cs} is the actual tracer concentration in the tank (mg L^{-1}), and V_R is the actual volume rate (L ha^{-1}) calculated after each treatment using the actual forward speed.

c) Normalized deposit per 100 L of water

This normalization process was adapted to consider the effect of the volume rate on the results. Following previous research, [52] it was determined using equation 4:

$$d_{100} = (d_N \times 100)/V_R \qquad (4)$$

where d_{100} is the deposit per 100 L applied per hectare (µg cm^{-2}/100 L ha^{-1}), d_N is the normalized tracer deposit (µg cm^{-2} leaf), and V_R is the actual volume rate (L ha^{-1}).

Additionally, the deposit efficiency factor F (dimensionless) was defined with the purpose of quantifying the efficiency of each spray event [53]. F compares the actual deposition value with that expected based on the adjusted *i-LWA* rate, considering the leaf density, i.e. gaps in the canopy wall. Leaf density is not considered in the LWA dose expression, despite it can certainly influence the catchment efficiency (foliar interception) of the canopy wall. F establishes the relationship between the actual deposits on leaves and those expected theoretically. F was compared with values obtained assuming no gaps in the canopy wall (L_{fd} =1) (F_1). The F values were calculated according to Equation 5:

$$F = (d_N \times L_{fd} \times 10^5) / (i\text{-}LWA \times T_{cs}), \qquad (5)$$

where F is the efficiency value (dimensionless), d_N is the normalized tracer deposit (µg cm^{-2} leaf), Lf_d is the ratio of canopy gaps (m^2 leaf m^{-2} canopy wall), *i-LWA* is the volume rate (L 10^4 m^{-2} canopy), and T_{cs} is the actual tracer concentration in the tank (mg L^{-1}).

Statistical analyses were performed using R software (R Development Core Team, Vienna, Austria, 2012). Differences between spray technology and volume rates were analyzed using an ANOVA ($P \leq 0.05$) test and a Student–Neuman–Keuls Test post-hoc test. Before statistical analysis, the data were transformed to follow a normal distribution. The normalized deposit d_N was adjusted to a square root transformation following the same procedure as that used in previous works. [42, 44]

3. RESULTS AND DISCUSSION

3.1 Overview of general deposits on leaves and coverage

3.1.1 Comparison between coverage and leaf deposit

Figure 3A presents the relationship between the average coverage measured in WSP and the average values of normalized deposits on leaves d_N. Even if the regression is not very high (R^2 = 0.59), these results are aligned with previous studies in vineyards comparing water sensitive paper, filter paper, and real leaves as collectors. [25] In general, we observed that the greater the deposition of the product on the leaves, the greater the coverage. For d_N values higher than 3.5 µg cm^{-2} leaf, the coverage on the WSP samples presented values above 40%, which is considered to exceed the optimal coverage value for pest and disease control. [54,55] Therefore, this could suggest that in some cases leaves were over sprayed, resulting in a loss of efficiency.

3.1.2 Relationship between deposition and volume rate

Figure 3B indicates the relationship between the average d_N and *i-LWA* volume rates for all the sprayers tested. Results revealed a positive effect in terms of leaf deposition with increasing values of *i-LWA*. For volume rates greater than 750 L ha^{-1}, d_N exceeded 3.5 µg cm^{-2} leaf, suggesting that this could be the highest volume rate, above which a loss of efficiency becomes evident. Detailed analysis suggested a power trend between parameters for *i-LWA* values ranging from 400 to 800. This relationship, thus, became unpredictable for lowest and highest *i-LWA* values.

3.1.3 Analysis of uniformity of distribution

Absolute values of deposition on leaves are useful to assess distribution over the canopy. To evaluate the uniformity of distribution, Figure 3C presents the relationship between the average deposit and the standard deviation measured at the nine sampling points distributed over the canopy in each experimental plot. Interestingly, for higher deposition values standard deviation tends to increase, with a concomitant reduction of deposition uniformity. This tendency could be explained by the increased heterogeneity of spray deposition observed at large volume rates, where very high deposition values were observed in the external canopy zones, while the lowest values were obtained in the internal part of the canopy.

A detailed analysis of the heterogeneity of deposits and its relationship with volume rates can be observed in Figure 4, which presents the normalized depositions in each of the three growth stages evaluated (Table 1). Specifically, at the first crop stage, for all tested spray technologies (PB and HB) the largest heterogeneity was obtained with the largest applied volume. For the other two crop stages, this tendency has not been observed.

At the early canopy stage (BBCH 55; Fig. 4A), the optimum results in terms of uniformity were achieved with the lowest volume rates, 200 L ha^{-1} LWA with the reference sprayer TMS and with HBS. Conversely, the largest heterogeneity was obtained with the largest volume rate, either with HBS or with PBS.

At the intermediate stage of canopy development (BBCH 65; Fig. 4B), the heterogenicity of spray deposition tended to increase for TMS and PBS. On the contrary, the uniformity provided by HBS, fitted with a vertical boom adapted to the canopy height, was greater than that obtained with either TMS or with PBS. Furthermore, for HBS normalized deposition was significantly uniform across the three volume rates.

Finally, at the full vegetation stage (BBCH 75; Fig. 4C), the use of PBS resulted in highly heterogeneous deposits at all volume rates tested. Furthermore, for PBS average values around the optimum could be roughly attained only with the 1000 l ha^{-1} volume rate. On the other hand, TMS and HBS showed comparable variabilities in spray deposits. The spray distribution obtained with the HBS at 800 L ha^{-1} LWA was the least heterogeneous, followed by the 370 L ha^{-1} LWA volume rate with both HBS and TMS.

3.2 Detailed analysis of results at the three different canopy growth stages

3.2.1 BBCH 55 - Inflorescences swelling, flowers closely pressed together

An evaluation of normalized deposit on leaves (d_N) at BBCH 55 (Fig. 4A) revealed significant differences among all the spraying technologies and volume rates, with the following three groups: a) the highest deposition group, obtained with HBS at 600 L ha^{-1} LWA and with PBS at 1250 L ha^{-1} LWA; b) an intermediate group, with no significant differences between HBS and PBS, for corresponding intermediate volume rates; and c) the lowest deposition was observed for TMS at the lowest volume rate (200 L ha^{-1} LWA). In terms of optimum average deposition, i.e. around 3.5 µg cm^{-2}, these were attained with HBS at 200 and 400 L ha^{-1} and with PBS at 750 and 1000 L ha^{-1}.

Figure 5 presents the percentage of coverage obtained after the analysis of WSP strips. In this case, two main groups were identified. The first group includes excess coverage values (even over 50-60%) obtained with high volume rates (600 L ha^{-1} LWA with HBS and 1000-1250 L $ha^{-1}$with PBS). The second group corresponds to tractor mounted sprayer (TMS) and both portable devices (HBS and PBS) with low and intermediate volume rates, with average values of coverage around what should be considered the optimum, i.e. of 30-40%. [54, 55]

Figure 6A depicts corresponding coverages at BBCH 55 and their distribution across the canopy. The image of the six samples of WSP allocated to the selected zones of the canopy suggests greater uniformity in deposition across the canopy sections for TMS and the lower volume rates of HBS (200 and 400 L ha^{-1} LWA) and PBS (750 L ha^{-1}). On the contrary, the highest volume rates (600 L ha^{-1} LWA for HBS and 1000 and 1250 L ha^{-1} LWA for PBS) resulted in excess, non-uniform deposits in some parts of the canopy.

Results on the relative deposition, based on the amount of tracer applied per hectare d_G at BBCH 55 (Figure 7A), reveal the higher efficiency of HBS, at all volume rates. Both PBS at 750 L ha^{-1} and TMS achieved an intermediate level of relative efficiency. Finally, PBS at 1000 and 1250 L ha^{-1} showed the least efficiency relative to the amount of tracer applied per hectare.

As shown in Figure 8A, HBS at all volume rates tested showed as well the highest efficiencies in the deposition, relative to the amount applied per 100 L of spray water (d_G). The average relative efficiencies d_G of PBS and TMS were 50% lower than those provided by HBS.

3.2.2 BBCH 65 – Full flowering

The data on absolute normalized deposition d_N obtained at BBCH 65, as shown in Figure 4B, suggests that TMS at 370 L ha^{-1} LWA, HBS at 370 and 600 L ha^{-1} LWA, and PBS at 750 L ha^{-1} LWA, all achieved the theoretical optimal deposition on leaves (3.1-3.5 µg cm^{-2} leaf). On the contrary, HBS at 800 L ha^{-1} LWA and PBS at 1000-1250 L ha^{-1} LWA provided either too low or too high deposition rates, respectively.

At BBCH 65 the influence of a wider canopy, as compared to the previous stage, becomes evident when observing the corresponding WSP strips (Fig. 6B), which reveal reduced deposition in the internal parts of the canopy for both TMS and HBS (in this last case, probably owing to the lack of air assistance). In contrast, PBS showed good penetration inside the canopy, although combined with excess coverage, thus increasing the risk of run-off.

Analysis of data on average coverage at BBCH 65 (Fig. 5B) revealed no statistical differences between HBS and PBS at any of the volume rates tested. On the other hand, TMS provided and average coverage significantly lower, probably due to the smaller droplet size produced when combining hollow cone nozzles with high working pressure.

Data on average normalized deposits d_G for BBCH 65 (Fig. 7B), relative to the amount of tracer applied per ground hectare, shows that the most efficient treatment corresponded to the lowest volume rate for HBS (370 L ha^{-1} LWA), probably linked to an optimum adaptation of the vertical spray boom to the treated canopy height. Conversely, HBS at the highest volume rate (800 L ha^{-1}) provided the lowest efficiency, whereas TMS and PBS (at all volume rates tested) fell in an intermediate efficiency level.

For BBCH 65, efficiency data based on the amount of tracer per 100 L (d_{100}), is shown in Fig. 8B. The highest efficiency value was obtained with TMS and HBS (both at a volume rate of 370 L ha^{-1} LWA), while HBS (at 400 and 800 ha^{-1} LWA) and PBS (at 1000 and 1250 ha^{-1} LWA) provided intermediate efficiencies. The lowest efficiencies corresponded to HBS at the highest volume rate (800 L ha^{-1} LWA). The conventional sprayer TMS displayed variabilities notably larger than the manual devices.

3.2.3 BBCH 75 – Berries pea-sized, bunches hanging.

Results on normalized deposition (d_N) are displayed in Figure 4C. For all volume rates tested, PBS provided excess deposition rates, whereas for HBS at all volume rates and TMS normalized deposits on leaves were in the range of the optimal values.

A detailed view of the penetration capacity of the different sprayers is presented in figure 8C. Similarly to the outcome at BBCH 65, at BBCH 75 the need for air assistance became conspicuous for HBS at any volume rate: the limited deposition in the central part of the canopy points out to the need for air assistance for this manual device.

Results of coverage at BBCH 75 are shown in Figure 5C. Average values around the optimum range (30-40%) could only be attained with TMS and with HBS at 370 and 800 L ha^{-1} LWA. The remaining treatments produced excess coverage, with extreme values over 80% with PBS at 1250 L ha^{-1} LWA.

Figure 6C, which shows the aspect of WSP strips at BBCH 75, indicates the excess deposition provided with PBS at high volume rates. On the contrary, sprays with both TMS and HBS resulted in good coverage and uniformity over the entire canopy.

Figure 7C presents the relative values of deposition considering the total tracer applied per unit area d_G obtained at BBCH 75. The highest relative values of deposition were attained with TMS and with HBS and PBS at low volume rates (370 and 750 L ha^{-1} LWA, respectively). Therefore, even at the full vegetation stage, low volume rates resulted in the highest relative efficiencies. This trend was corroborated by the results of the normalized deposit relative to the volume applied d_{100} (Fig. 8C): the highest efficiencies were attained with TMS and with HBS and PBS at low volume rates (370 and 750 L ha^{-1} LWA, respectively).

3.3 Estimation of efficiency and difficulties of the LWA method

The LWA method is based on the total wall area, and the amount of spray liquid is determined considering the canopy height as a basic measurement [56]. However, the canopy density (i.e. percentage of gaps in the canopy wall) can have an important influence on the efficiency of spray deposition on leaves. Assuming L_{fd} as the relative value of wall canopy uniformity (considering the presence of canopy gaps) ranging from 0.3 at BBCH 55, 0.6 at BBCH 65, and 1.0 m^2 leaf m^{-2} canopy wall at BBCH 75 [57], an estimation of the leaf deposit efficiency (*F and* F_1) was calculated (Fig. 9). The obtained *F* values were compared to the theoretical efficiency achieved assuming the canopy wall as a uniform area (F_1) (L_{fd} = 1.0 m^2 leaf m^{-2} canopy wall), as proposed by the LWA method. As shown in Fig. 9, efficiency values decreased when canopy density was considered. The presence of gaps in the canopy wall has an important effect on spray efficiency and, consequently, on the determination of the optimal volume rate. This parameter has already been included in the recently developed Dosaviña DSS to adjust the volume rate for spraying PPPs in vineyards. [57]

3.4 Effect of sprayer type and canopy development on efficiency

Efficiency factors (*F* and F_1) were used to evaluate the influence of the type of sprayer and canopy development. Figure 10 illustrates the average values obtained for each sprayer and crop stage, either considering the percentage of gaps in the canopy or assuming the canopy wall as a uniform area. For the experimental devices HBS and PBS, the highest efficiency values were obtained when using low volume rates (370-600 and 750 L ha^{-1} LWA, respectively). These efficiency levels were reasonably comparable to those achieved with TMS, across the three growth stages evaluated.

Concerning the effect of spray technology on efficiency, two key factors should be considered: spray swath and air assistance. HBS provided high F values in early growth stages, with limited canopy development, owing to an optimum distribution along with the treated canopy height. This fact could be explained by the use of a vertical boom with multiple nozzles. Efficiency results for HBS changed abruptly at full vegetation, when the absence of air assistance results in heterogeneous deposits, with conspicuous differences between inner and outer portions of the canopy. The number of active nozzles could also be considered an important factor affecting the efficiency values obtained with PBS. In this case, using a single output limits the achievement of a uniform spray deposit, and adoption large volume rates doesn't improve its performance. As shown in Fig. 10, distinct LWA volume rates should be chosen for each sprayer type, to attain spray efficiencies comparable to those provided by conventional orchard sprayers. Nevertheless, despite the limitations shown by the experimental equipment used in this research, namely lack of air assistance for HBS and reduced spray swath for PBS, we could identify LWA volume rates providing spray efficiencies close to those determined for TMS.

Considering conventional tractor mounted orchard sprayers as the reference technology for spraying PPPs, the relative efficiency parameter (RF) has been defined according to equation 6:

$$RF = F_{Sprayer\ x} / F_{TMS} \qquad (6)$$

Where RF is the relative efficiency (dimensionless); $F_{\text{Sprayer x}}$ is the efficiency value obtained for the spray "x"; and F_{TMS} the efficiency obtained with the tractor mounted sprayer.

The purpose of this relative efficiency factor (RF) is to compare the efficiency values (F) obtained with alternative technologies, with those obtained with the conventional orchard sprayer, assuming that the selected i-LWA value for the conventional sprayer has been demonstrated as the optimal value for vineyard spray applications. [23,24,38,42]

Results of relative comparisons among the technologies evaluated in this research are presented in Fig. 11. Assigning a constant value of 1 (RF = 1) to conventional orchard sprayer TMS, RF values for both HBS and PBS show a negative trend with increasing volume rates. Across BBCH stages, the line intersections of HBS and PBS with the reference efficiency level point to optimum volume rates between 400 and 600 L ha^{-1} LWA. In light of these results and considering the overall performance of each device as summarized in Table 5, for the future development of experimental devices aimed at closely reproducing the spray characteristics of conventional field sprayers, we suggest combining adaptable spray swath with air assistance.

4. Conclusions

- For vineyards conducted as a uniform vertical wall, canopy characterization based on LWA expression provided a good basis for adjustment of water volumes. However, the important effect of canopy density (percentage of gaps in the canopy wall) shouldn't be neglected for the determination of the most efficient spray volume rates.

- The spray efficiencies of two manual devices, suited for field experimentation with PPPs, were compared with those provided by a conventional orchard sprayer in a trellised vineyard. Spray technology had a decisive effect on the efficiency and uniformity of deposition, which were in turn dependent on canopy development and corresponding LWA volume rates.
- HBS, a hydraulic backpack sprayer fitted with a vertical spray boom with 3-4 nozzles, attained high efficiency values and uniformity of distribution at early growth stages when using volume rates between 200 and 600 L ha^{-1} LWA. Nevertheless, at full vegetation HBS achieved limited penetration into the canopy, pointing to the need of air assistance when confronted with dense canopies.
- PBS, a motorized pneumatic backpack sprayer with a single nozzle, and adapted out of specification to achieve high-volume rates, achieved good penetration into the canopy at all growth stages, owing to the air assistance. For PBS, the best results in terms of spray efficiency and uniformity of deposits were obtained at the lowest volume rate tested of 750 L h^{-1} LWA, indicating that spray quality could be improved when using even lower volume rates.
- To achieve spray efficiency values close to those provided by TMS, the tested experimental sprayers HBS and PBS should have used volume rates between 400 and 600 L ha^{-1} LWA.

- Reliability of field trials conducted to ascertain optimal PPP doses and spray volume rates could be improved with the adoption of portable spray technologies resulting in efficiencies closer to those provided by conventional field sprayers. In order to closely reproduce the spray efficiencies provided by conventional field sprayers, devices used in experimentation should combine adaptable spray swath with air assistance.

5. ACKNOWLEDGEMENTS

This research has been partially funded by EU LIFE PERFECT Project - Pesticide Reduction using Friendly and Environmentally Controlled Technologies (LIFE 17 ENV/ES/000205). Bayer CropScience S.L. provided financial and technical support for the conduct of this research.

6. REFERENCES

1. Walklate PJ, Cross JV, Richardson B, Baker DE and Murray RA, A generic method of pesticide dose expression: Application to broadcast spraying of apple trees. *Ann Appl Biol* **143**: 11–23 (2003).
2. Triloff P, An extended tree row volume dosing model: adjusting pesticide dose rate, water volume rate and air volume rate by forward speed. *Ann Rev Agr Eng* **4**: 69-80 (2005).
3. EPPO, Dose expression for plant protection products. *EPPO Bulletin* **42**: 409–415 (2012).
4. Walklate PJ and Cross JV, An examination of LWA dose expression. *Crop Prot* **35**: 132–134 (2013).
5. Dubuis PH, Viret O, Bloesch B, Fabre AL, Le dosage adapté: facile, économique et bon pour l’environnement. *Revue Suisse Viticulture, Arboriculture, Horticulture* **47**: 67–69 (2015).

6. Garcerá C, Doruchowski G and Chueca P, Harmonization of plant protection products dose expression and dose adjustment for high growing 3D crops: A review. *Crop Prot* **140**: 105417 (2020).
7. EPPO, Conclusions and recommendations. *Workshop on harmonized dose expression for the zonal evaluation of plant protection products in high growing crops*, Vienna, Austria (2016). [Online]. Available: https://www.eppo.int/media/uploaded_images/MEETINGS/Conferences_2016/dose_expression/Conclusions_and_recommendations.pdf [1 June 2019].
8. Doruchowski G, Harmonization of dose expression is the key to dose adjustment. *Association of Applied Biologist - Dose Expression Workshop*, Barcelona, Spain (2018).
9. EPPO. Standard measurement procedure in high growing crop trials (2018). [Online]. Available: https://www.eppo.int/media/uploaded_images/ACTIVITIES/plant_protect_products/Dose_exp_measure_procedure.pdf [1 June 2019].
10. Balsari P and Gil E, The dose expression dilemma. State of the art in Europe. *Association of Applied Biologist - Dose Expression Workshop*, Barcelona, Spain (2018).
11. Rosell JR and Sanz R, A review of methods and applications of the geometric characterization of tree crops in agricultural activities. *Comput Electron Agric* **81**: 124-141 (2012).
12. Van de Zande J, Importance and methods for an accurate canopy characterization. *Association of Applied Biologist - Dose Expression Workshop*, Barcelona, Spain (2018).
13. Garcerá C, Fonte A, Moltó E and Chueca P, Sustainable use of pesticide applications in citrus: A support tool for volume rate adjustment. *Int J Environ Res Public Health* **14**: 715 (2017).
14. Oerke EC, Crop losses to pests. *J Agric Sci* **144**: 31-43 (2006).
15. Giles DK, Akesson NB and Yates WE, Pesticide application technology: research and development and the growth of the industry. *Trans ASABE* **51**: 397-403 (2008).
16. Hilz E and Vermeer AW, Spray drift review: The extent to which a formulation can contribute to spray drift reduction. *Crop Prot* **44**: 75-83 (2013).
17. Toews R B, Huby J P, Pollmann B, Teichmann M, Schlotter P and Meier-Runge F. Dose rate expression in vertical growing crops – Need for harmonization from the perspective of the Plant Protection Product Industry. *Workshop on harmonized dose expression for the zonal evaluation of plant protection products in high growing crops*, Vienna, Austria (2016).
18. Langer I, Encountered problems for dose expression harmonisation. *Association of Applied Biologist - Dose Expression Workshop*, Barcelona, Spain (2018).
19. Koch H, Weisser P and Knewitz H, Sprayer adjustment in orchards – from dose to deposit. *Proc 6th Workshop on Spray Application Techniques in Fruit Growing*, Leuven, Belgium, pp. 28 (2001).

20. Walklate PJ, Cross JV, Richardson GM and Baker DE, Optimising the adjustment of label recommended dose rate for orchard spraying. *Crop Prot* **25**: 1080-1086 (2006 Oct).
21. Koch H, How to achieve conformity with the dose expression and sprayer function in high crops. *Bayer Crop Sci. J.* **60**: 71-84 (2007).
22. Walklate PJ, Cross JV and Pergher G, Support system for efficient dosage of orchard and vineyard spraying products. *Comput Electron Agric* **75**: 355-362 (2011).
23. Gil E, Llorens J, Landers A, Llop J and Giralt L, Field validation of DOSAVIÑA, a decision support system to determine the optimal volume rate for pesticide application in vineyards. *Eur J Agron* **35**: 33-46 (2011).
24. Escolà A, Rosell-Polo JR, Planas S, Gil E, Pomar J, Camp F, Llorens J and Solanelles F, Variable rate sprayer. Part 1 – Orchard prototype: Design, implementation and validation. *Comput Electron Agric* **95**: 122-135 (2013).
25. Gil E, Gallart M, Llorens J, Llop J, Bayer T and Carvalho C, Spray adjustments based on LWA concept in vineyard. Relationship between canopy and coverage for different application settings. *Asp Appl Biol* **122**: 25-32 (2014).
26. Garcerá C, Fonte A, Salcedo R, Soler A and Chueca P, Dose expression for pesticide application in citrus: influence of canopy size and sprayer. *Agronomy* **10**: 1887 (2020).
27. European Parliament, Council of the European Union. Regulation (EC) No 1107/2009 of the European Parliament and of the Council of 21 October 2009 concerning the placing of plant protection products on the market and repealing council directives 79/117/EEC and 91/414/EEC, Off. J. Eur. Union: Luxembourg City, Luxembourg, 1–50 (2009).
28. Mironet V, Compilation Questionnaires “Dose expression” Southern zone: France, Spain, Portugal, Greece, Italy and Croatia. *Workshop on harmonized dose expression for the zonal evaluation of plant protection products in high growing crops*, Vienna, Austria (2016).
29. Furness GO, Distance calibration and a new pesticide label format for fruit trees and grapevines in Australia. *Proc 7th Workshop on Spray Application Techniques in Fruit Growing*, Cuneo, Italy, pp. 293-303 (2003).
30. Viret O, Siegfried W, Bloesch B, Taillens J and Mittaz C, Dosage des fongicides adaptés à la surface foliaire: Résultats en 2006. *Revue Suisse De Vitic. Arboric. Hortic.* **39**: 65-68 (2007).
31. Pergher G and Petris R, Pesticide dose adjustment in vineyard spraying and potential for dose reduction. *Agric. Eng. Int.: The CIGR Ejournal X* (2008).
32. Codis S and Douzals JP, Comparaison des systèmes d’expression des doses de produits de protection de la vigne dans 5 pays européens et les besoins d’une harmonisation. *AFPP - CIETAP - Conference sur les techniques d’application de produits de protection des plantes*, Lyon, France, pp. 10 (2012).
33. Manktelow DWL, Gurnsey SJ and MacGregor AM, Deposit variability and prediction in fruit crops: what use are label rates anyway? *Asp Appl Biol* **71**: 269-278 (2004).

34. Landers A. Effective Vineyard Spraying: A Practical Guide for Growers 2nd edition (2016). ISBN-10: 1495188450; ISBN-13: 978-1495188459. Edited by https://effectivespraying.com

35. Nansen, C., Ferguson, J.C., Moore, J. et al. Optimizing pesticide spray coverage using a novel web and smartphone tool, SnapCard. *Agron. Sustain. Dev*. **35**: 1075-1085 (2015). https://doi.org/10.1007/s13593-015-0309-y

36. Shen Y, Zhu H, Liu H, Chen Y, Ozkan HE. Development of a Laser-Guided, Embedded-Computer-Controlled, Air assisted precision sprayer. *Transactions of the ASABE.* **60**(6): 1827-1838 (2017).

37. Ahmad H, Mohamed H and Sherif A G, Effect of spray application techniques on spray deposits and residues of bifenthrin in peas under field conditions. *Journal of Pesticide Science* **41**: 49-54 (2016). https://doi.org/10.1584/jpestics.D15-071

38. Gil E. Tratamientos en viña: Equipos y técnicas de aplicación. (2003). Edicions UPC, Barcelona, 148pp. URI: http://hdl.handle.net/2099.3/36721 ; ISBN: 9788498803228

39. Michael C, Gil E, Gallart M, Kanetis L and Stavrinides MC, Evaluating the effectiveness of low volume spray application using air-assisted knapsack sprayers in wine vineyards. *Int J Pest Manage* **1-10** (2020)

40. Michael C, Gil E, Gallart M and Stavrinides MC, Influence of spray technology and application rate on leaf deposit and ground losses in mountain viticulture. *Agric* **10**: 615

41. Meier U. BBCH-Monograph. Growth stages of plants - Entwicklungsstadien vo Pflanze - Estadios de las plantas - Développement des Plantes. BlackwelWissenschaftsverlag, Berlin und Wien. 622 (1997).

42. Gil E, Escolà A, Rosell JR, Planas S and Val L, Variable rate application of plant protection products in vineyard using ultrasonic sensors. *Crop Prot* **26**: 1287-1297 (2007).

43. ISO 10625. Equipment for Crop Protection. Sprayer Nozzles. Colour coding for identification. International Standardization Organization (2018).

44. Llorens J, Gil E, Llop J and Escolà A, Variable rate dosing in precision viticulture: Use of electronic devices to improve application efficiency. *Crop Prot* **29**: 239-248 (2010).

45. Salcedo R, Llop J, Campos J, Costas M, Gallart M, Ortega P and Gil E, Evaluation of leaf deposit quality between electrostatic and conventional multi-row sprayers in a trellised vineyard. *Crop Prot* **127**: 104964 (2019).

46. Pergher G, Recovery rate of tracer dyes used for spray deposit assessment. *Trans ASAE* **44**: 787-794 (2001).

47. TOPPS-Prowadis Project, Best Management Practices to Reduce Spray Drift. (2014). [Online]. Available: http://www.topps-life.org/ [15 October 2019].

48. BOE (Boletín Oficial del Estado). Real Decreto 1311/2012, de 14 de septiembre, por el que se establece el marco de actuación para conseguir un uso sostenible de los productos fitosanitarios. BOE N 223 de 15 de septiembre de 2012, 65127-65171.

49. Rueden, C. T.; Schindelin, J. & Hiner, M. C. et al. (2017), "ImageJ2: ImageJ for the next generation of scientific image data", BMC Bioinformatics 18:529, PMID 29187165, doi:10.1186/s12859-017-1934-z (on Google Scholar).

50. Cross JV, Walklate PJ, Murray RA and Richardson GM, Spray deposits and losses in different sized apple trees from an axial fan orchard sprayer: 1. Effects of spray liquid flow rate. *Crop Prot* **20**: 13-30 (2001).
51. Pergher G, Gubiani R and Tonetto G, Foliar deposition and pesticide losses from three air-assisted sprayers in a hedgerow vineyard. *Crop Prot* **16**: 25-33 (1997).
52. Codis S, Carra M, Delpuech X, Montegano P, Nicot H, Ruelle B, Ribeyrolles X, Savajols B, Vergès A and Naud O, Dataset of spray deposit distribution in vine canopy for two contrasted performance sprayers during a vegetative cycle associated with crop indicators (LWA and TRV). (2018). *Data in Brief* Volume **18**, June 2018, Pages 415-421. https://doi.org/10.1016/j.dib.2018.02.012
53. Gil E. Crop adapted spraying in vineyard. Leaf area distribution (crop profile) and uniformity of deposition (CV) as a tool to evaluate the quality of applications. (2002). In: International Conference on Agricultural Engineering, AgEng'02. Budapest (Hungary).
54. Holownicki R, Doruchowski G, Godyn A and Swiechowski W, PA – Precision agriculture: variation of spray deposit and loss with air-jet directions applied in orchards. *J Agric Eng Res* **77**: 129-136 (2000)
55. Chen Y, Ozkan HE, Zhu H, Derksen RC and Krause CR, Spray deposition inside tree canopies from a newly developed variable-rate air-assisted sprayer. *Trans ASABE* **56**: 1263-1272 (2013).
56. Campos J, Llop J, Gallart M, García-Ruíz F, Gras A, Salcedo R, and Gil E, Development of canopy vigor maps using UAV for site-specific management during vineyard spraying process. *Precision Agric*. **20**: 1136-1156 (2019). https://doi.org/10.1007/s11119-019-09643-z
57. Gil E, Campos J, Ortega P, Llop J, Gras A, Armengol E, Salcedo R and Gallart M, DOSAVIÑA: Tool to calculate the optimal volume rate and pesticide amount in vineyard spray applications based on a modified leaf wall area method. *Comput Electron Agric* **160:** 117-130 (2019). https://doi.org/10.1016/j.compag.2019.03.018

7. TABLES

Table 1. Main factors and definitions

Symbol	**Concept**
$i\text{-}LWA_A$	Actual volume rate (L $ha^{-1}{}_{canopy}$)
V_R	Actual volume rate (L ha^{-1})
w	Amount of deionized water (ml)
T_A	Amount of tracer per hectare
L_a	Area of sample leaf (cm^2)
Lf_d	Canopy wall gaps ratio ($m^2{}_{leaf}$ $m^{-2}{}_{canopy\ wall}$)
f_{VR}	Correction factor for spray volume
f_{TC}	Correction factor for tracer concentration
C	Coverage (%)
$BBCH$	Crop stage
d	Deposit per unit leaf area ($\mu g \cdot cm^{-2}$)
F	Efficiency considering canopy gaps
F_1	Efficiency not considering canopy gaps
$i\text{-}LWA_E$	Estimated volume rate (L $ha^{-1}{}_{canopy}$)
V_T	Intended volume rate (L ha^{-1})
S_a	Leaf sample area (cm^2)
d_N	Normalized leaf deposit (μg cm^{-2} leaf)
d_G	Normalized leaf deposit per unit of applied tracer (μg cm^{-2}/kg tracer ha^{-1})
d_{100}	Normalized leaf deposit per 100 L applied (μg cm^{-2}/100 L ha^{-1})
RF	Relative efficiency ($S_{prayer\ X}$ / F_{TMS})
T_{cl}	Tracer concentration in washing solution ($\mu g \cdot L^{-1}$)
T	Tracer concentration in the sprayer's tank (mg L^{-1})
WSP	Water Sensitive Paper

704

Table 2. Arrangement of every field tests at the three different crop stages

Trial	Date	BBCH-scale		Row distance (m)	Mean canopy height (m)	Mean LWA (m^2 canopy ha^{-1})
		Code	Growth stage			
1	May 18th	55	Inflorescences swelling, flowers closely pressed together	3.0	0.59	4143
2	June 1st	65	Full flowering: 50% of flower hoods fallen	3.0	0.86	5731
3	June 22nd	75	Berries pea-sized, bunches hang	3.0	1.14	7613

Table 3. Estimated application parameters (i-LWA$_E$ and V$_T$) and values selected or spray process

BBCH scale	LWA (m^2 canopy ha^{-1})	Sprayer	*i-LWA$_E$* (L ha^{-1} LWA)	V$_T$ (L ha^{-1})	Pressure (MPa)	# nozzles	Nozzle type	Nozzle manufacturer	Spray pattern [a]	Spray quality [b]	Forward speed (km h^{-1})
55	4133	TMS	200	83	1.00	4	ATR Brown	Albuz	HC	VF	6.5
	3800	HBS	200	76	0.15	2	ISO 110 015	Teejet	FF	F	4.4
	3933	HBS	400	157	0.15	2	ISO 110 03	Teejet	FF	M	4.3
	4600	HBS	600	276	0.15	2	ISO 110 04	Teejet	FF	M	3.3
	4067	PBS	750	305	-	1	Diffusor	Solo	HC	-	5.8
	4000	PBS	1000	400	-	1	Diffusor	Solo	HC	-	4.4
	4467	PBS	1250	558	-	1	Diffusor	Solo	HC	-	3.8
65	6440	TMS	370	246	0.80	6	ISO 80 015	Lechler	HC	VF	4.8
	4907	HBS	370	182	0.15	3	ISO 110 025	Teejet	FF	M	4.7
	5013	HBS	600	301	0.15	3	ISO 110 04	Teejet	FF	M	4.5
	5693	HBS	800	455	0.15	3	ISO 110 06	Teejet	FF	C	4.5
	6227	PBS	750	467	-	1	Diffusor	Solo	HC	-	4.2
	6373	PBS	1000	637	-	1	Diffusor	Solo	HC	-	3.1
	5467	PBS	1250	683	-	1	Diffusor	Solo	HC	-	2.5
75	7360	TMS	370	272	0.80	8	ISO 80 015	Lechler	HC	VF	5.7
	8213	HBS	370	303	0.15	4	ISO 110 025	Teejet	FF	M	3.8
	8333	HBS	600	500	0.15	4	ISO 110 04	Teejet	FF	M	3.6
	7120	HBS	800	609	0.15	4	ISO 110 06	Teejet	FF	C	4.5

	6893	PBS	750	517	-	1	Diffusor	Solo	HC	-	2.8
	7133	PBS	1000	713	-	1	Diffusor	Solo	HC	-	2.1
	8240	PBS	1250	1030	-	1	Diffusor	Solo	HC	-	1.7

[a] HC: hollow cone; FF: flat fan; [b] Following the BCPC droplet size classification. VF: very fine; F: fine; M: medium; C: coarse

Table 4. Actual application values (i-LWA$_A$ and V_R) and main results obtained with the different spray technologies

BBCH	**Sprayer & *i-LWA***	**i-LWA$_A$^{1}**	$\boldsymbol{V_R}$ ^{2}	$\boldsymbol{T_A}$ ^{3}	$\boldsymbol{f_{VR}}$ ^{4}	$\boldsymbol{f_{TC}}$ ^{5}	$\boldsymbol{d_N}$ ^{6}	$\boldsymbol{d_G}$ ^{7}	**d$_{100}$ ^{8}**	**F ^{9}**	**F$_1$ ^{10}**	**C ^{11}**
55	TMS 200	200	99	0.16	1.54	1.21	1.18	7.19	1.19	0.12	0.30	20.72
	HBS 200	200	81	0.15	1.73	1.10	2.22	15.42	2.78	0.23	0.58	28.54
	HBS 400	400	158	0.30	1.48	1.04	3.85	12.69	2.43	0.20	0.50	29.12
	HBS 600	600	220	0.50	1.68	0.88	5.87	11.84	2.66	0.22	0.55	49.34
	PBS 750	750	305	0.60	1.00	1.03	3.83	6.49	1.25	0.11	0.26	40.77
	PBS 1000	1000	396	0.80	1.00	0.98	3.36	4.16	0.85	0.07	0.16	59.61
	PBS 1250	1250	554	1.12	1.00	0.98	5.24	4.64	0.94	0.08	0.21	49.22
65	TMS 370	332	214	0.14	1.11	4.03	2.84	6.70	1.33	0.30	0.43	32.40
	HBS 370	423	208	0.38	0.85	1.97	2.91	7.52	1.40	0.25	0.36	55.90
	HBS 600	685	347	0.66	0.87	1.04	3.74	5.63	1.08	0.20	0.29	49.04
	HBS 800	858	485	0.93	0.93	1.03	2.31	2.47	0.48	0.10	0.14	55.12
	PBS 750	768	478	1.03	0.97	1.03	4.02	4.34	0.84	0.19	0.27	70.97
	PBS 1000	979	632	1.01	1.02	1.02	5.44	4.35	0.86	0.20	0.28	70.18
	PBS 1250	1253	688	1.35	0.99	1.01	6.68	4.92	0.97	0.19	0.27	67.59
75	TMS 370	387	285	0.54	0.95	1.05	3.57	6.62	1.25	0.34	0.49	42.90
	HBS 370	346	189	0.32	1.06	1.16	3.12	9.60	1.65	0.37	0.53	42.13

	HBS 600	542	440	0.76	1.10	1.16	2.98	3.92	0.67	0.22	0.32	51.58
	HBS 800	955	647	1.11	0.83	1.16	3.29	2.95	0.51	0.14	0.20	35.02
	PBS 750	711	524	1.11	1.05	0.94	7.91	6.33	1.34	0.33	0.47	78.87
	PBS 1000	1066	723	1.82	0.93	0.79	4.92	2.71	0.68	0.13	0.18	53.45
	PBS 1250	1088	1054	2.67	1.14	0.79	6.85	2.57	0.65	0.17	0.25	83.35

[1] i-LWA$_A$ (L ha^{-1} LWA); [2] V_R (L ha^{-1}); [3] T_A (Kg ha^{-1}); [4] f_{VR} (dimensionless); [5] f_{TC} (dimensionless); [6] d_N (µg cm^{-2}); [7] d_G (µg cm^{-2}/kg tracer ha^{-1}); [8] d_{100} (µg cm^{-2}/100 L ha^{-1}); [9] F (dimensionless); [10] F$_1$ (dimensionless); [11] C (%)

Table 5. Global evaluation of tested technologies based on the obtained results

	i-LWA	d_N	d_G	d_{100}	*C (%)*	*F*	F_1
HBS	**L**	-	+++	+++	+++	++	+++
	M	+	++	+++	+++	++	++
	H	++	++	++	++	+	++
PBS	**L**	+	+	+	+	+	+
	M	++	-	-	-	-	-
	H	+++	-	-	-	-	-
TMS		++	+	++	++	++	+++

FIGURE CAPTIONS

Figure 1. Spraying equipment tested: a) tractor-mounted air-assisted sprayer (TMS); b) Hydraulic backpack sprayer (HBS); and c) Pneumatic backpack sprayer (PBS).

Figure 2. Layout scheme and distribution of trials in the parcel

Figure 3. A) Relationship between normalized deposit on leaves d_N and coverage measured using water-sensitive paper; B) Relationship between normalized deposit on leaves d_N and volume rate i-LWA; C) Relationship between normalized deposit on leaves and uniformity of deposition on the entire canopy, measured by the standard deviation.

Figure 4. Average normalized deposit (dN) and dispersion of measurements for all combinations of the sprayer-volume rate tested. A) Results for BBCH 55; B) results for BBCH 65; C) results for BBCH 75.

Figure 5. Average values of coverage and dispersion of measurements for all combinations of the sprayer-volume rate tested. A) Results for BBCH 55; B) results for BBCH 65; C) results for BBCH 75.

Figure 6. Evaluation of coverage on water-sensitive paper placed in the whole canopy. A) coverage for BBCH 55; B) coverage for BBCH 65; C) coverage for BBCH 75.

Figure 7. Average normalized deposit per amount of tracer (d_G) and dispersion of measurements for all combinations of sprayer-volume rate tested. A) Results for BBCH 55; B) results for BBCH 65; C) results for BBCH 75.

Figure 8. Average normalized deposit per volume rate (d_{100}) and dispersion of measurements for all combinations of sprayer-volume rate tested. A) Results for BBCH 55; B) results for BBCH 65; C) results for BBCH 75.

Figure 9. Evolution of efficiency value (F and F_1) depending on the spray volume rate (L ha^{-1} LWA).

Figure 10. Effect of spray technology on efficiency values observed

Figure 11. Efficiencies of the hydraulic backpack sprayer (HBS) and the pneumatic backpack sprayer (PBS), relative to the tractor-mounted air-assisted sprayer (TMS), at corresponding BBCH growth stages.

Figure 1. Spraying equipment tested: a) tractor-mounted air-assisted sprayer (TMS); b) Hydraulic backpack sprayer (HBS); and c) Pneumatic backpack sprayer (PBS).

254x190mm (300 x 300 DPI)

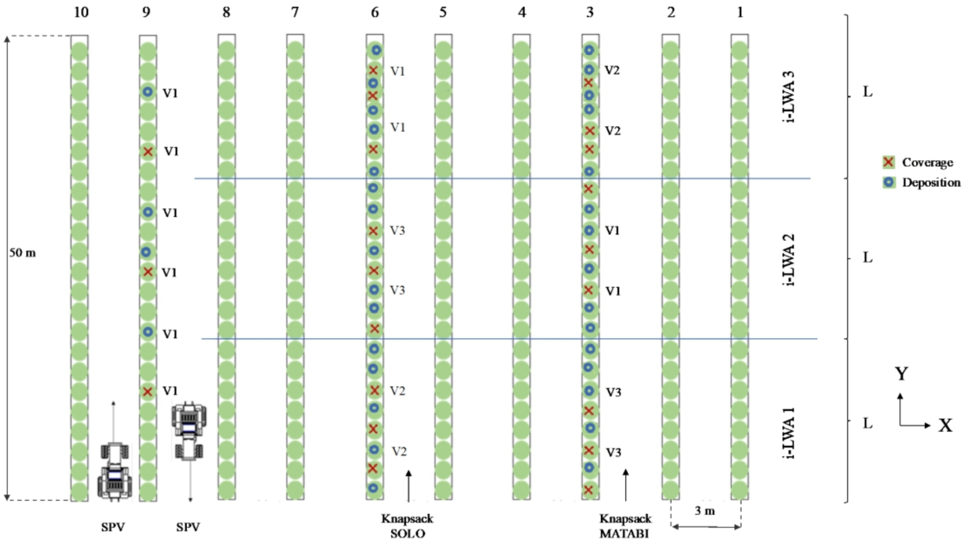

Figure 2. Layout scheme and distribution of trials in the parcel

254x190mm (300 x 300 DPI)

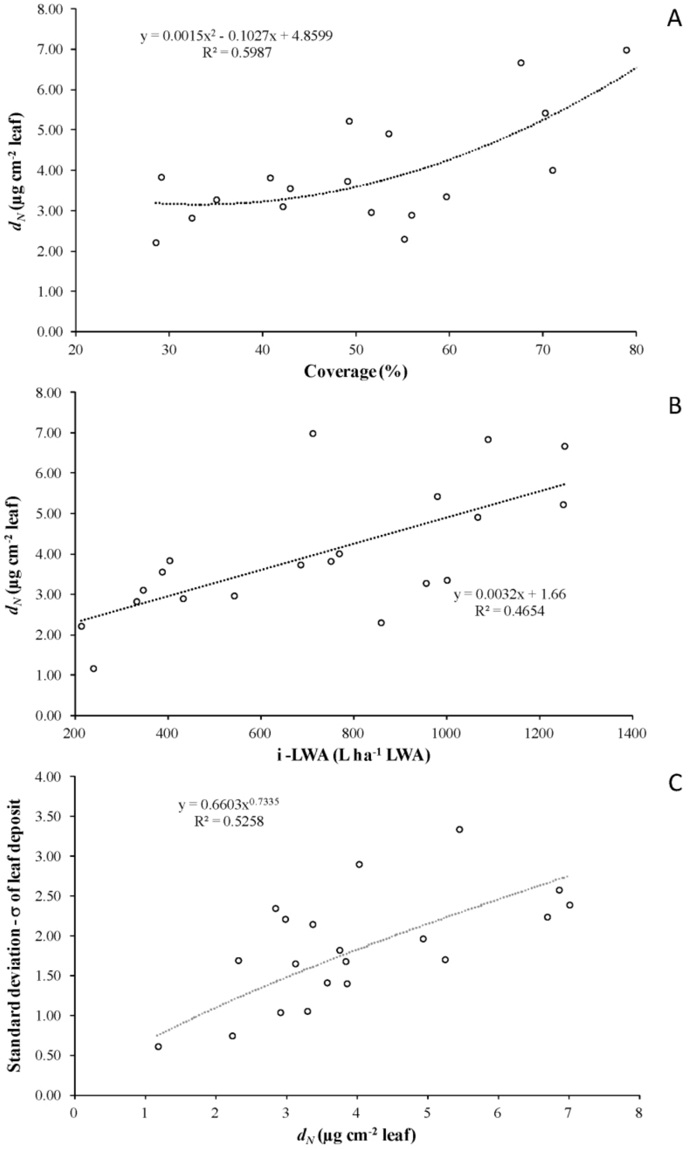

Figure 3. A) Relationship between normalized deposit on leaves dN and coverage measured using water-sensitive paper; B) Relationship between normalized deposit on leaves dN and volume rate i-LWA; C) Relationship between normalized deposit on leaves and uniformity of deposition on the entire canopy, measured by the standard deviation.

190x254mm (300 x 300 DPI)

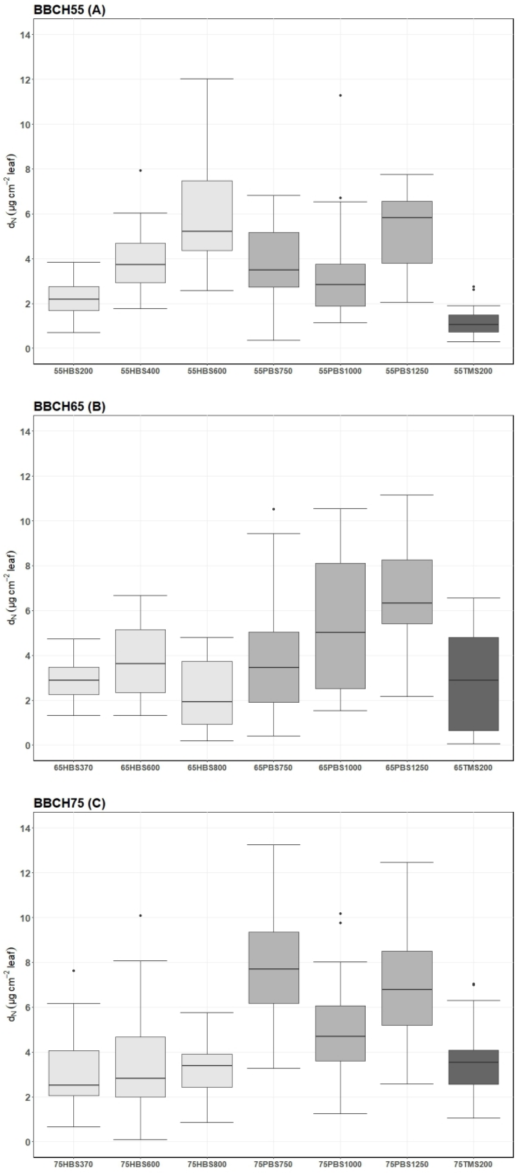

Figure 4. Average normalized deposit (dN) and dispersion of measurements for all combinations of the sprayer-volume rate tested. A) Results for BBCH 55; B) results for BBCH 65; C) results for BBCH 75.

190x254mm (300 x 300 DPI)

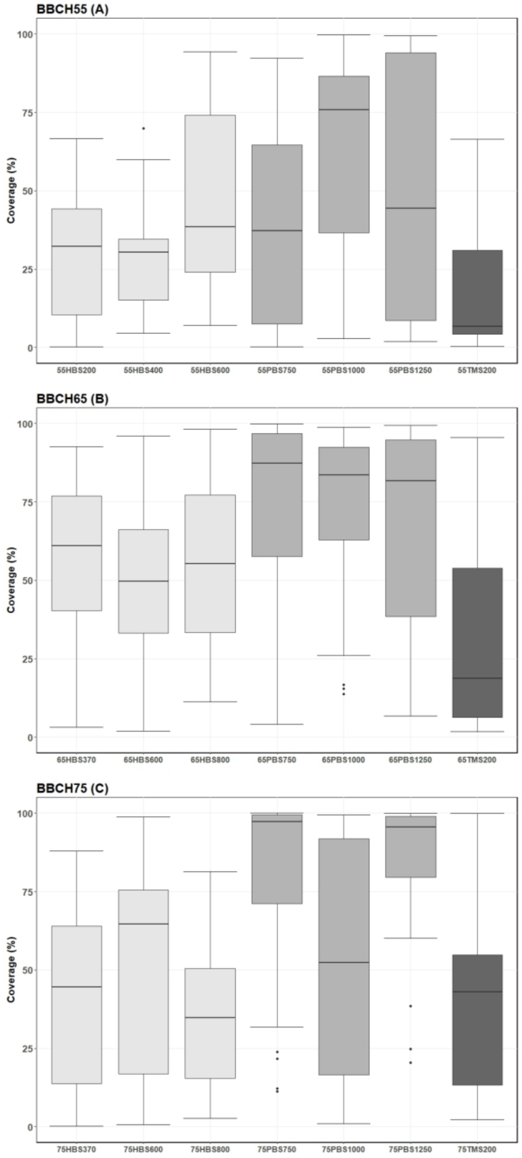

Figure 5. Average values of coverage and dispersion of measurements for all combinations of the sprayer-volume rate tested. A) Results for BBCH 55; B) results for BBCH 65; C) results for BBCH 75.

190x254mm (300 x 300 DPI)

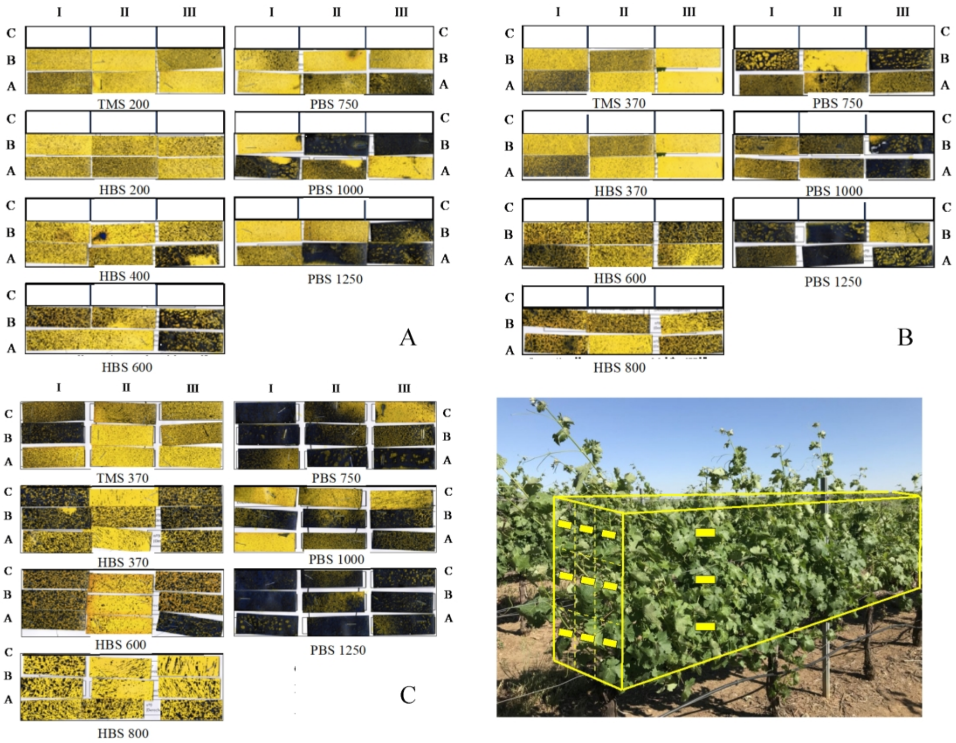

Figure 6. Evaluation of coverage on water-sensitive paper placed in the whole canopy. A) coverage for BBCH 55; B) coverage for BBCH 65; C) coverage for BBCH 75.

254x190mm (300 x 300 DPI)

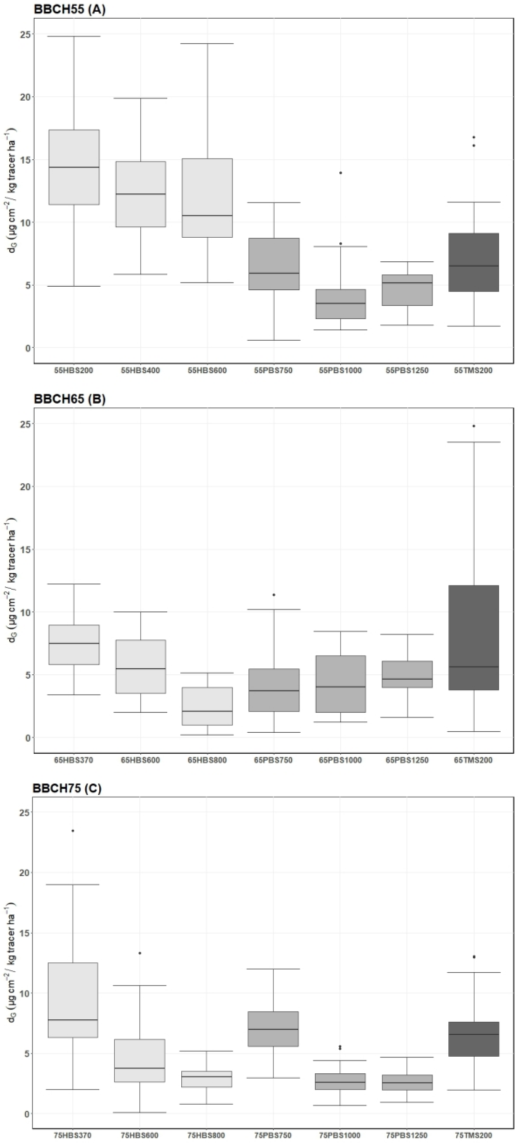

Figure 7. Average normalized deposit per amount of tracer (dG) and dispersion of measurements for all combinations of sprayer-volume rate tested. A) Results for BBCH 55; B) results for BBCH 65; C) results for BBCH 75.

190x254mm (300 x 300 DPI)

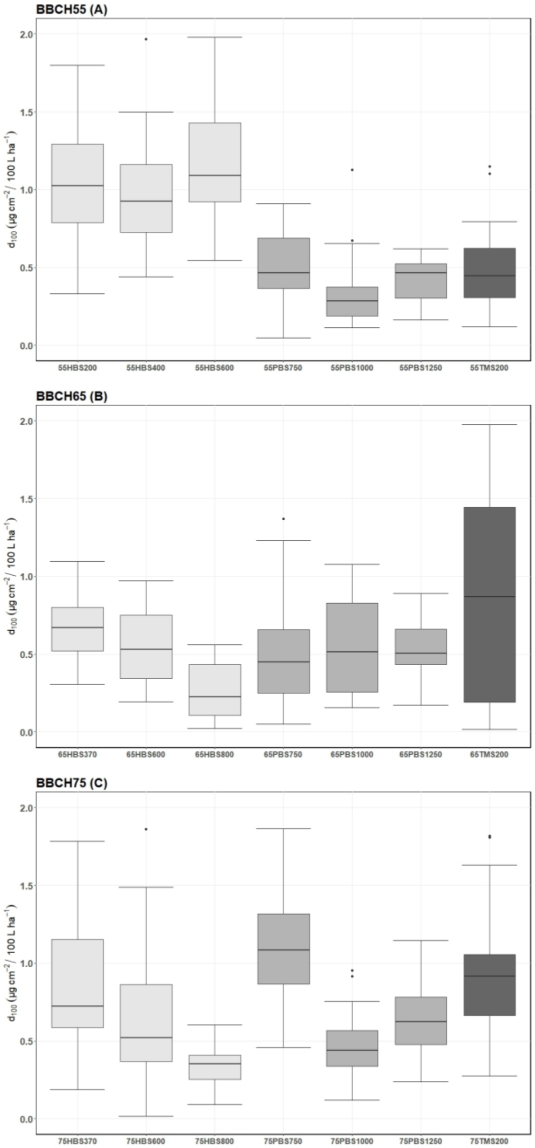

Figure 8. Average normalized deposit per volume rate (d100) and dispersion of measurements for all combinations of sprayer-volume rate tested. A) Results for BBCH 55; B) results for BBCH 65; C) results for BBCH 75.

190x254mm (300 x 300 DPI)

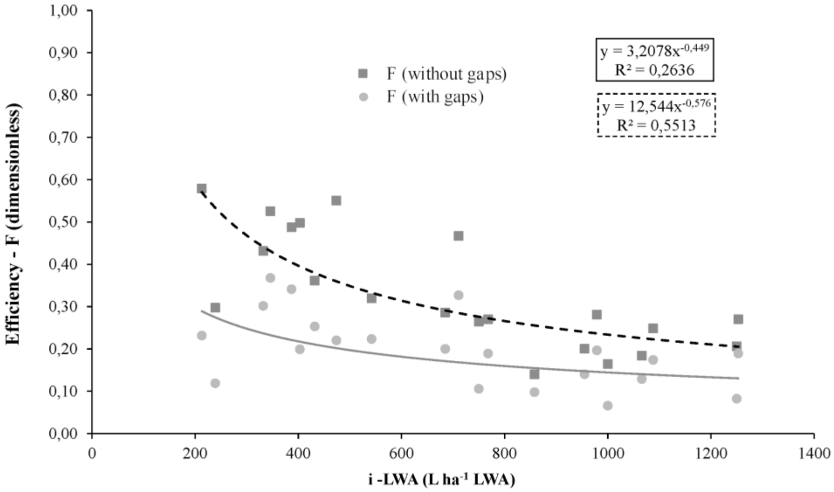

Figure 9. Evolution of efficiency value (F and F1) depending on the spray volume rate (L ha-1 LWA).

254x190mm (300 x 300 DPI)

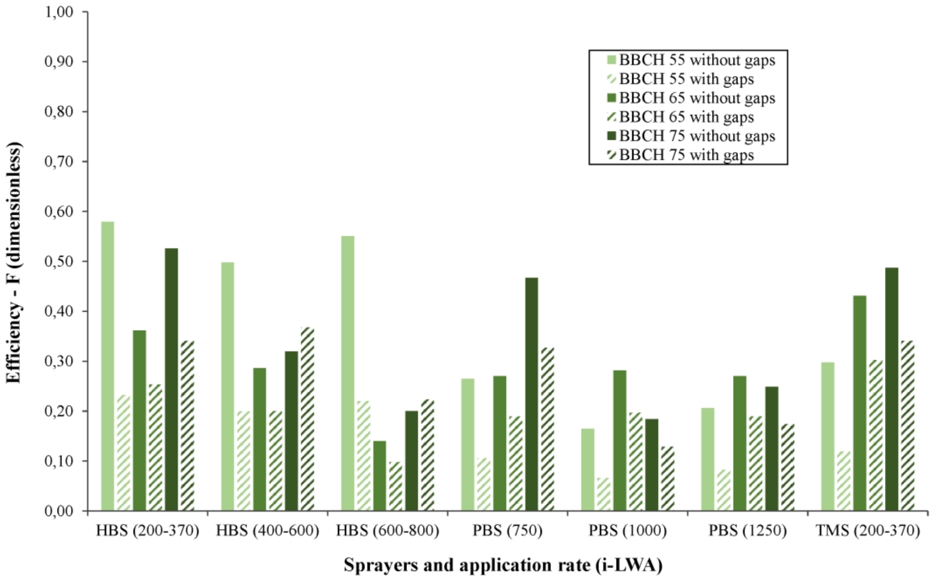

Figure 10. Effect of spray technology on efficiency values observed

254x190mm (300 x 300 DPI)

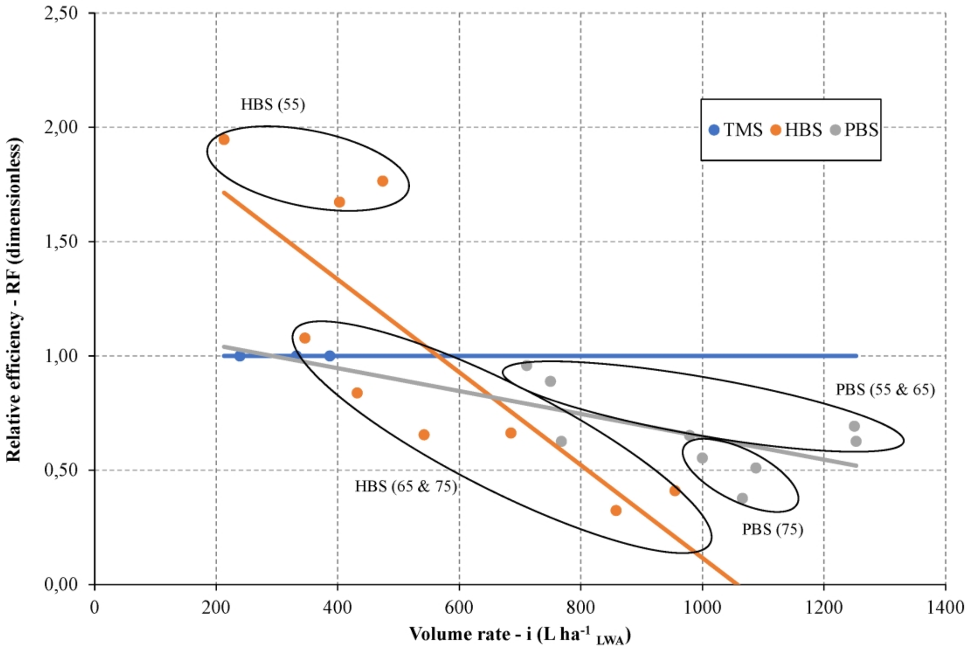

Figure 11. Efficiencies of the hydraulic backpack sprayer (HBS) and the pneumatic backpack sprayer (PBS), relative to the tractor-mounted air-assisted sprayer (TMS), at corresponding BBCH growth stages.

254x190mm (300 x 300 DPI)