Biosystems Engineering 241 (2024) 1–14

Contents lists available at ScienceDirect

Biosystems Engineering

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

EvaSprayViti: A flexible test bench for comparative assessment of the 3D deposition efficiency of vineyard sprayers at multiple growth stages

A. Cheraiet [a,*], S. Codis [b], A. Lienard [b], A. Vergès [b], M. Carra [a], D. Bastidon [a], J.F. Bonicel [a], X. Delpuech [b], X. Ribeyrolles [a], J.P. Douzals [a], F. Lebeau [c], J.A. Taylor [a], O. Naud [a]

[a] UMR ITAP, University of Montpellier, INRAE, Institut Agro, B.P. 5095, F-34196, Montpellier Cedex 5, France
[b] IFV, French Vine and Wine Institute, Site de INRAE B.P. 5095, F-34196, Montpellier Cedex 5, France
[c] Biosystems Dynamics and Exchanges (BioDynE), TERRA Teaching and Research Center, Gembloux Agro-Bio Tech, University of Liege, Gembloux, Belgium, 2 passage déportés, 5030, Gembloux, Belgium

ARTICLE INFO

Keywords:
Vineyard sprayer
Sprayer assessment
Test facility
Spray deposition efficiency

ABSTRACT

The main approach to protect grapes against diseases involves the use of plant protection products. Understanding the quantitative amount and the distribution of these products on the vines is essential to assess the effectiveness of spray equipment and to evaluate the relationship between dosage and response when targeting pathogens. Improving the targeting of sprayers is an important lever to reduce the quantities of phytosanitary inputs applied, taking into account various cropping systems and training. For this purpose, a regularly distributed artificial canopy, adjustable in height and width was designed to mimic three grapevine growth stages for two of the most common trellised training systems encountered in France for 'wide row vineyards' (Royat cordon and Guyot, inter-row width 2.5 m). This artificial canopy was evaluated with the perspective of using it as a testing facility for classifying sprayers. Using a dye tracer, spray deposits were directly recovered after the rinsing of artificial leaves. A first series of experiments defined the most adapted sampling strategy in the canopy according to the crop stage, with the comparison of two contrasted sprayers. A second series of experiments compared the quantities of deposits obtained from both the artificial and a real vine, for several sprayers at a full growth stage and for one sprayer at three growth stages. Deposition patterns and mean deposits on both targets were found comparable, allowing a realistic perspective for the classification of spray application modalities using the artificial vine. A third series of experiments compared deposition at three crop stages on artificial and real vines for one type of sprayer. A fourth series of experiments on the artificial vineyard discriminated between three behaviour classes within 65 spraying modalities that combined sprayer types and sprayer settings (such as nozzle types). The discrimination was achieved using a PCA analysis that confirmed the soundness of the sampling strategy used. Overall, these results highlight the ability of the EvaSprayViti test facility to assess and rank the performance of vineyard sprayers.

1. Introduction

Grapes (*Vitis* sp.) are a widely grown perennial crop, with ~7.6 million ha worldwide. It is a crop of great importance and economic value for France, which is the largest wine exporter in value worldwide (OIV report, 2019). Viticulture is still highly dependent on plant protection products (PPPs), with e.g. 7 to 19 treatments per cropping season in France depending on the prevailing pedoclimate, the grape variety and the target market (Merot & Smits, 2020). The current regulatory context in Europe (SUD Directive 2009/128/EC, Farm to Fork Strategy, French national action plans Ecophyto 2008, Ecophyto 2018, Ecophyto II+), and the very high societal demand for a reduction in the use of chemical PPP in viticulture, has led to a reconsideration of dose notions for high growing crops (EPPO, 2016). Various efforts have been carried out worldwide to identify ways to reduce the use of conventional PPPs, from decision support tools (Garcera et al., 2021; Pertot et al., 2017; Planas et al., 2022), to research into disease-resistant varieties (Lamichhane et al., 2015), or the development and testing of biocontrol agents (Ortega et al., 2023).

When applying PPP with sprayers, a fraction of the product drifts

* Corresponding author.
E-mail address: anice.cheraiet@inrae.fr (A. Cheraiet).

https://doi.org/10.1016/j.biosystemseng.2024.03.008
Received 6 November 2023; Received in revised form 17 March 2024; Accepted 20 March 2024
Available online 26 March 2024

during the treatment, while some falls to the ground and will either infiltrate the soil system or be lost in run-off (Nieder et al., 2018). With poorly performing sprayers, these losses can be high, with only a relatively small quantity of the products reaching the target. The order of magnitude of effective deposition has been reported to be as low as 20–30% of the product sprayed at early growth stages and only 50–60% at full vegetation stages (Gil et al., 2021; Grella et al., 2022). Therefore, in the first instance, a shift to the use of more efficient sprayers that better target the vegetation is an important lever for reducing the quantities of PPP used in viticulture and the off-target load being lost to the environment. More specifically, if the efficiency of a sprayer can, as a first step, be defined by the percentage of product that reaches the vegetation, it can also be thought of as the capacity to deliver an amount of product per unit of surface of foliage, and other organs to protect, everywhere in the vegetation. The term efficiency should be then understood in this broader sense in the following.

The current reality is that mechanised viticulture sprayers are available in a great diversity of geometries and technologies (Fig. 1) that have contrasting efficiencies. The three main types are airblast sprayers, multi-row sprayers and pneumatic arch sprayers. Airblast and multi-row sprayers both use hydraulic nozzles combined with air assistance to carry the droplets to their target. Airblast sprayers consist of an axial fan surrounded by a series of nozzles. They are used every second row, with the consequence that only one of the two sides of the row is directly targeted. Conversely, multi-row sprayers have air-assisted vertical booms, fitted with nozzles, positioned on either side of the rows of vines and perform a symmetrical treatment of vegetation. With multi-row sprayers, both sides of the rows are directly sprayed. Some models are supplemented with recovery panels, to capture and recycle some of the spray that is not deposited on the vegetation (tunnel sprayers). Pneumatic arch sprayers produce droplets by streaming the spray liquid into fast airflow outlets located along and above the vine row (Grella et al., 2020; Naud et al., 2014). These sprayers can be used at their best every second row but are often used every three or four rows for productivity sake (Codis et al., 2018). Note that there are also multi-rows sprayers with pneumatic technology, but few of them are currently deployed in the vineyards (McCoy et al., 2021; Salcedo et al., 2020).

Several factors influence grape growers when choosing and purchasing a sprayer, including cost, user-friendliness and versatility. Due regulations and incentives, the on-going trajectory to reduce conventional PPPs is now increasingly motivating growers to choose more efficient sprayers when replacing their equipment.

The current system of PPP dose expression in France is based on a fixed dose, defined per unit area of ground (L or kg ha^{-1}). This leads to very variable quantities of deposition per area of organs to protect (leaves and bunches). These quantities indeed depend on both the amount of vegetation to be protected and the sprayer used. Historically, this fixed dose approach has been used in product efficacy trials and has also been systematically used in fields with sprayers that differ from those used in the efficacy trials, many of which are sprayers with poor efficiency. Growers using poorly efficient sprayers usually obtain effective protection despite this inefficiency. It follows that, when using high performance sprayers, a reduced dose would be equally as effective in providing protection in most situations. High-emitted dose rates ensure that even with inefficient sprayers, the areas of the canopy that get the lowest level of deposition are still well protected. Lower emitted dose rates taking into account sprayer efficiency would reduce the loss of PPPs into the atmosphere and/or the soil system. However, if lower dose rates are to be recommended, accurate methods to rapidly assess the performance of sprayers at different dose rates and different canopy conditions are needed so that more repeatable and measurable performance specifications can be given to growers to ensure that the crop is still well protected.

Crop protection treatments are carried out at different stages of growth that change quickly during the season depending on the cultivar and climatic conditions. Since fungicides may be applied from early development to full vegetation stages, the evaluation of the deposition performance must necessarily consider different crop stages. The total leaf area within a vineyard block has been shown to range from 0 to 2.5 m^2 during the growing season (Siegfried et al., 2007).

Different protocols are found in the literature to quantify and evaluate foliar deposition in tree and vine crops (Codis et al., 2018; Giles & Downey, 2003; Salcedo et al., 2020), and the results are often incomparable because of variability in the crop development and crop training (Forster et al., 2014). In order to standardise the sampling method for spray deposition trials, the ISO 22 522 standard (ISO, 2007, pp. 1–19) was developed. This standard supports sound evaluations when implemented under commercial vineyards condition with careful sampling (Cheraiet et al., 2021) but it is still difficult in practice to extrapolate results from one field region to another, or from one assessment team to another, when it comes to evaluate the deposition efficiency.

Differences in the deposition rate at the same growth stage have been observed (Pergher & Petris, 2007) for different plots with differing training systems and vegetation vigour. At the vine scale, Pergher et al. (1997) observed a coefficient of variations ranging from 30 to 82% when measuring deposits on leaves at different locations in the canopy (according to a depth-height plane). The intra-and inter-vine variability in deposition rates requires the organisation of trials in different situations, and consequently limits the number of sprayers that can be compared for deposition efficacy.

These known constraints have led some researchers to organise testing facilities and construct benches using synthetic plant components to compare a variety of spray application devices on a given artificial canopy structure. Trials on artificial vegetation have been conducted in arboriculture (Dekeyser et al., 2014; Duga et al., 2015) and in viticulture (Catania et al., 2011; Michael et al., 2020). The artificial vegetation is structured to mimic real vegetation conditions, using tissue or plastic leaves. For this purpose, synthetic leaves are arranged on artificial trunks and branches to simulate the complexity of the real vegetation.

Such arrangements have proved useful to assess the importance of air-assist velocity on the efficiency of viticulture treatments (Catania

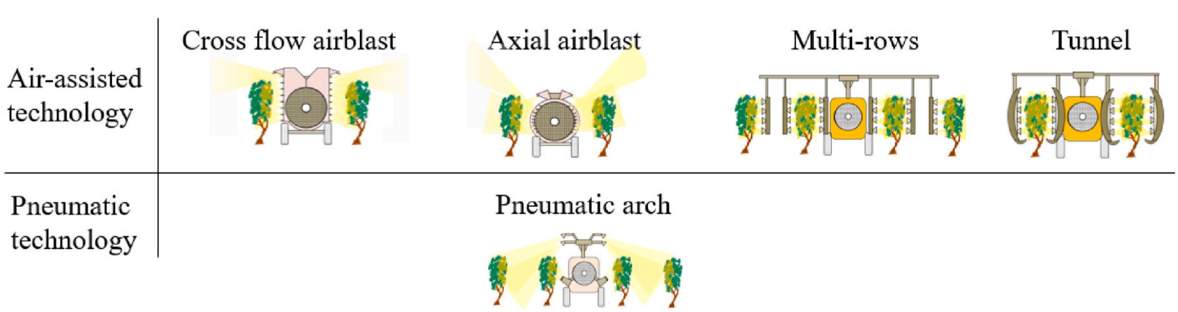

Fig. 1. Schematic illustration of the typical spray patterns (yellow spray) and expected deposition areas (yellow canopy) of the main spray technologies and configurations used in French viticulture. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

et al., 2011; Pergher et al., 2013), the importance of sprayer design and settings on foliar deposition (Pascuzzi et al., 2017) and soil losses (Dekeyser et al., 2014). Furthermore, by replicating the randomness of the leaf distribution, similar levels of intercepted depositions have been obtained between real leaves and artificial collectors (Dekeyser et al., 2014). It has nevertheless been acknowledged that, to date, the use of artificial targets in real vines has limited the capability to reproduce trials because of the intrinsic difficulty in reproducing the random 3D structure of vine canopies. When using artificial vegetation that imitates the randomness of real vegetation, this reproducibility issue is reduced, but the capacity to extrapolate might still be limited. The capacity to discriminate and analyse fine differences between sprayers may also be limited.

This is why, with the objective to assess vineyard sprayers with regard to their relative capacity to reduce emitted doses while still ensuring sufficient protection, the EvaSprayViti testing facility was developed at INRAE, the French National Research Institute for Agriculture, Food and Environment, and IFV, the French Institute of Vine and Wine (Codis et al., 2015). The primary aim of the EvaSprayViti facility was to assess mean or median deposition rates as well as variations of deposition between zones according to depth and height dimensions in the canopy. The artificial canopy of EvaSprayViti was designed with a regularly distributed structure that can be adapted to mimic several growth stages.

Therefore, the objective of this study was to investigate how well an artificial canopy structure, such as implemented in the EvaSprayViti testing facility, can mimic the essential 3D properties of vegetation at different stages of growth and be used for comparative needs assessment of sprayers. The specific objectives of this research were:

- To propose and validate a sampling strategy of the deposits on the EvaSprayViti test bench;
- To study and compare, at three growth stages, the deposit distributions intercepted on artificial collectors positioned in a real vine canopy and on the EvaSprayViti test bench, both being spatially recorded in a grid according to depth and height dimensions;
- To evaluate, at a given growth stage, the ability of the EvaSprayViti testing facility to discriminate the performance of several dozen of spray application configurations.

2. Materials and methods

2.1. The EvaSprayViti testing facility

2.1.1. Description

As described above, EvaSprayViti was developed by INRAE and IFV to comparatively assess deposition by vineyard sprayers. The details of EvaSprayViti artificial canopy structure have not previously been thoroughly described in the scientific literature, so they are given here before presenting the experiments. The testing facility originated from previous works at IFV and INRAE (Gil et al., 2007). When designed, three factors needed to be considered: i) consistent overall dimensions of the canopy in terms of height and depth for different growth stages, ii) a capacity to adapt the artificial leaf area index (LAI) to correctly mimic the real LAI at any given growth stages and, iii) a regular distribution of leaves in both height and depth dimensions.

The EvaSprayViti test bench illustrated in Fig. 2 was designed in two parts to simulate a trellised vineyard. The first part is a 2 m 'measurement section' that enables the collection of spray deposits from the artificial leaves. This measurement section is surrounded by metal structures with windbreak nets to mimic the effect of vine porosity on spray behaviour. These are positioned before and after the measurement section within the spray measurement row and form the artificial vine rows adjacent to the measurement section.

Fig. 3A, B and 3C depict the evolution of the measurement section of the test bench, according to growth stages. In these sections, the collectors act as artificial leaves and can be sampled individually or collectively as needed according to the type of study being undertaken.

Fig. 2. EvaSprayViti test bench. Sprayer spraying along EvaSprayViti, showing the measurement section with the artificial PVC collectors and the windbreak netting to mimic canopy porosity before and after the measurement section and on adjacent rows.

The measurement section of the test bench is always constructed using n ranks of m poles evenly placed on a locking roller frame that is 300 mm above ground level. The poles are 1.1 m high, giving a maximum canopy height of 1.4 m. Fig. 4 shows in more detail the exact geometry of the arrangement of the artificial leaves (collectors) for a full growth stage ($n = 6$, $k = 14$) with top (Fig. 4A) and side-on (Fig. 4B) views.

At full growth stage ($n = 6$ and $m = 10$), the poles are staggered from one rank to the next as indicated by the dimensions in Fig. 4. The poles are spaced at a regular distance (q) of 72.8 mm across the measurement section and a distance (i) of 200 mm within a rank along the measurement section. At the front and the rear of each pole, a number (k) of 40 mm long crocodile clips are soldered onto the pole at p = 200 mm spacing. When considering both the front and the rear of a pole, the spacing of the clips on alternate sides is p/2 = 100 mm. Polyvinyl chloride (PVC) square collectors (Ren-peck Technology Ltd, Hong Kong) of L = 100 mm length and 300 μm thickness are attached by a corner to the crocodile clips and creased at the level of the clip end, which allows for a bending oscillation of the collector around the x-axis in the presence of airflow.

The measurement section was designed to have an adjustable height and width to be able to characterise three different growth stages: early, middle and full growth. For this purpose, the number of ranks and the number of PVC collectors per pole are adaptable. For early growth stages, n = 2, and the number k' on which square collectors are placed is 3. For medium growth stages, n = 4, and the number k' on which square collectors are placed is 12. m is always 10. The letters ⟨ and ® in Fig. 4 designate respectively a sampling slice and a thin slice. A thin slice has one pole per rank. Because of the staggered arrangement of the facility, the thin slices are not all the same. On the contrary, a sampling slice has all positions in depth and height of leaves and is identical to its neighbours.

The second part of the test bench is composed of windbreak nets mounted on custom-designed variable geometry metal frames to simulate various levels of canopy porosity. These nets (Texinov, France) are used to reduce the wind speed by up to 45% (Roux et al., 2006). In the first instance, 4 m long sections are located in line and at both ends of the measurement section, in order to avoid boundary effects. Thus, the complete row, which includes the 2 m measurement section, is 10 m long. In addition, 10-m windbreak net rows are placed on either side of this combined collection row to mimic the adjacent vine rows. The

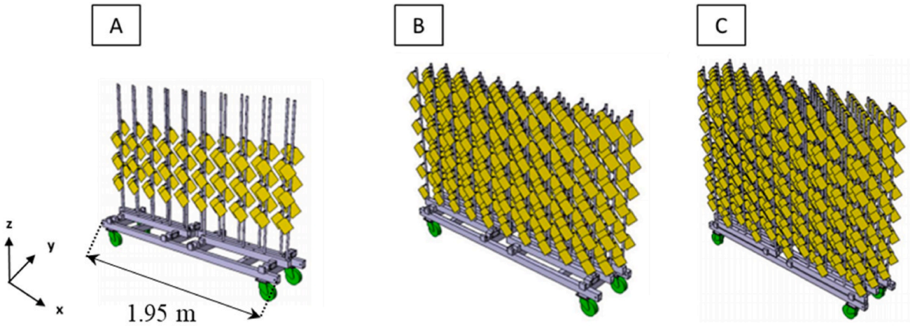

Fig. 3. Schematic of the measurement section at early growth stage (A1), middle growth stage (A2) and full growth stage (A3). The *x*-, *y*- and *z*-axes represent the travel direction of the tractor, the crop depth and the crop height respectively.

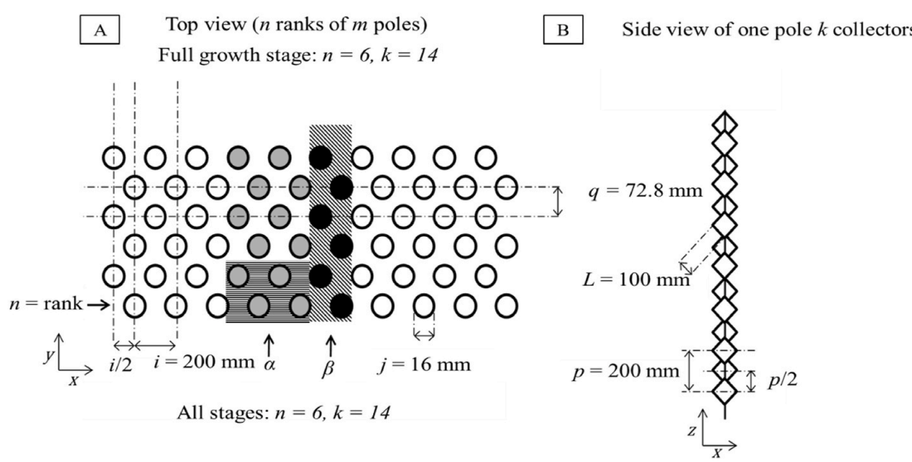

Fig. 4. A: Spatial arrangement of poles that carry collectors (top view of the facility). B: Arrangement of collectors on a pole (side-on view of the facility).

height and width of the windbreak net structures are always set to be equal to the measurement section. As a whole, the EvaSprayViti testing facility is typically set up with three vine rows of 10 m length, with the measurement section in the middle of the central row. The inter-row spacing is fixed at 2.5 m, which is the usual inter-row spacing in southern French vineyards. In order to avoid ground irregularities during trials, the testing facility is installed on a concrete slab.

Some sprayers, such as pneumatic arches, can spray up to four rows at the same time. In these cases, the proximal row and the distal row are treated by different actions of the sprayer. This results in different deposit patterns on the two rows being treated. Thus, when such practices are assessed, a second measurement section needs to be added on the distal row. In this case, there are still three vineyard rows in total with two measurement rows. For other multi-row sprayers, such as face-to-face sprayers, the tractor traverses different inter rows so that different sections of the sprayer can be assessed along the central measurement section.

2.1.2. Measuring in 3D at various growth stages

2.1.2.1. EvaSprayViti configurations. For the four experiments outlined later, a fixed configuration was used to simulate small, medium and full canopy conditions. The characteristics of the measurement section of EvaSprayViti for each of the three simulated growth stages are described in Table 1, including the simulated total number of leaves and the corresponding LAI when an inter row spacing of 2.5 m is considered. For the early vegetation, only the two middle ranks were used. For the mid-season simulations, this was expanded to four ranks (four middle ranks in Fig. 4A), and to all six ranks for the full-canopy tests. The proposed geometric configurations (Table 1) have an elementary pattern that when replicated can reproduce the target vegetation size along the whole measurement section of the facility.

Table 1
Characteristics of the measurement section of EvaSprayViti.

	Growth Stage		
EvaSprayViti Parameters	Early	Middle	Full
Total number of collectors	120	440	840
Leaf area index for 2.5 m of inter row spacing	0.24	0.88	1.68
Collectors per pole	6	11	14
Simulated height of the canopy (m)	0.6	1.1	1.4
Number (*n*) of ranks to define the canopy width (*y*-axis)	2	4	6
Simulated width of the canopy (m)	0.17	0.32	0.47

2.1.2.2. Aggregation of collectors into compartments. In order to facilitate a qualitative and quantitative comparison between results on the EvaSprayViti artificial canopy and real vegetation, the distribution of tracer can be evaluated by segmenting the vegetation structure into compartments. At the early stage, the collectors can be grouped into four depths, without distinction of height class, as shown in Fig. 5A and B. At this stage of vegetation, each depth is defined as a half row. For the middle stage of vegetation, six compartments can be defined (left and right at three heights: low, middle, high) as shown in Fig. 6A and B. For the full growth stage, the collectors can be grouped in three heights (low, middle and high) and three depths (left = back, middle and right = forward) as described in Fig. 7A. In total, for this growth stage, nine compartments can be defined, as shown in Fig. 7B. The deposition rates can be measured at the compartmental level, rather than for each artificial leaf, in order to save time. One objective of Experiment 1 described hereafter

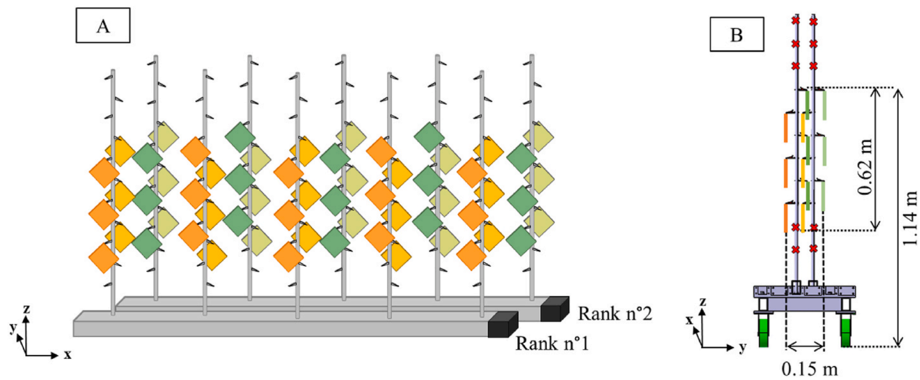

Fig. 5. Side view (A) and cross-sectional view (B) of the EvaSprayViti collection compartments at early-stage vegetation. The different colours distinguish the four compartments defined by depth. The red crosses symbolise positions where collectors have not been positioned. Measurements provided are indicative. For convenience of graphics, only half of the poles are represented on the side view. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

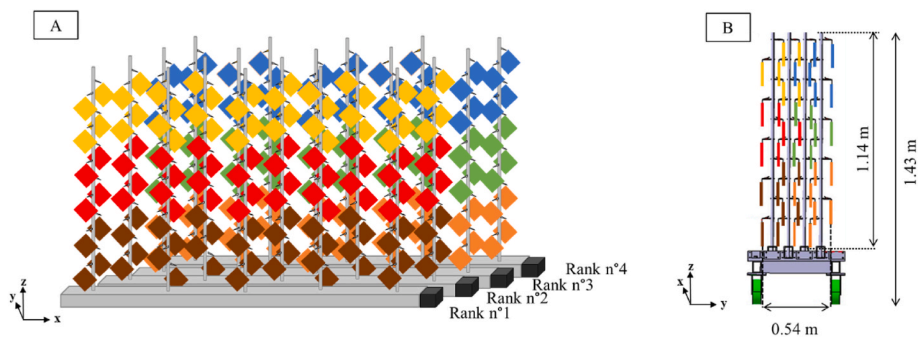

Fig. 6. Side view (A) and cross-section (B) of the EvaSprayViti collection compartments at a mid-stage vegetation. Each colour variation represents one compartment, resulting in a grouping into two depths along the *y*-axis and three heights along the z-axis. The different measurements are indicative. For convenience of graphics, only half of the poles are represented on the side view. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

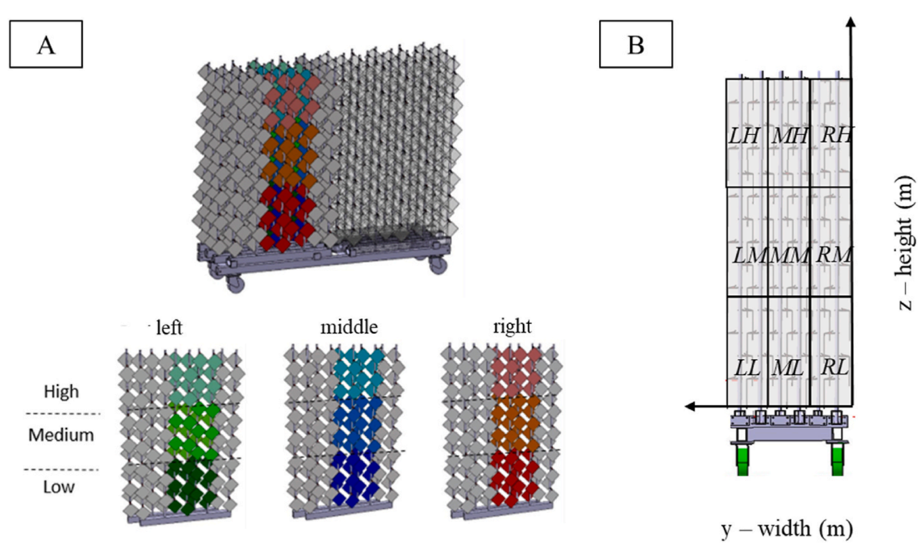

Fig. 7. A: Side view of EvaSprayViti collectors grouping at full growth stage. Each colour variation represents a compartment, yielding a grouping in three depths along the *y*-axis (green, blue, red) and three heights along the *z*-axis (light, normal and dark colour). B: represents the position of the nine compartments on a cross-section of the test facility. The first letters *L, M, R* correspond to left, middle and right respectively and the second-letter *L, M, H* corresponds to low, medium and high. The coloured collectors represent both the groupings into compartments and the selection of collectors in a sampling slice (Fig. 4). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

was to assess if this aggregation preserved enough information.

2.2. Spray deposits measurement on EvaSprayViti

Trials were performed at INRAE, Montpellier, France. During the tests, wind velocity and wind direction were measured using an ultrasonic 2D anemometer (Vaisala, Vantaa, Finland) placed at 2.50 m in height and 10 m upwind from the testing facility. Air temperature and relative humidity were recorded using a thermo-hygrometer (Hanna, Woonsocket, USA). Trials were only performed in meteorological conditions where spraying is allowed by French law (wind speed <5.27 m s-1). In all trials, the temperature was <30 °C and the relative humidity >40%.

As recommended by ISO 22522:2007, tartrazine (E102, 85% w/w, Alpa Sud, France) was used as a tracer. During a test, the vineyard sprayer passed through the testing facility at a constant speed, while spraying a mixture of dye and water with a nominal dye concentration of 10 g L^{-1} of water. The different sprayer settings were tuned either by a manufacturer's representative or by a trained operator to target the vegetation. The quantity of product deposited on the collectors was expressed in ng of collected dye per dm^2, and then normalised by the applied quantity sprayed per ground surface area.

The volume rate Y (L ha^{-1}) was calculated from the total sprayers flow rate Q (L min^{-1}), the sprayer's forward speed (calculated over the test duration) v (km h^{-1}), and l (m) the sprayed area width, according to Eq. (1):

$$Volume\ rate: Y = \frac{600 * Q}{v * l} \qquad \text{Eq 1}$$

Note that $l = R * IRS$ where R is the number of rows treated in a single path and IRS is the inter-row spacing.

Before each test, sprayer flow rate was calibrated. Once the sprayer had passed through the test facility, the artificial collectors were removed. They were then washed in a known quantity of distilled water and the tartrazine concentration was later determined through the reading of the absorbance level of the washing solution using a spectrophotometer (Uviline 9100, Secomam, France) at a wavelength of 427 nm. Results of depositions were then expressed as the quantity of product collected by collectors surface area for 1 g of dye sprayed on 1 ha ground surface (ng dm^2 for 1 g ha^{-1}), according to the following equation (Eq. (2)):

$$Deposit = \frac{A_f}{A_0}\frac{V_d * 10^6}{S_f * Y} \qquad \text{Eq 2}$$

where A_f and A_0 are respectively the absorbance values of the diluted sample (dried deposits diluted in water) and of the stock solution (taken from the sprayer tank for each trial), respectively, V_d (ml) is the dilution volume for the sample, Y (L ha^{-1}) is the volume rate calculated from Eq (1), S_f (dm^2) is the surface collector area. Note that, in practice, the measurement of A_0 itself may require a dilution of the stock solution to fit in the range of the spectrophotometer and verify the Beer-Lambert law.

2.3. Experiments

Four different types of experiments (Table 2) were carried out in order to characterise and evaluate the sensitivity of the EvaSprayViti test bench to be able to simulate a real vine row at different growth stages, as well as to facilitate the assessment of the deposition performance of vine sprayer typologies through repeatable measures.

2.3.1. Definition of the sampling strategy on the artificial canopy

To characterise the ability of the proposed 3D sampling approach to characterise sprayer deposits at the EvaSprayViti testing facility, the deposits on each of the 840 collectors (all collectors on all poles) at a full-growth stage configuration of the measurement section were measured individually. Two sprayers, a pneumatic arch and a tunnel sprayer corresponding to contrasting technologies regarding spray deposits homogeneity and coverage efficiency, were compared. The settings for the two models chosen for the experiment are listed in Table 3. A pneumatic arch (v. 1990, Pulsar, Tecnoma®, Epernay, France) was used to spray 4 rows in one path. According to this practice, only the side of the row closest to the sprayer is directly exposed to the spray nozzles so only the row closest to the nozzles was analysed with the pneumatic arch. The tunnel sprayer used for this experiment was a Koleos (Dhughes®, Vilemoustaussou, France).

2.3.2. Comparison of deposition on the artificial canopy and in a vineyard at full growth stage

To evaluate the consistency of the deposit measurements at the EvaSprayViti testing facility with deposit measurements in vineyards, three spray modalities (sprayers & settings) were tried in both the testing facility and in a real vineyard (Table 4). For the measurements on the real vineyard, the protocol of ISO 22522 was followed, but with a higher spatial resolution as described in Codis et al. (2018). The PVC collectors 8 × 5 cm^2 were stapled on vine leaves within the canopy compartments. The compartments were defined in 0.2 m height increments (a maximum of seven) and 0.1 m depth increments (a maximum of 5) as presented in Fig. 8. For each modality, deposit measurements were repeated on 4 consecutive vines located along the same row. Tartrazine collected on the artificial targets was quantified using the protocol described previously (Spray deposit measurement on

Table 3
Sprayer characteristics used to assess the collection of deposits on the artificial canopy.

M&M	ST	Tech	N	N-P	V
Tecnoma-Pulsar	Pneumatic arch 1	Pneumatic	4	Teejet-CP4916-29	150
Dhuges-Koleos	Tunnel sprayer 1	Air-assisted	2	Lechler-IDK-90-01	140

Legend: M&M is sprayer manufacturer & model, ST is sprayer type, Tech is spraying technology, N is number of rows treated in a single path, N-P is a manufacturer and characteristics of Nozzle or spout Plate, V is application rate (L ha^{-1}).

Table 2
Objectives and experiments.

Exp	Objective	Sprayers	Artificial vegetation			Real vegetation		
			Early	Middle	Full	Early	Middle	Full
1	Define a sampling strategy on the artificial vegetation – 1 stage	PA 2 rows			X			
		TS			X			
2	Compare deposition at a single crop stage on artificial and real vegetation	PA 2 rows			X			X
		PA 4 rows			X			X
		MR			X			X
3	Compare deposition at three crop stages on artificial and real vegetation	MR	X	X	X	X	X	X
4	Compare different modalities at full growth in artificial vegetation	65 spray modalities			X			

Legend: PA: Pneumatic Arch (spraying every 2 or 4 rows); TS: Tunnel sprayers; MR: Multi-row sprayer.

Table 4
Sprayer and settings used for deposits comparison trials between EvaSprayViti testing facility and a real vineyard.

M&M	ST	Tech	N	R	N-P	V
Calvet-Eco+	Pneumatic arch 2	Pneumatic	2	all	Teejet-CP4916-49	220
Calvet-Eco+	Pneumatic arch 2	Pneumatic	4	proximal	Teejet-CP4916-29	110
Calvet-Eco+	Pneumatic arch 2	Pneumatic	4	distal	Teejet-CP4916-29	110
Tecnoma-Vectis precijet	Multi-row sprayer 1	Air assisted	3	all	Teejet-TVI-80-01	190

Legend: M&M is sprayer manufacturers & model, ST is sprayer type, Tech is spraying technology, N is a number of rows treated in a single path, R tells whether row is distal or proximal for pneumatic sprayers used every 4 rows, N-P is a manufacturer and characteristics of nozzle or spout plate, V is the application rate (L ha^{-1}).

EvaSprayViti). The field experiments were conducted in a *Vitis vinifera* L. cv Cabernet Franc trellis vineyard with 2.5 m inter-row spacing in the Massillan estate, located in Le Crès, France. The vineyard on which measurements were made was at an advanced stage of vegetation development (BBCH 69, end flowering) (Lorenz et al., 1994), and results are compared with the 'full growth stage' at the EvaSprayViti testing facility described in Table 1. It should be noted that there is a spatial difference in the sampling performed with EvaSprayViti and in the real vineyard. The number of compartments considered for EvaSprayViti was nine (three heights x three depths) taken on a sampling maxi slice (see Fig. 4, a sampling slice bears 168 leaves on 12 poles at full growth stage, which were grouped into 9 compartments, with 24 leaves in each of the 3 top compartments and 30 leaves in the others). The number of collectors, which were analysed individually, was 30 (six height x five depth) in the real vine canopy.

2.3.3. *Comparison of deposition on the artificial canopy and vineyard at three growth stages with a single sprayer configuration*

In viticulture, the target canopy to spray evolves over the cropping season, becoming higher and larger. To simulate this evolution, three growth stages were simulated at the EvaSprayViti testing facility. The mean dimensions of the vineyard and the corresponding dimensions simulated at the EvaSprayViti testing facility configurations are presented in Table 5. Under these conditions, the consistency of the evolution of deposits between the artificial canopy and a vineyard was tested with a multi-row sprayer known to deliver a regular profile of spray deposition (Table 6). Trials were conducted on a Vitis vinifera L. cv Marselan trellised vineyards at Mas Piquet, Montpellier, France. The three measurements in the field corresponded respectively to BBCH 53 (inflorescences clearly visible), BBCH 57 (inflorescences fully developed; flowers separating) and BBCH 77 (berries beginning to touch), that correspond to three contrasting treatment periods. The protocol used for deposit assessment was the same as that described for Experiment 2 for a full growth stage. For medium growth stage, the collectors were placed in the vineyard according to the same grid as for the full growth stage, resulting in *x* and *y*-axes. The sampling slice for EvaSprayViti was similar as for full growth stage, except n (number of ranks) was 4 and there were 3 heights and 2 depths, thus 6 compartments. The top compartments had 12 leaves and the others had 16 leaves, with a total of 88 collected leaves. For early growth stage, the collectors were placed in the vineyard according to the same grid as for a medium growth stage, resulting in *x* and *y*-axes. The sampling for EvaSprayViti at early growth stage was specific to this stage and is depicted in Fig. 5 with n = 2.

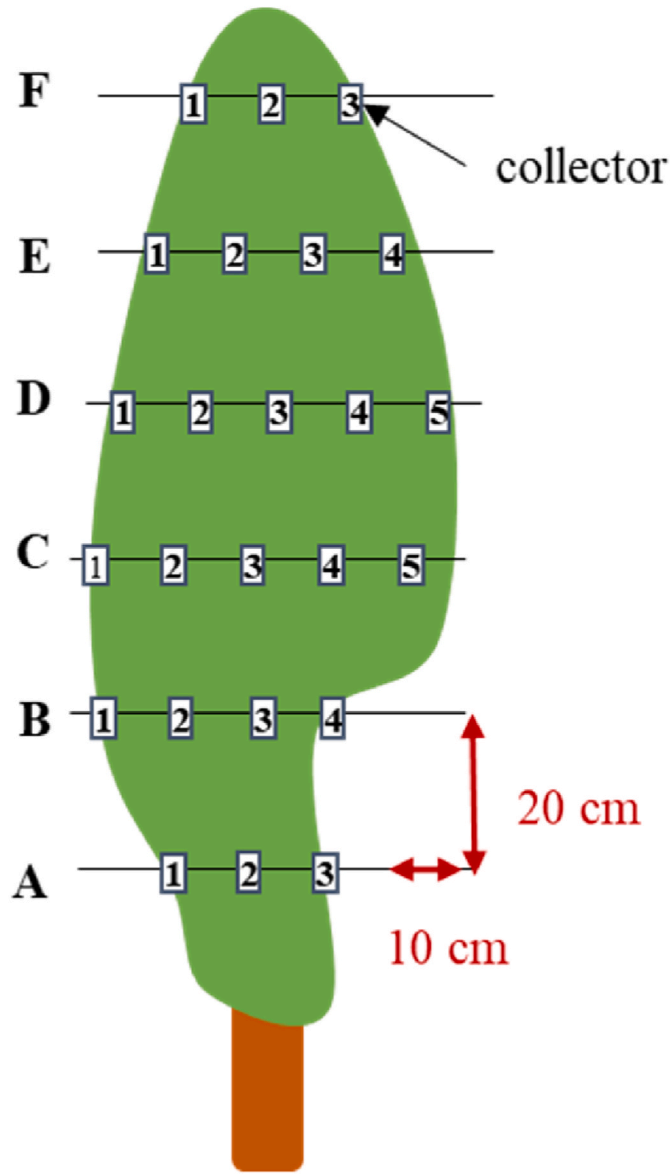

Fig. 8. Sampling distribution in canopy 'compartments' real vineyards defined by fixed height (0.2 m; A – F) and depth (0.1 m; 1–5) increments, adapted from Codis et al. (2018).

Table 5
Dimensions of EvaSprayViti artificial canopy for different stages and average vegetation size during the experiments.

Growth stage	Height dimension (m)		Width dimension (m)	
	Natural vegetation	Artificial vegetation - EvaSprayViti	Natural vegetation	Artificial vegetation - EvaSprayViti
Early	0.50	0.60	0.30	0.17
Middle	0.90	1.1	0.40	0.32
Full	1.30	1.4	0.50	0.47

2.3.4. *Testing the ability of the EvaSprayViti test bench to differentiate 65 spraying configurations based on treatment quality at full growth stage*

The EvaSprayViti artificial canopy was sampled at full growth stage using the idea of nine canopy compartments as proposed in Fig. 7B. A set of 65 different spray application configurations were performed, varying both the sprayer configurations and the sprayer settings (Table 7). A total of twelve sprayers were used to implement the 65 different

Table 6
Sprayer and settings used for deposits comparison trials between EvaSprayViti testing facility and a real vineyard.

M&M	ST	Tech	N	N-P	GS	V
Tecnoma-Vectis precijet	Multi-row sprayer 1	Air assisted	3	Teejet-TXA-80-0067	Early Middle Full	60 90 120

Legend: M&M is sprayer manufacturers & model, ST is sprayer type, Tech is spraying technology, N is the number of rows treated in a single path, N-P is manufacturer and characteristics of nozzle or spout plate, GS is Growth Stage, V is the application rate (L ha^{-1}).

Table 7
Sprayers tested at the EvaSprayViti testing facility.

M&M	ST	Tech	NT	V
Calvet-Axial	Axial airblast 1	Air assisted	3 (1.o+2.W)	[140−150]
Calvet-Cross flow	Cross flow airblast 1	Air assisted	3 (1.o+2.W)	[150−180]
Ideal-Loire	Cross flow airblast 2	Air assisted	5 (5.o)	[95−210]
Dhuges-Koleos	Tunnel sprayer 1	Air assisted	6 (4.o+2.W)	[160−280]
Bertoni-Arcrobaleno	Tunnel sprayer 2	Air assisted	6 (2.o+4.W)	[170−260]
Friuli-Drift recovery 2000	Tunnel sprayer 3	Air assisted	6 (4.o+2.W)	[100−240]
Weber-NC1000	Tunnel sprayer 4	Air assisted	6 (2.o+1.v+3.W)	[110−200]
Tecnoma-Vectis precijet	Multi-row sprayer 1	Air assisted	4 (1.o+3.W)	[140−150]
Nicolas-Rafale	Multi-row sprayer 2	Pneumatic	2	[150−200]
Tecnoma-Pulsar	Pneumatic arch 1	Pneumatic	10	[135−165]
Calvet-Eco+	Pneumatic arch 2	Pneumatic	11	[100−200]
Nicolas-Zephyr	Pneumatic arch 3	Pneumatic	3	[120−130]

Legend: M&M is sprayer manufacturers & model, ST is sprayer type, Tech is spraying technology, NT is the number of trials (symbol o designates classical nozzle producing small droplets, flat flan or hollow cone, symbol W designates drift reducing air-injection nozzles producing bigger droplets, and symbol v designates drift reducing nozzle with pre-atomiser producing droplets of intermediate size), V is range of application rates (L ha^{-1}).

scenarios. The configurations were selected based on expert knowledge for diversity and representativeness of observed practices by winegrowers. Results were analysed using a principal component analysis (PCA). As the granulometry of nozzles is one of the settings that may have an impact, the number of trials per type of nozzle, with regards to granulometry, is provided in the column labelled NT.

2.4. Statistical analysis

2.4.1. Descriptive and exploratory statistics of foliar spray deposition

Descriptive statistics (mean, coefficient of variation and standard error) were calculated for each spray modality tested and at each growth stage, in real vineyards and on the EvaSprayViti artificial canopy as an exploratory analysis of intercepted deposits. Because the artificial collectors in the real vineyard and from EvaSprayViti were normalised for surface area, they could be compared despite their differences in size. As the deposition data were not normal, a logarithmic normalisation transformation was performed to obtain residual normality and homoscedasticity. To represent the mean deposition rate and its variability, box plots were made. The box plots show the median (solid line) and the mean (cross). The lower and upper limits of the box plots correspond to the first and third quartiles respectively, and the error bars indicate the minimum and maximum values.

2.4.2. Definition of the sampling strategy on the artificial canopy

In order to describe the spatial distribution of intercepted deposits at the EvaSprayViti testing facility, representations in the form of heat map graphs were generated using the R software (R Development Core Team, 2022) with the packages ‘ggplot2’ (Wickham & Chang, 2016) and ‘RColorBrewer’ (Neuwirth, 2014). Representations to visualise the intercepted deposits on the artificial canopy as a function of longitudinal position (section), height and depth were made. This allowed the intercepted deposition information to be plotted in a gridded space to provide an initial indication of the overall spatial distribution of deposition and its variability on the artificial collectors in this study. It is important to note that this analysis, which does not involve geostatistics, is only a visual indication of the spatial distribution and variance of deposits collected within the EvaSprayViti facility.

To investigate the effect of longitudinal position (sampling slices denoted as sections S1 to S5) at full growth stage, a one-factor ANOVA was performed. As the deposition data were not normal, a logarithmic transformation was performed to obtain residual normality and homoscedasticity before the ANOVA.

In the case where the explanatory variable had a significant effect on the mean, a Tukey post-hoc test was used to compare all pairwise means and distinguish between groups ($\alpha = 5\%$). This test was performed to identify variations in deposition due to the transition of airflow over the collection area of the facility after the shading net section. From prior experience with EvaSprayViti artificial canopy, this is known to have an impact on the spray deposition. Collectors were not grouped into compartments for this experiment.

2.4.3. Comparison of deposition on the artificial canopy and vineyard at full growth stage

To investigate whether there was a significant difference in the mean deposition observed at a full growth stage between four contrasting spray techniques on the artificial canopy and on collectors positioned in a vineyard, a two-factor ANOVA was performed. In order to take account of the unbalanced experimental design (the number of observations was different between the EvaSprayViti facility, for which leaves were grouped into compartments and the real vineyard), the adjusted group means were compared in pairs using a type III ANOVA and the Tukey post-hoc test was then performed to identify significantly different groups.

2.4.4. Comparison of deposition on the artificial canopy and vineyard at three different growth stages with a single sprayer configuration

To assess the ability of the EvaSprayViti test bench to correctly describe the mean deposition at different growth stages, a one-way ANOVA was performed to determine if there was a significant difference between the mean deposition observed on the EvaSprayViti artificial canopy and on PVC collectors positioned in a real vineyard at three different growth stages. In order to take account of the unbalanced experimental design, as it was the case for both experiments 2 and 3, the adjusted group means were compared in pairs using a type III ANOVA and the Tukey post-hoc test was then performed to identify significantly different groups.

2.4.5. EvaSprayViti test bench’s ability to differentiate 65 spraying configurations based on treatment quality at full growth stage

In order to evaluate the capacity of the EvaSprayViti test bench to discriminate a greater number of spray configurations in terms of quantitative and qualitative deposition, a principal component analysis (PCA) was applied to the data set (65 modalities of spraying) on the full growth stage configuration of the EvaSprayViti artificial canopy. The evaluation was carried out on standardised values (Z scores) of the mean deposition observed per compartment (nine compartments in total: *LL, LM, LH; ML, MM, MH; RL, RM, RH*), as defined in Fig. 7B, which makes it possible to quantify the effect of different sprayer adjustment parameters on the spraying process in viticulture. Each variable corresponds to the deposits in one of the nine compartments. These statistical analyses were performed using the FactoMineR library (Lê et al., 2008) using the R software.

3. Results and discussion

3.1. Variability and distribution of intercepted deposits on the artificial canopy

The deposition on EvaSprayViti artificial canopy for a pneumatic arch (used every 4 rows) and a tunnel sprayer are shown in Fig. 9, where the side views (A1 and B1) and top views (A2 and B2) are averaged along the y and z-axis respectively.

The deposition patterns corresponding to the pneumatic arch and the tunnel sprayer are clearly contrasted in the two planes presented in Fig. 9. For the pneumatic arch, a periodic pattern is clearly observed along the *x*-axis (Fig. 9A1). Advancing along the *x*-axis, the poles and collectors are placed in a staggered pattern. This means that at any defined height, a collector positioned on the front of the pole (and directly exposed to the spray) has two neighbouring collectors on the adjacent poles that are placed behind the poles and will therefore receive less deposits. This results in the high-low patterning in neighbouring grid cells in Fig. 9A1. Fig. 9A2 illustrates the rapid decline in deposits along the *y*-axis (width of the canopy) for the pneumatic arch sprayer, which only sprays on a single side of the canopy. For the tunnel sprayer, a more regular deposition pattern is observable along the direction of travel (Fig. 9B1). It was observed that, regardless of the position along the measurement section, the highest amount of deposits always occurred at a mid-height (which approximates the cordon height), while the upper and lower compartments showed lower amounts (Fig. 9B1). Fig. 9B2 shows the characteristic spray pattern for this type of over-the-row spray equipment, which treats both sides of the vegetation row simultaneously (symmetrically) and has a trend in decreasing deposition rates with increasing depth into the canopy.

A one-way ANOVA test was performed to determine if there was a significant difference ($\alpha = 0.05$) in terms of mean deposits and uniformity of observed mean deposits between the different sections defined by longitudinal position (section S1 to S5). The result is that there was a significant difference in the mean deposit observed between the section classes for the pneumatic arch (*p-value* = 0.014) and for the tunnel sprayer (*p-value* = 0.021) (Table 8). Furthermore, a significant difference in the uniformity of the distribution of the mean deposit was observed, independent of the sprayer considered, for the pneumatic arch (*p-value* = 0.017) and for the tunnel sprayer (*p-value* = 0.019).

By analysing the mean deposit, the Tukey test was able to classify the longitudinal sections on EvaSprayViti artificial canopy into two distinct groups that were significantly different from each other: an outer group (S1, S5) and an inner group (S2, S3, and S4) (Table 8). The results highlight that the first and last sections had different characteristics compared to the three central sections. This is a validation of the previously observed influence of the windbreak netting section on airflow, and consequently deposition rates, within the test facility measurement area. To minimise the impact of the border effects, the first and last sections were excluded and only the three central sections (denoted S2-S4) are used for subsequent analyses. This effectively kept sections S2, S3 and S4 as three replicates of the same measurement in an experiment (Fig. 9).

The coefficient of variation was calculated for the three central sections (S2-S4) including all collectors located in the whole vertical profile along the (*y,z*) plane for the two sprayers tested (Table 9). For the two sprayers, the coefficient of variation was first calculated by considering the deposition value on the maxi slice (168 individual collectors of a section) and then when grouping these collectors into nine compartments per section. The grouping of collectors reduced on average the coefficient of variation by 11% for the pneumatic arch and 14% for the tunnel sprayer (not shown). Hence, most of the deposits variability within the canopy was retained after the grouping of the collectors (Fig. 7B). Grouping the collectors considerably reduced the time spent to generate results.

This first experiment provided clear evidence for redefining both the sampling zones (section S2-S4) based on the regularity of deposition and the sampling strategy (by grouping the collectors into nine compartments). This knowledge and these amended protocols were used for all subsequent experiments that were aimed at comparing the depositions in the EvaSprayViti artificial canopy with deposition onto artificial collectors positioned in a real vineyard.

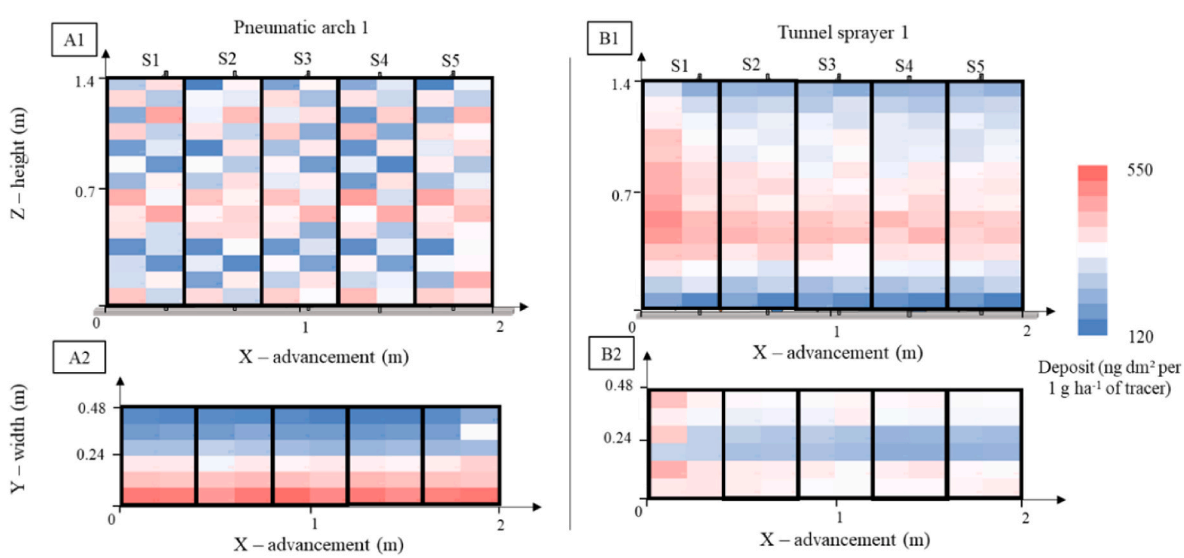

Fig. 9. Spray deposits measured at full growth stage on EvaSprayViti artificial canopy, in side view (A1, B1) and top view (A2, B2) for pneumatic arch sprayer 1 (left) and tunnel sprayer 1 (right). For side views, all y positions corresponding to a single position in the (*z,x*) plane are averaged. For top views, all z positions corresponding to a single position in the (*y,x*) plane are averaged. Black boxes delimit the five sections (S1-S5 respectively) of the test facility that are used later as three replicas of the same measurement. The value selected for the divergence of the colour scale is 39 ng dm^2 for 1 g ha^{-1}. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 8
Significance obtained in a one-way ANOVA for mean spray deposition (ng dm^2 for 1 g ha^{-1}) and distribution uniformity (CV in %).

	Section	Spray deposition			Distribution uniformity		
		Mean	*p-value*[a]	Groups	CV	*p-value*[a]	Groups
Pneumatic arch 1	S1	315.9	0.014*	a	96.7	0.017*	a
	S2	353.1		b	90.8		a
	S3	355.5		b	94.7		a
	S4	353.2		b	97.4		a
	S5	399.3		a	121.3		b
Tunnel sprayer 1	S1	573.9	0.021*	a	72.9	0.019*	a
	S2	510.4		b	43.3		b
	S3	504.2		b	42.1		b
	S4	501.5		b	36.3		b
	S5	496.7		a	45.8		b

[a] Statistical significance level: NS *p-value*> 0.05; * *p-value* <0.05; ** *p-value* <0.01; *** p-value <0.001.

Table 9
Variability of deposits observed within the three central sections of EvaSprayViti artificial canopy (noted S2, S3 and S4) in terms of the coefficient of variation (CV, %), along the vertical plane (*y,z*). Comparison of the coefficient of variation (%) values calculated by taking into account all the collectors located in the whole vertical profile for each section (n = 84) (noted 'Non Aggregated') and by grouping the collectors into nine distinct compartments (noted 'Aggregated'), for pneumatic arch 1 and tunnel sprayer 1.

Sprayer type[a]	Section	CV (%)	
		Non-Aggregated	Aggregated
Pneumatic arch 1	S2	103	91
	S3	106	95
	S4	108	97
Tunnel sprayer 1	S2	43	30
	S3	42	27
	S4	49	36

[a] Details for sprayers given in Table 3.

3.2. Comparison of depositions from contrasted sprayers on the artificial canopy and in a vineyard at full growth stage

Fig. 10 shows a graphical comparison of the deposit distribution profile for sprayers with different spraying configurations measured on both the EvaSprayViti artificial canopy and on a vineyard at a full growth stage. The observations at the EvaSprayViti testing facility and at the vineyards showed similar spatial trends in deposition patterns, whatever the scenario tested. The mean of the values measured on the artificial targets positioned in the real vineyard during an experiment and of the values from compartments of EvaSprayViti artificial canopy differed by 5% for the multi-row sprayer, 9% for the tunnel sprayer, 13% for the pneumatic arch spraying every 2 rows and 15% for the pneumatic arch spraying every 4 rows (data not shown). The measurements were coherent with expectations based on the geometry of the treatment. For example, when the spray was applied on both sides of the row, deposits appeared symmetrical on the two sides of the canopy and were homogenous and relatively high, especially for the multi-row sprayers. When the treatment was performed using the pneumatic arch driving in one row out of 4, only one side of the row was directly sprayed, resulting in much lower deposits on the canopy side not directly exposed to the spray. A treatment with the same pneumatic arch when spraying every two rows allowed a more homogenous treatment, as shown in Fig. 10.

A two-factor ANOVA test was carried out to determine whether there was a significant difference (α = 0.05) in terms of mean deposition observed between the measurements carried out at the EvaSprayViti testing facility and in the real vineyard and the four spraying techniques considered. In general, the result was that the mean deposit obtained at the testing facility did not differ significantly (*p-value* = 0.24) from those observed in the vineyard for the four configurations tested, e.g. observed values of 255.9 and 248.8 ng dm^2 for 1 g ha^{-1} for the multi-row sprayer at the testing facility and in the vineyard respectively (Fig. 11).

However, the dispersion around the mean of these data was different, it was higher in the vineyards than on EvaSprayViti artificial canopy (Fig. 11). On average, the standard deviation of the deposition measurements made in the real vineyard was 17% higher than at the EvaSprayViti testing facility across the four spraying techniques (Fig. 11). Experiment 1 showed that although most of the variability using EvaSprayViti is retained when performing a grouping of collectors, it is reduced significantly (see Table 3). The regular structure of the EvaSprayViti artificial canopy and the flat ground was expected to improve the regularity of measurements. Previous work has demonstrated the heterogeneity of the spatial distribution of vegetation in the vineyard (Llorens et al., 2011; Weiss & Baret, 2017). Hence, measurements on real vegetation are of a contingent nature and affected by the actual spatial distribution of the foliage at the exact spot where measurements occur.

In order to investigate further whether the intercepted spray measurements at the EvaSprayViti testing facility and in real vineyards allowed for an equivalent evaluation and ranking of spraying techniques, a closer examination of the deposition data was done. In general, the highest mean deposition was found with the multi-row sprayer, with values that ranged from 215 to 255 ng dm^2 on EvaSprayViti artificial canopy and from 180 to 260 ng dm^2 in real vineyards (Fig. 11). An identical classification of sprayer typologies was observed independently of whether the measurement was carried out at the EvaSprayViti testing facility or in the vineyard. Considering the mean deposition, the multi-row sprayer involves higher deposits followed by the pneumatic arch sprayer passing every 2 rows, then the pneumatic arch sprayer passing every 4 rows on the proximal row, and finally the distal side of the row (Fig. 11). Standard deviations calculated between the compartments of the same cross-section (Fig. 11) revealed that the highest deposition variability was observed for the pneumatic arch sprayer passing every 4 rows on the proximal row, followed by the distal side of the row for the same spray pattern, both in real vines and at EvaSprayViti testing facility.

The second part of the two-way ANOVA test performed showed that there was a significant difference in the mean deposit observed between the four spray techniques (*p-value* = 0.019 > 0.05) (data not shown). Tukey's test showed that the rankings of the different spray configurations tested at the EvaSprayViti testing facility and in the real vineyard were equivalent, which underlines the suitability of the artificial canopy to assess the quality of spray applications for grapevine crops with similar cultural practices to those tested (Fig. 11). This second test demonstrated the relative similarity in the quantitative and qualitative deposition values between both the artificial or natural vegetation on a full growth stage, with contrasted spraying configurations. Such a comparison was then extended to two additional crop stages.

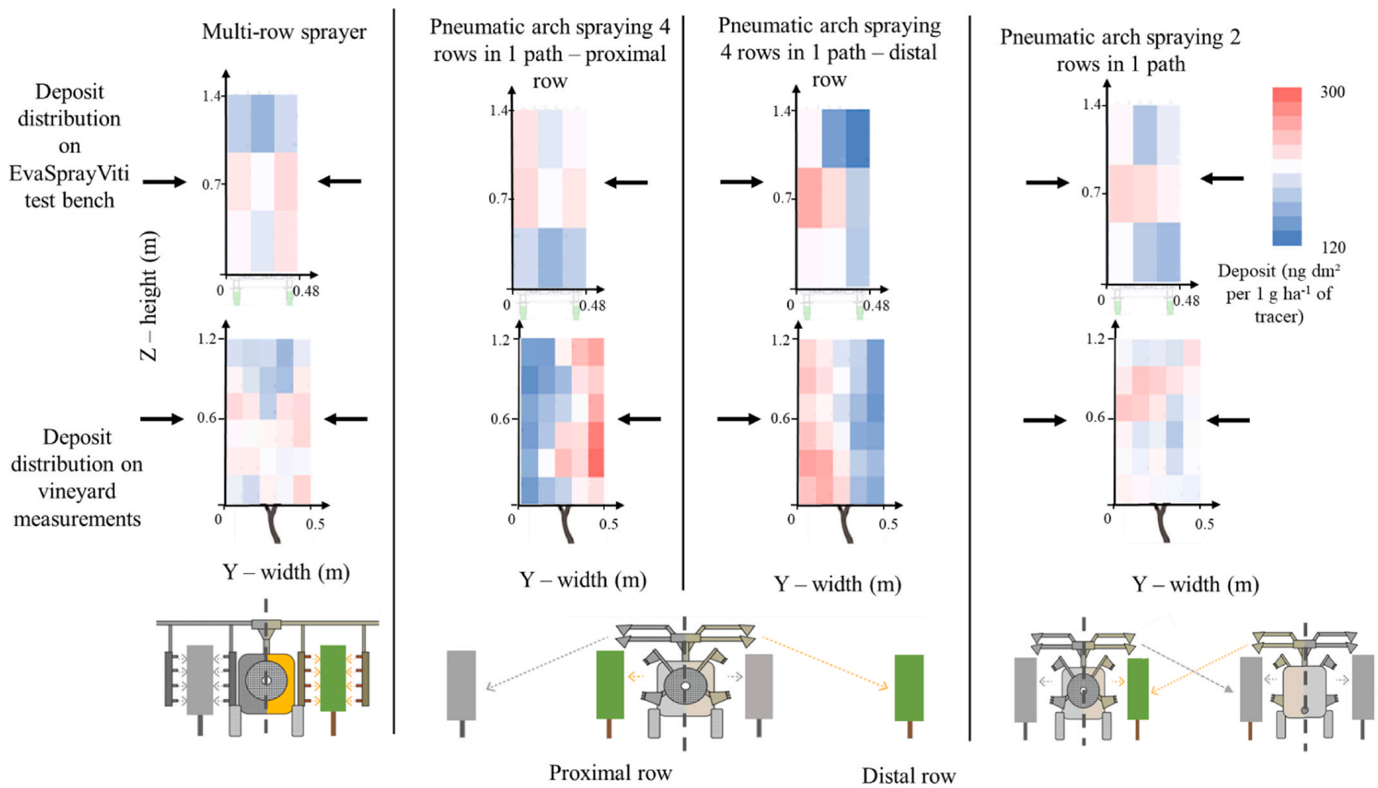

Fig. 10. Spray deposits profiles in the (*y,z*) plane (canopy cross-section) from four different spraying configurations as measured at the EvaSprayViti testing facility (upper row) and in a vineyard (lower row) at a full growth stage. Units are in ng dm^2 per 1 g ha^{-1} of tracers. The lower part of the Figure illustrates the corresponding spray modality. Schematics and graphs have the same orientation; the left of the test facility on the schematic (green) corresponds to the left of the related graph (low *y* values). The value selected for the divergence of the colour scale is 16 ng dm^2 for 1 g ha^{-1}. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

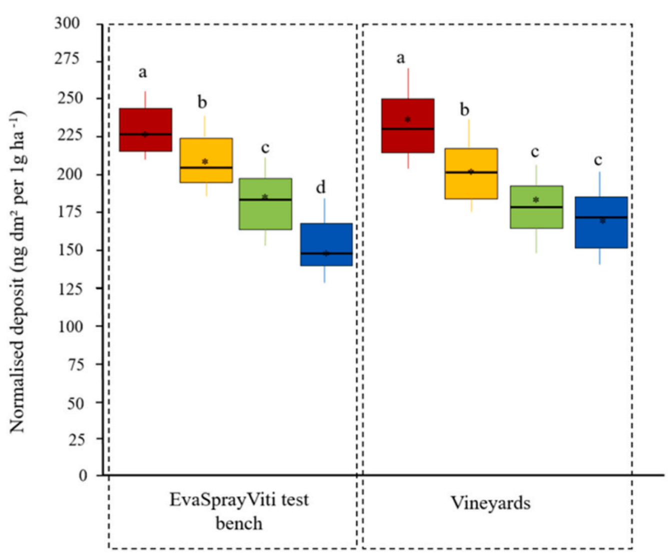

Fig. 11. Box plots of the mean deposits calculated between the compartments measured in vineyards and at the EvaSprayViti testing facility at full growth stage for the four spraying techniques considered: Multi-row sprayer (red), pneumatic arch passing every 2 rows (orange), pneumatic arch passing every 4 rows on the proximal (green) and distal (blue) canopy. The box plot shows the median (solid line) and mean (cross). The different letters above the box plots represent significant differences between the different spray types (Tukey's test, $\alpha < 0.05$) in terms of intercepted spray deposit within settings. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.3. Comparison of deposit measurements on the artificial canopy and a vineyard at various growth stages

The same sprayer (multi-row sprayer 1) was used both at the EvaSprayViti testing facility at three growth stages and in a real vineyard three times during the growing season. Fig. 12 presents the evolution of spray deposition along the season in both situations. Starting from the early stage of canopy development, the mean amount of deposition was 790 and 820 ng dm^2, then 320 and 350 ng dm^2 and finally 190 and 220 ng dm^2 for the real vineyard and EvaSprayViti respectively. The results show a clear decrease of the deposits per unit of the leaf surface along the growing season (*p-value* <0.05), in line with previous observations (Siegfried et al., 2007), directly correlated to the increase of the leaf area index under a constant dosage that results in the same amount of product being applied to a larger target area. Furthermore, increasing vegetation development creates physical obstructions that induces lower deposits inside the canopy, with a logical increase in the deposition variability between compartments.

A similar trend was observed on the EvaSprayViti artificial canopy with the proposed configurations that emulate three different growth stages of vineyards. According to Fig. 12, mean deposits at the EvaSprayViti testing facility and in the vineyard were not significantly different at any given stage. The discrepancy in mean deposition between the two targets was lower than 5% for the three growth stages. For the early growth stage, the higher variability can be explained by the uneven nature of the foliage at this time, resulting in highly variable deposits.

Results from experiment 3 highlighted the fact that the different EvaSprayViti artificial canopy configurations were able to mimic the evolution of deposits along the growing season. This result paves the way to the evaluation of the performance of a greater number of sprayers

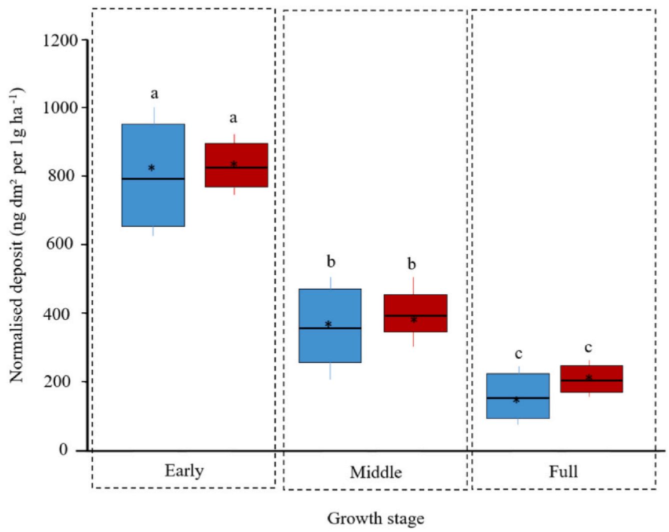

Fig. 12. Box plots for the evolution of the mean deposition as a function of three growth stages of a vineyard (blue pattern) and the configurations of the EvaSprayViti facility (red pattern) to simulate the same growth stages for the multi-row sprayer 1. The different letters above the column indicate that for a given phenological stage, the real vine and EvaSprayViti facility modalities are significantly (Tukey's test, $\alpha = 0.05$) different in terms of intercepted mean spray deposit. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

at early growth stages, which is very difficult to do on real vegetation because of the rapid development of the vine at the start of the growing season.

3.4. EvaSprayViti test bench's ability to differentiate 65 spraying configurations based on treatment quality at full growth stage

The capability of EvaSprayViti testing facility to assess and rank a larger number of spraying configurations in terms of quantitative and qualitative deposition was studied through a principal component analysis (PCA) that considered the mean deposition per compartment (Fig. 13). The PCA analysis was performed on measurements from 65 different spray scenarios on the full growth stage configuration of the EvaSprayViti artificial canopy. The first two principle components (PC) accounted for 82.6% of the total variance. The 65 tested scenarios were clearly split into three groups (Fig. 13A). The distinction between these three groups is illustrated by three confidence ellipses (CI = 99%) around the barycentre of each category. Group 1, located in the bottom left of the PC1 vs PC2 plot, enclosed by a green ellipse, included all multi-row sprayers, whether they were equipped with recovery panels or not. Group 2 in the top left, enclosed by an orange ellipse, included the pneumatic arches tested. Group 3 on the right, enclosed by a red ellipse, represented airblast sprayers. These three sprayer configurations are known for their contrasting performance in the field (Bastianelli et al., 2017; Codis et al., 2018) and the deposition patterning in the EvaSprayViti facility was clearly able to delineated these groupings. The PC1 split the airblast sprayers from the other two sprayer types (multi-row and pneumatic), while PC2 was able to distinguish the multi-row and pneumatic depositions.

Fig. 13B shows the vectors within the PC plot associated with deposition within the nine compartments sampled spatially in the EvaSprayViti facility. The PC1 divides along the deposition on the right (*RH/RM/RL*) and left (*LM/LH/LL*) sides of the canopy, effectively identifying sprays that only effectively treat only one side of the canopy (i.e. airblast sprayers).

PC2 distinguishes scenarios according to the symmetrical deposition observed in the canopy, with multi-row spray configurations generating more uniform distributions in the different compartments (Figs. 11 and 12) compared to the pneumatic sprayers, a problem that has been highlighted previously by Codis et al. (2015). This is because pneumatic sprayers used every 4 rows only allow direct treatment of one side of the row, leading to more variable deposits, especially on the unexposed side. The vectors show that the depositions into the centre of the canopy (MM) and the lower right (RL) compartment are particularly different between the two groups (multi-row and pneumatic sprayers).

These results conform with expectations and demonstrate that the EvaSprayViti test bench was able to distinguish spray application methods known to perform differently regarding the quality of the treatment (Codis et al., 2015), which is what was expected from the design of the bench. Results also highlighted that the deposit variations caused by sprayer setting is of lower importance than those resulting from the sprayer technology and configuration.

4. Conclusions

A test bench with a regularly organised artificial canopy was designed to measure the deposits of viticulture sprayers in standardised conditions. Three configurations of the test bench were proposed to mimic three growth stages (early, medium and full growth stages) of a trellis vineyard with 2.5 m row spacing and assess the performance of the sprayers over the vegetative cycle.

The exhaustive sampling of the collectors in the artificial canopy showed that the deposits present patterns without edge effects in the centre of the measurement section. The repeatability and reproducibility of the deposit values in the centre of the collection area along the driving direction was established and was used to define a relevant sampling of

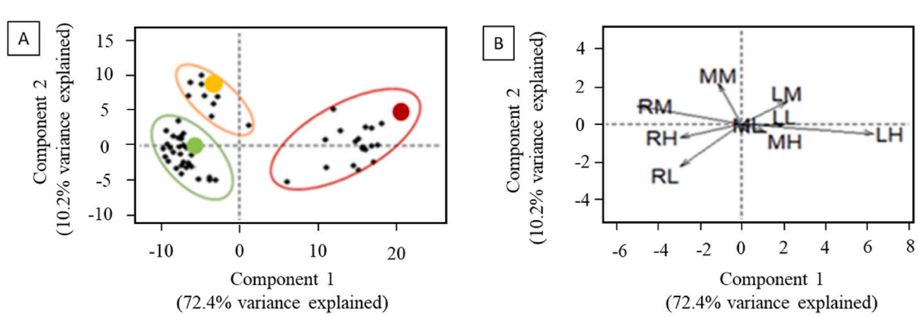

Fig. 13. Principal Component Analysis (PCA), A: bi-plot for the first two principal components: PC1 vs. PC2, which explains 82.6% of variance in the PCA analysis of sprayer configurations, tested using the EvaSprayViti test bench. Green, orange and red ellipses respectively represent groupings associated with the multi-row sprayers, pneumatic arch sprayers and airblast sprayers tested. The confidence ellipses define the region that contains 99% of all samples that can be drawn from the underlying Gaussian distribution. B: Vectors associated with variability in depositions in the nine measured compartments, highlighting spatial differences in deposition in the canopy associated with the first two PCS. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the collectors. The pattern of the deposits along the vertical (z) and transverse (y) axes was greatly dependent on both the sprayer model and settings, and was similar to the patterns observed on real vine vegetation. Trials demonstrated the capability of the regular pattern of the artificial canopy of the test bench to collect the spray in a way that allows to build interpretations that are consistent with the ones that can be made when experimenting in real vineyards.

The measurement of deposits at a reduced resolution by a grouping into nine compartments offered a good compromise between the quantity of measurements and the capability to discriminate the quality of the spray application. Of course, this collection strategy also drastically reduced the amount of chemical analysis to perform, which offers the benefit of increasing the number of trials that the same workforce can perform at the cost of reduced spatial resolution. The EvaSprayViti test bench presents the advantage of a well-defined spatial distribution of targets, which facilitates the comparative assessment of different spraying devices and settings, and its reproducibility. The reduced variability also reduces the amount of trials required to identify significant effects on spray application quality. As deposits observed on the test bench were similar to the one observed in vineyards, this test bench can be used to rank application techniques with confidence in the representativeness of the results.

Funding

This project has received funding from the French National Agency for Biodiversity (OFB) as part of the national Ecophyto plan (ECOSPRAYVITI-PULVEPERF-LABELPULVE-projects). This work was supported by the French National Research Agency under the Investments for the Future Program, referred to as ANR-16-CONV-0004.

CRediT authorship contribution statement

A. Cheraiet: Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **S. Codis:** Funding acquisition, Methodology, Formal analysis, Project administration, Supervision. **A. Lienard:** Data curation, Methodology. **A. Vergès:** Formal analysis, Funding acquisition, Methodology. **M. Carra:** Funding acquisition, Methodology. **D. Bastidon:** Funding acquisition. **J.F. Bonicel:** Funding acquisition. **X. Delpuech:** Formal analysis, Methodology. **X. Ribeyrolles:** Funding acquisition. **J.P. Douzals:** Methodology, Writing – review & editing. **F. Lebeau:** Writing – original draft. **J.A. Taylor:** Writing – review & editing. **O. Naud:** Conceptualization, Investigation, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

C. Auvergne (Departmental Agricultural Council, Gard, France) and R. Cavalier (Departmental Agricultural Council, Hérault, France) are gratefully acknowledged for their help. The authors would also like to thank all the sprayer manufacturers involved (Tecnoma, Calvet, Berthoud, Dhughes, Bertoni, Friuli, Nicolas).

References

Bastianelli, M., Rudnicki, V. D., Codis, S., Ribeyrolles, X., & Naud, O. (2017). Two vegetation indicators from 2D ground Lidar scanner compared for predicting spraying deposits on grapevine. In *Proceedings of the 2017 EFITA WCCA conference* (pp. 153–154). Montpellier, France.

Catania, P., Inglese, P., Pipitone, F., & Vallone, M. (2011). Assessment of the wind influence on spray application using an artificial vineyard. *European Journal of Horticultural Science, 76*(3), 102–108.

Cheraiet, A., Naud, O., Carra, M., Codis, S., Lebeau, F., & Taylor, J. (2021). Predicting the site-specific distribution of agrochemical spray deposition in vineyards at multiple phenological stages using 2D LiDAR-based primary canopy attributes. *Computers and Electronics in Agriculture, 189*. https://doi.org/10.1016/j.compag.2021.106402

Codis, S., Carra, M., Delpuech, X., Montegano, P., Nicot, H., Ruelle, B., Ribeyrolles, X., Savajols, B., Vergès, A., & Naud, O. (2018). Dataset of spray deposit distribution in vine canopy for two contrasted performance sprayers during a vegetative cycle associated with crop indicators (LWA and TRV). *Data in Brief, 18*, 415–421. https://doi.org/10.1016/j.dib.2018.02.012

Codis, S., Verges, A., Auvergne, C., Bonicel, J. F., Diouloufet, G., Cavalier, R., Douzals, J. P., Magnier, J., Montegano, P., Ribeyrolles, X., & Ruelle, B. (2015). Optimization of early growth stage treatments of the vine: Experimentations on the artificial vine EvaSprayViti. In *Proceeding of SUPROFRUIT 2015 - 13th Workshop on spray application in fruit growing* (pp. 47–48), 15-18 July 2015, Lindau - DE.

Dekeyser, D., Foqué, D., Duga, A. T., Verboven, P., Hendrickx, N., & Nuyttens, D. (2014). Spray deposition assessment using different application techniques in artificial orchard trees. *Crop Protection, 64*, 187–197. https://doi.org/10.1016/j.cropro.2014.06.008

Duga, A. T., Ruysen, K., Dekeyser, D., Nuyttens, D., Bylemans, D., Nicolai, B. M., & Verboven, P. (2015). Spray deposition profiles in pome fruit trees: Effects of sprayer design, training system and tree canopy characteristics. *Crop Protection, 67*, 200–213. https://doi.org/10.1016/j.cropro.2014.10.016

EPPO. (2016). Workshop on harmonized dose expression for the zonal evaluation of plant protection products in high growing crops. *Austrian Agency for Health and Food Safety (AGES): Vienna, Austria*, 2016 https://www.eppo.int/MEETINGS/2016_meetings/wk_dose_expression. (Accessed 26 October 2020).

Forster, W. A., Gaskin, R. E., Strand, T. M., Manktelow, D. W. L., & Van Leeuwen, R. M. (2014). Effect of target wettability on spray droplet adhesion, retention, spreading and coverage: Artificial collectors versus plant surfaces. *New Zealand Plant Protection, 67*, 284–291. https://doi.org/10.30843/nzpp.2014.67.5727

Garcerá, C., Doruchowski, G., & Chueca, P. (2021). Harmonization of plant protection products dose expression and dose adjustment for high growing 3D crops: A review. *Crop Protection, 140*. https://doi.org/10.1016/j.cropro.2020.105417

Gil, E., Salcedo, R., Soler, A., Ortega, P., Llop, J., Campos, J., & Oliva, J. (2021). Relative efficiencies of experimental and conventional foliar sprayers and assessment of optimal LWA spray volumes in trellised wine grapes. *Pest Management Science, 77*(5), 2462–2476. https://doi.org/10.1002/ps.6276

Gil, Y., Sinfort, C., Brunet, Y., Polveche, V., & Bonicelli, B. (2007). Atmospheric loss of pesticides above an artificial vineyard during air-assisted spraying. *Atmospheric Environment, 41*(14), 2945–2957. https://doi.org/10.1016/j.atmosenv.2006.12.019

Giles, D. K., & Downey, D. (2003). Quality control verification and mapping for chemical application. *Precision Agriculture, 4*(1), 103–124. https://doi.org/10.1007/s11119-010-9171-8

Grella, M., Marucco, P., Oggero, G., Manzone, M., Gioelli, F. S., & Balsari, P. (2022). Environmental evaluation of vineyard airblast sprayers through a comprehensive spray mass-balance approach. In M. Biocca, E. Cavallo, M. Cecchini, S. Failla, & E. Romano (Eds.), *Safety, health and welfare in agriculture and agro-food systems. SHWA 2020. Lecture notes in civil engineering* (Vol. 252, pp. 383–393). Cham, Switzerland: Springer.

Grella, M., Miranda-Fuentes, A., Marucco, P., & Balsari, P. (2020). Field assessment of a newly-designed pneumatic spout to contain spray drift in vineyards: Evaluation of canopy distribution and off-target losses. *Pest Management Science, 76*(12), 4173–4191. https://doi.org/10.1002/ps.5975

ISO. (2007). *ISO 22522 Crop protection equipment — field measurement of spray distribution in tree and bush crops*. ISO Stand.

Lamichhane, J. R., Dachbrodt-Saaydeh, S., Kudsk, P., & Messéan, A. (2015). Toward a reduced reliance on conventional pesticides in European agriculture. *Plant Disease, 100*, 10–24. https://doi.org/10.1094/PDIS-05-15-0574-FE

Lê, S., Josse, J., & Husson, F. (2008). FactoMineR: an R package for multivariate analysis. *Journal of Statistical Software, 25*, 1–18. https://doi.org/10.18637/jss.v025.i01

Llorens, J., Gil, E., Llop, J., & Queraltó, M. (2011). Georeferenced LiDAR 3D vine plantation map generation. *Sensors, 11*(6), 6237–6256. https://doi.org/10.3390/s110606237

Lorenz, D. H., Eichorn, K. W., Bleiholder, H., Klose, U., Meier, U., & Weber, E. (1994). Phänologische entwicklungsstadien der Weinrebe (Vitis vinifera L. spp. vinifera). (Phenological stages of grapevine (Vitis vinifera L. spp. vinifera)). *Viticultural and Enological Science, 49*, 66–70.

McCoy, M. L., Hoheisel, G. A., Khot, L. R., & Moyer, M. M. (2021). Assessment of three commercial over-the-row sprayer technologies in Eastern Washington vineyards. *American Journal of Enology and Viticulture, 72*(3), 217–229. https://doi.org/10.5344/ajev.2021.20058

Merot, A., & Smits, N. (2020). Does conversion to organic farming impact vineyards yield? A diachronic study in southeastern France. *Agronomy, 10*(11). https://doi.org/10.3390/agronomy10111626

Michael, C., Gil, E., Gallart, M., & Stavrinides, M. C. (2020). Influence of spray technology and application rate on leaf deposit and ground losses in mountain viticulture. *Agriculture, 10*(12). https://doi.org/10.3390/agriculture10120615

Naud, O., Vergès, A., Hebrard, O., Codis, S., Douzals, J. P., & Ruelle, B. (2014). Comparative assessment of agro-environmental performance of vineyard sprayers using a physical full-scale model of a vineyard row. In *Proceedings of the AgEng 2014* (pp. 1–7). Switzerland: Zurich. https://doi.org/10.13140/2.1.3509.4402.

Neuwirth, E. (2014). RColorBrewer: ColorBrewer palettes. *R package version, 1*, 1–2.

Nieder, R., Benbi, D. K., & Reichl, F. X. (2018). Health risks associated with pesticides in soils. In *Soil components and human health*. Dordrecht: Springer. https://doi.org/10.1007/978-94-024-1222-2_10.

OIV. (2019). *Statistical report on world vitiviniculture*. Paris, France: International Organisation of Vine and Wine. https://www.oiv.int/public/medias/6782/oiv-2019-statistical-report-on-world-vitiviniculture.pdf.

Ortega, P., Salcedo, R., Sánchez, E., & Gil, E. (2023). Biopesticides as alternatives to reduce the use of copper in Spanish and Portuguese viticulture: Main trends in adoption. *European Journal of Agronomy, 151*. https://doi.org/10.1016/j.eja.2023.126996

Pascuzzi, S., Cerruto, E., & Manetto, G. (2017). Foliar spray deposition in a 'tendone' vineyard as affected by airflow rate, volume rate and vegetative development. *Crop Protection, 91*, 34–48. https://doi.org/10.1016/j.cropro.2016.09.009

Pergher, G., Gubiani, R., Cividino, S. R., Dell'Antonia, D., & Lagazio, C. (2013). Assessment of spray deposition and recycling rate in the vineyard from a new type of air-assisted tunnel sprayer. *Crop Protection, 45*, 6–14. https://doi.org/10.1016/j.cropro.2012.11.021

Pergher, G., Gubiani, R., & Tonetto, G. (1997). Foliar deposition and pesticide losses from three air-assisted sprayers in a hedgerow vineyard. *Crop Protection, 16*(1), 25–33. https://doi.org/10.1016/S0261-2194(96)00054-3

Pergher, G., & Petris, R. (2007). Canopy structure and deposition efficiency of vineyard sprayers. *Journal of Agricultural Engineering, 38*(2), 31–38. https://doi.org/10.4081/jae.2007.2.31

Pertot, I., Caffi, T., Rossi, V., Mugnai, L., Hoffmann, C., Grando, M. S., Gary, C., Lafond, D., Duso, C., Thiery, D., Mazzoni, V., & Anfora, G. (2017). A critical review of plant protection tools for reducing pesticide use on grapevine and new perspectives for the implementation of IPM in viticulture. *Crop Protection, 97*, 70–84. https://doi.org/10.1016/j.cropro.2016.11.025

Planas, S., Román, C., Sanz, R., & Rosell-Polo, J. R. (2022). Bases for pesticide dose expression and adjustment in 3D crops and comparison of decision support systems. *Science of the Total Environment, 806*. https://doi.org/10.1016/j.scitotenv.2021.150357

Rcore Team. (2022). R: A language and environment for statistical computing. https://www.r-project.org.

Roux, P., Herbst, A., Richardson, G., & Delpech, P. (2006). Full-scale measurement of spray-drift from a vineyard sprayer in a controlled wind-tunnel environment. *Journal of Wind Engineering and Industrial Aerodynamics, 94*(1), 1–17.

Salcedo, R., Llop, J., Campos, J., Michael, C., Gallart, M., Ortega, P., & Gil, E. (2020). Evaluation of leaf deposit quality between electrostatic and conventional multi-row sprayers in a trellised vineyard. *Crop Protection, 127*. https://doi.org/10.1016/j.cropro.2019.104964

Siegfried, W., Viret, O., Huber, B., & Wohlhauser, R. (2007). Dosage of plant protection products adapted to leaf area index in viticulture. *Crop Protection, 26*(2), 73–82. https://doi.org/10.1016/j.cropro.2006.04.002

Weiss, M., & Baret, F. (2017). Using 3D point clouds derived from UAV RGB imagery to describe vineyard 3D macro-structure. *Remote Sensing, 9*(2), 17. https://doi.org/10.3390/rs9020111

Wickham, H. (2016). Data analysis. In *ggplot2. Use R*. Cham: Springer. https://doi.org/10.1007/978-3-319-24277-4_9.