Simulation of pesticide application in vineyards using CFD: study of drift and treatment optimization

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Summary

Computational Fluid Dynamics (CFD) has been used to simulate the application of pesticides on a vineyard by using an air-assisted sprayer. The selected sprayer, inverted u-shaped, consisted of vertical ducts, facing the crop hedge, through which the air generated by a turbine came out, transporting the pulverized drops until its deposition on the crop. Considering this air-assisted sprayer, CFD modelling has been used to develop a dispersed model including both, liquid and air phases, with the goal of analysing the effects of the main setting parameters of the sprayer: liquid flow, droplet size, air flow and forward speed. The dispersed phase has been added to the model according to a Rossin-Rammler distribution. Once the CFD models have been obtained, the percentage of simulated drops that have reached the crop and those that have impacted the soil have been accounted. Finally, optimum theoretical treatment configuration and the influence of each variable studied have been discussed.

Key words: CFD – Computational Fluid Dynamics, vineyard, air assistance, viticulture

Introduction

The application of pesticides in agriculture is essential, but its use involves environmental risks [1]. It is important to maximize the effectiveness of the treatment, reducing doses as much as possible and being environmentally friendly. In fruit orchards, pesticides are generally applied by air-assisted sprayers, which generate air currents that drag the drops towards the crop and, additionally, facilitates the penetration of the product into the crop. The efficiency of the treatment depends on many factors: sprayer type, spray nozzle, air flow rate, forward speed, phenological state of the crop, crop and orchard geometry, wind velocity, temperature, relative humidity, etc. In addition, the results of the application are also affected by the turbulence created by the sprayer itself [2].

Therefore, only a part of the product sprayed by the nozzles successfully reaches the crop. Focusing on vineyard cultivation, the tests carried out to date show a large disparity in deposition percentages: an experimental study with an axial fan sprayer [3] indicated drift losses between 30 and 50 %; Porras et al., [4] developed a research with several types of sprayers, including a tunnel type (similar to the one to be studied here), obtaining a range of 10 to 80 % leaf coverage with different pressures; [5, 6] performed its experiments on several types of vineyard formations, finding a coverage between 50 and 80%. Another study [7], with an experimental design of a tunnel-type sprayer with a recycler (device that captures drops not caught by the crop and sprays them again) indicated a maximum efficiency of 50%, even with this sophisticated machine. Similar results have been obtained in apple orchards [8] with ranges of efficiency according to the conditions under which the treatment is carried out, from 8.5 to 65.8%; losses due to air drift up to 25.8% and losses to the ground between 21.2 and 47.8%.

Considering that real experiments are costly both in time and money, and are not repetitive because the results depends on atmospheric variables, the use of computers to perform simulations of treatments is a useful tool. On the one hand, mathematical models [9, 10, 11] have been developed to predict the results of the treatment by solving complex mathematical models developed and calibrated for specific conditions. On the other hand, more recently, the increase in computing power of PC, has allowed developing approaches from Computational Fluid Dynamics (CFD), which allows a more general and flexible study, being able to adapt to any type of sprayer. Air currents generated by different types of sprayers can be simulated [12, 13,14]. However the simultaneous study of the liquid phase (pulverized droplets) and the gas phase (air currents) is more complex, [15, 16, 17, 18]. And it is even more difficult to study their interaction with the crop [8].

This work aims to apply the CFD modelling to simulate the performance of an air-assisted sprayer of inverted u-shaped geometry by developing a dispersed model including both, liquid and air phases, with the goal of analysing the effects of the main setting parameters of the sprayer: liquid flow, droplet size, air flow and forward speed

Material and methods

Sprayer description

The analysed sprayer is a tunnel multi-row air-assisted sprayer, inverted u-shaped, adapted to the line geometry of a vineyard (Figure 1). A detailed description of the machine is found in [19].

Figure 1: Multi-row air-assisted sprayer adapted to the vineyard geometry. The centrifugal turbine directs the air flow to four vertical ducts (left), each having four air-liquid outlet groups, parallel to the sides of the vineyard line. Each air-liquid outlet group consists of two hydraulic nozzles and four air outlets (right).

CFD Model

As explained in [19], a two-stage experimentally validated model has been developed. In the first stage, the geometry of the sprayer ducts is modelled, and the average air velocity at the inlet of each duct is entered into the CFD program, obtaining its distribution in the air outlets. In this calculation stage, a computer file with x,y,z coordinates of each vertex of the cells with output contour condition, associated to an air velocity vector, is obtained for each duct.

It is in the second stage of calculation, with a very simple geometry (Figure 2) where the treatment settings can be configured. Basically, this model consists of an orthohedron that represents the space between the two ducts that enclose a vine row, with a hole in the middle, which represents the canopy of the vineyard. The model has just over 300,000 cells and they are mostly cubic, which allows a quick calculation [19]. CFD models develop in vineyards [20] concluded that the canopy, in advanced vegetative state, could be represented as a porous medium with a high coefficient of resistance. Previous models [20] have concluded that the resistance coefficient causes in the CFD model, both in the air currents and in the pulverized droplets, a behaviour very similar to that of a wall, so for simplicity, a hole has been adopted directly in the model that simulates a wall. The model is completed with surfaces on the sides, which represent the air intake of the first calculation stage.

The model was developed with ANSYS Fluent, adopting a k-ε turbulence model, in second order with the SIMPLE algorithm.

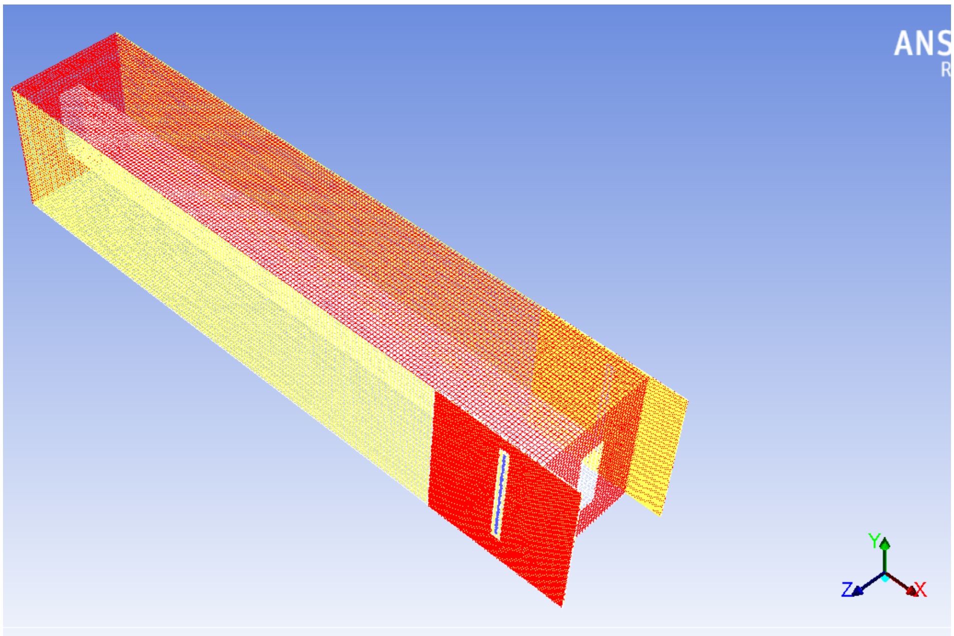

Figure 2: Calculation mesh in the CFD program.

Disperse phase

Although droplet modelling is part of the CFD model, some aspects should be explained as introduction. A Lagrangian method has been used to model the droplets: the DPM (Discrete Phase Model). This model introduces in the calculation some "model droplets" from which the software extrapolates the behavior of all the sprayed liquid. The number of simulated droplets must be sufficient to be representative, so it is recommended to make a sensibility study of the results obtained according to the number of droplets introduced into the model [13]. FLUENT has several possibilities to model nozzles. In our case, we have opted for the hollow cone type commonly used in air-assisted sprayers. The software does not model a continuous cone, but a series of paths along the surface of a cone. In our case we have introduced 64 trajectories by nozzle, each one of them with 20 diameters established according to a Rossin-Rammler distribution, which multiplied by 16 nozzles (8 by duct) gives a total of 20480 droplets, which are introduced in an instant of the calculation. The modelling of hollow cone nozzles in FLUENT requires that they must be defined at a given point in the space, which cannot be moved. In our model, which is transitory, and with moving parts (the sprayer advances in the field), this causes a problem, since if the droplets are injected into the model at the initial instant, the result will not be correct because the convergence of the gas phase of the CFD problem has not yet been reached. This has been solved by leaving some initial calculation iterations (in our case 50 "time steps") giving time to the software to allow the solution to reach tolerable convergence values while the machine in the model is moving, and positioning the nozzles to ensure their alignment injection point.

Variables

Three setting parameters of the sprayer have been studied:

- Type of nozzle: Three medium droplet sizes have been simulated: 150, 250 and 350 µm, with a Rossin-Rammler distribution of 20 droplet types, sprayed by hollow cone nozzles.
- Air flow supplied by the machine: Air velocities of 14, 18, 22, 26 and 30 m/s at the upper end of the duct have been considered. These values are only entered in stage 1 of the model [19]. These velocity values correspond to air flows of 670, 860, 1050, 1245 and 1435 m^3/h for each vertical duct.

- Forward speed: 4.5, 6 and 7.5 km/h. This speed is implemented in the stage 2 of the model by indicating the "sliding meshes" in FLUENT.

The developed model (Figure 3) aims to approach as simply as possible how the most important variables that can be controlled on a vine row in an advanced vegetative state influence the efficiency of the treatment. Neither the evaporation of the drops due to the effect of temperature, nor their break-up into smaller ones, nor possible coalescence, nor wind, have been taken into account, although all these variables could be introduced into the model for more precise studies if needed. Therefore, it must be said that as a simplified model, it is not intended to have an exact model of the spraying phenomenon under perfectly determined conditions, but to identify trends. A total of 45 simulations were carried out in a few hours of calculation (between 1 hour and 1.5 hours per simulation), providing data such as the place of impact of each simulated droplet, the nozzle from which it was sprayed and the time required to deposit it, something unthinkable to obtain experimentally in such a relatively short period of time. This information is supplied by FLUENT software in text files, in which each line contains the information of each droplet, so they can be easily imported and treated with a spreadsheet.

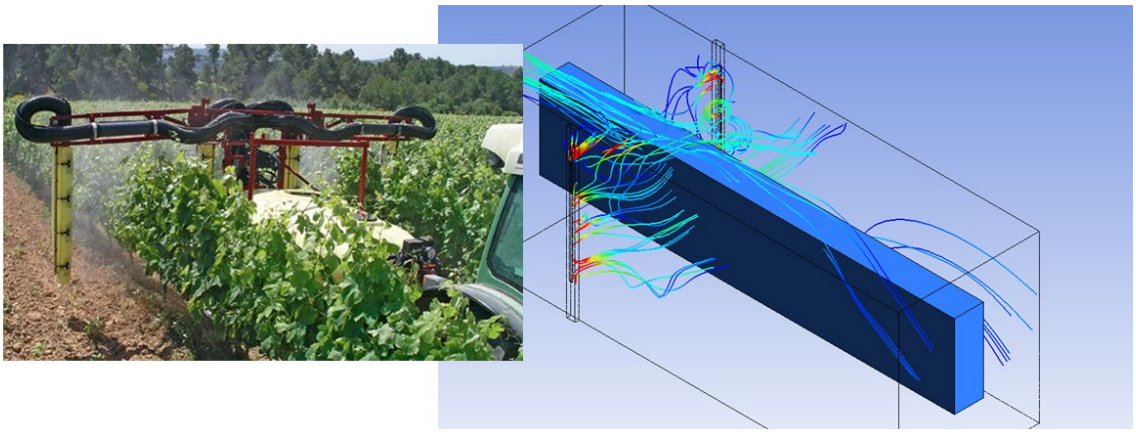

Figure 3: Left: Sprayer treating two vine rows at the same time. Right: CFD simulation of the treatment on a vine row line, representing the main current lines coming out of the machine ducts.

Results and discussion

Figure 4 shows the percentage of liquid pulverized that reaches the vineyard in each one of the simulations carried out with respect to the air velocity at the nozzle’s outlet. There is a positive correlation between efficiency and air velocity, especially if each nozzle and forward speed are considered separately.

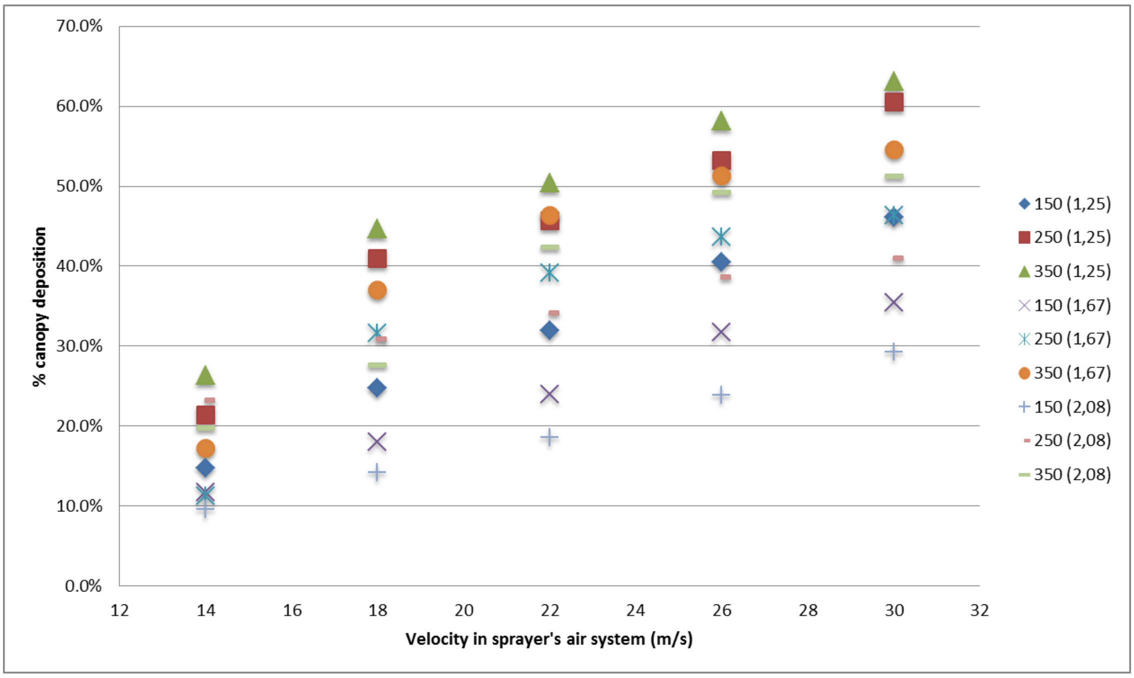

Figure 4: Percentage of sprayed liquid that theoretically reaches the vineyard in the models, according to the air speed (air flow) supplied by the sprayer. Each treatment distinguishes the average diameter of the pulverized particle (150, 250 or 350 µm) and the forward speed (1.25, 1.67 or 2.08 m/s).

Additional conclusions can be obtained from Figure 4, such as larger droplet sizes are more efficient than smaller diameters, and that treatments at lower forward speeds are more efficient than those made at high speeds.

The theoretical efficiency obtained ranged from 10 % to more than 60 %, a very wide range but in line with other authors [3, 4, 5, 8]. It should be noted that in reality, it can be expected that the efficiency is even lower, since in the model is computed every droplet that impacts with the vineyard, when in reality, some droplets are able to go through it without being captured by any leaf, or also, could suffer runoff.

If we otherwise represent the percentage of liquid lost in the soil (Figure 5), in this case the correlation is negative: the more air supplied by the machine, the less product is lost in the soil, which is logical because it will be more probably that thicker droplets are carried away by air currents.

A careful analysis of the results shows that the smallest losses to the ground occur with the smallest pulverized droplets and the lowest forward speed, which is expected. Less intuitive is the reason for the greater losses to the ground, which do not always correspond to the opposite of the previous case (large diameters, high speeds), since it occurs with intermediate nozzles (250 µm of average diameter, ground speed of 1.67 m/s). As a hypothesis, it is proposed that in this phenomenon the kinetic energy of the droplets would come into play, so that larger droplets could impact with the hedge while other very small ones would be at the mercy of the air currents of the sprayer. A medium size, however, would not have sufficient kinetic energy at the nozzle outlet to reach the hedge, but would be too heavy to be carried away by air currents, having none of the possibilities of larger or smaller droplets, and thus probably ending up on the ground.

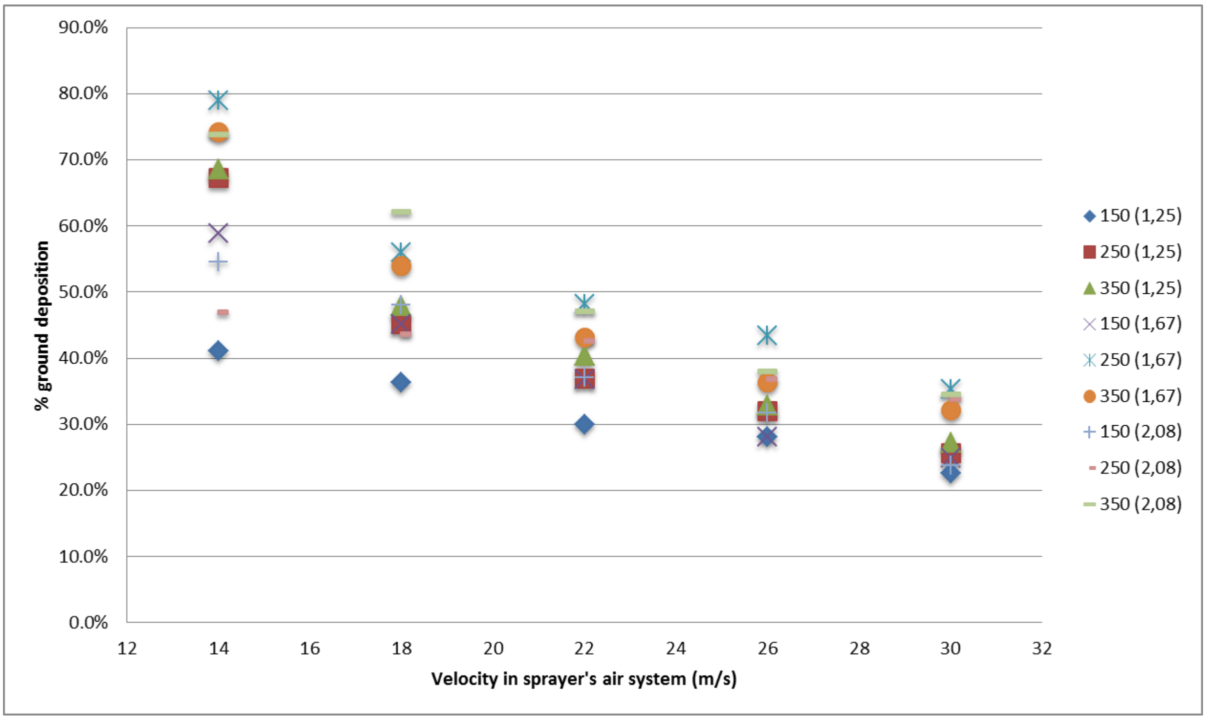

Figure 5: Percentage of sprayed liquid that is lost on the floor, depending on the flow of air supplied by the sprayer. It is represented the average diameter of sprayed particle (150, 250 or 350μm) and the forward speed (1.25, 1.67 or 2.08 m/s).

As for drift losses, it should be noted that they are calculated indirectly by subtracting from the amount of liquid sprayed those determined to have impacted the hedge and the soil. This is so because it is observed that even calculating a reasonable number of iterations in the simulation, there are always droplets (of small diameter) "floating" in the model. For this reason, "drift losses" are considered both the droplets that leave the calculation mesh by cells that are not the soil or the hedge, and those that remain inside it after about 3 seconds from spraying. The data calculated by the simulations indicate that if a droplet does not hit the hedge a few tenths of a second after being sprayed, it is unlikely to do so later. Figure 6 shows this approach is justified to not prolonging unnecessarily the calculation time of the models.

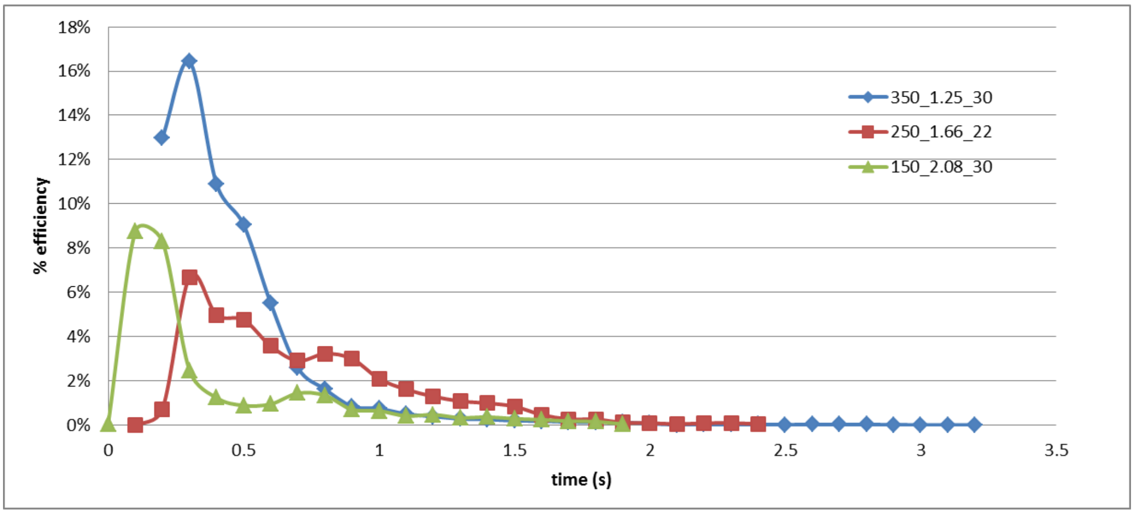

Figure 6: Percentage of liquid reached by the crop, in three different representative treatments (average droplet size-forward speed-air velocity), with respect to time. After 2 seconds, the probability that a droplet in the air reaches the crop is very low.

If we analyse the drift losses (Figure 7), there is no clear correlation, and the influence of the volume of air supplied by the machine is, contrary to what might be thought, unpredictable *a priori*. For example, treatment with nozzles of 350 μm and 1.67 m/s forward speed, tends to increase drift as the machine's airflow does, as might be expected, although very timidly; however, with the 150 µm nozzle and 1.25 m/s forward speed, the more air, the less drift loss.

The reason would be similar to the previous one, very small drops would be favoured by higher air velocities. In any case the drift is revealed as a very complex phenomenon whose response is not linear with the variables studied in the simulations.

It could also be justified by the tunnel configuration of the sprayer geometry: the air currents collide in the centre, counteracting each other. It would be the design of the sprayer itself responsible for this drift behaviour.

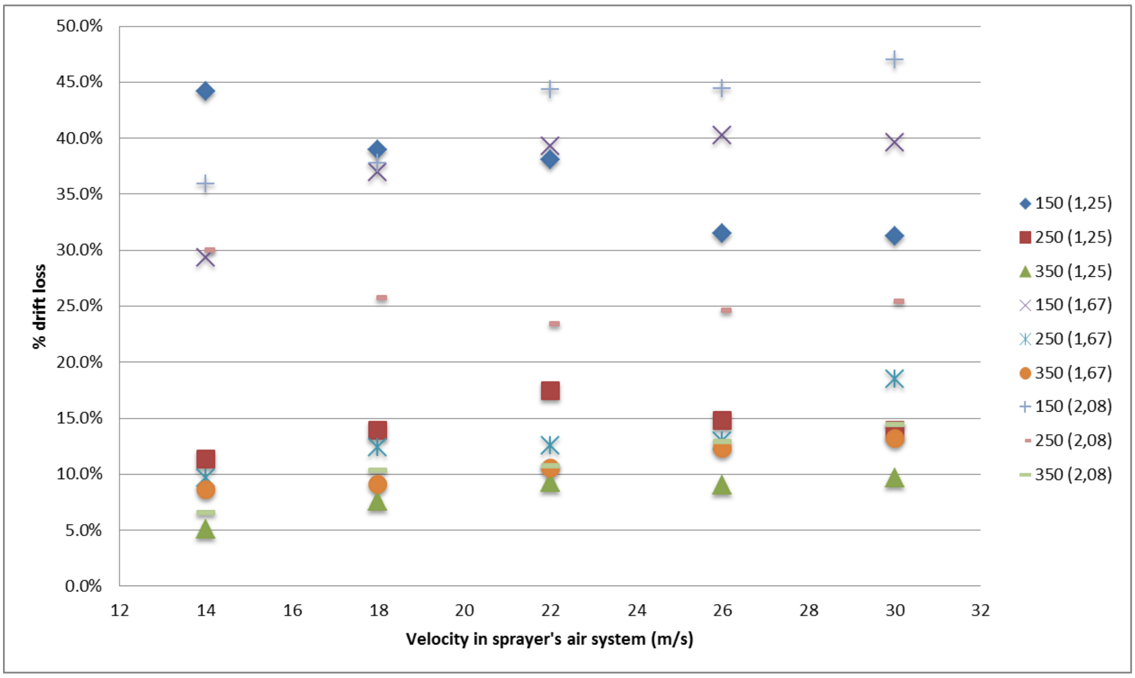

Figure 7: Percentage of sprayed liquid that is lost by drift in the models, depending on the flow of air supplied by the sprayer. The average diameter of the sprayed particle (150, 250 or 350 µm) and the forward speed (1.25, 1.67 or 2.08 m/s) are shown.

Once the results of all the simulations have been presented, if they are grouped by treatments using averages, we can obtain clearer conclusions.

If we group all treatments according to the flow of air supplied by the sprayer, distinguishing drift losses, soil losses, and the percentage of liquid reaching the crop (Figure 8), CFD models predict a positive correlation between airflow and treatment efficiency ($r^2 = 0.9574$), and a negative correlation between airflow and ground losses ($r^2 = 0.9567$). Statistically, the correlation between air flow and drift losses is also good ($r^2 = 0.8857$), but in this case the slope of the straight line is very low. It can therefore be considered that in this machine, the air flow does not influence the drift losses, but it improves the efficiency of the treatment.

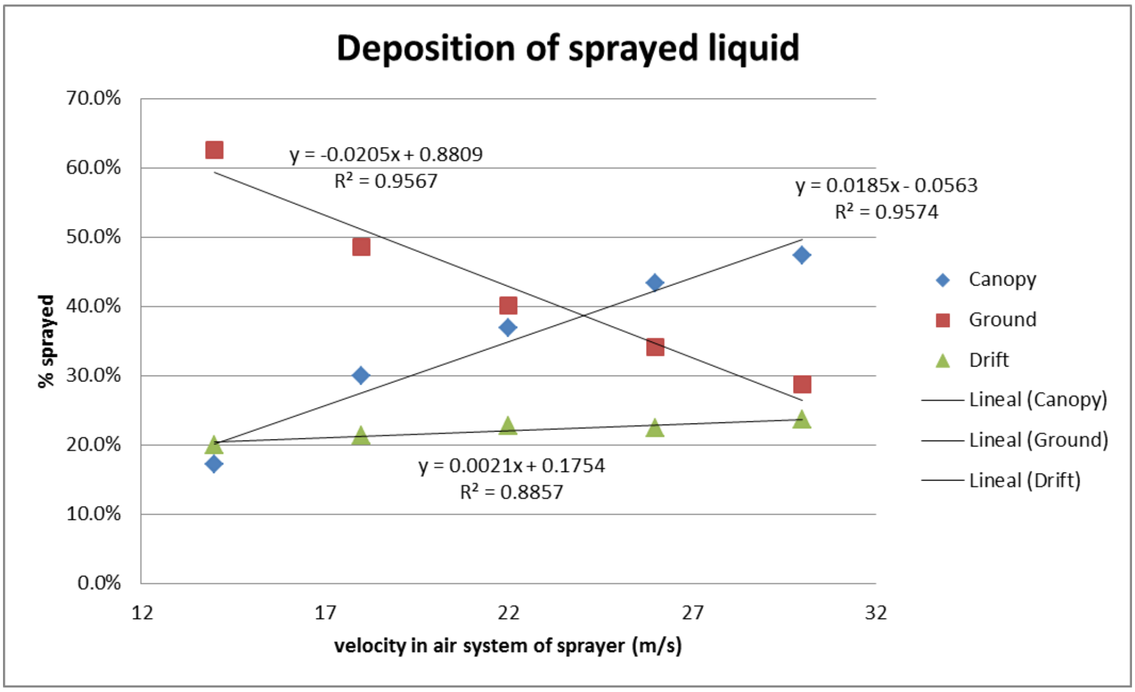

Figure 8: Correlation between air flow and liquid distribution (crop, soil and drift).

On the other hand, if we analyse the influence of the forward speed (Figure 9) on the liquid distribution, a clear negative correlation ($r^2 = 0.9325$) between treatment efficiency and forward speed is obtained. Drift losses as in the previous case would also have an acceptable statistical correlation but the slope of the straight line is modest, whereas ground losses would not be correlated with forward speed.

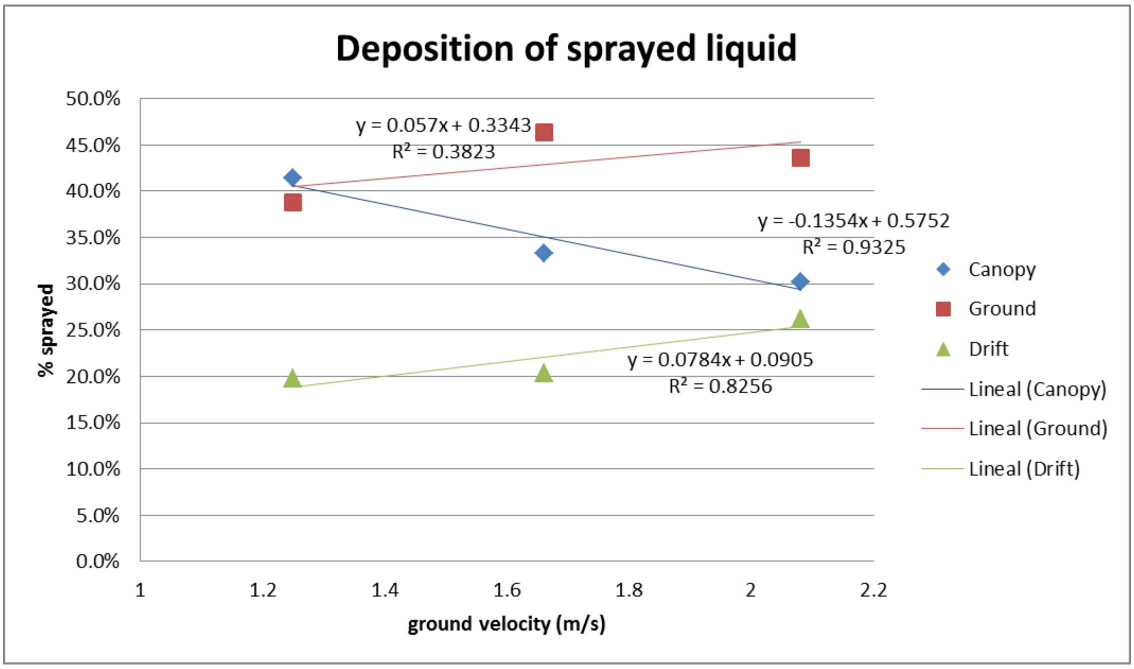

Figure 9: Correlation between forward speed and distribution of liquid (crop, soil and drift).

It should be noted that if the nozzles operate at a constant flow rate, the lower the forward speed, the greater the volume sprayed per linear metre of vine. But what Figure 9 reveals is an additional and complementary phenomenon: at a higher forward speed, not only would the volume of sprayed product per linear metre of row be reduced, but also the efficiency of the treatment decreases, with which we have a negative synergy.

Lastly, analysing the influence of the average size of the pulverized droplets (Figure 10), positive correlations are observed between drop size and (simultaneously) treatment efficiency and soil losses. In this sense, the treatment efficiency increases even though soil losses also increase, because drift losses are drastically reduced. According to the CFD models, the drift losses in the sprayer studied depend mainly on the nozzle characteristics.

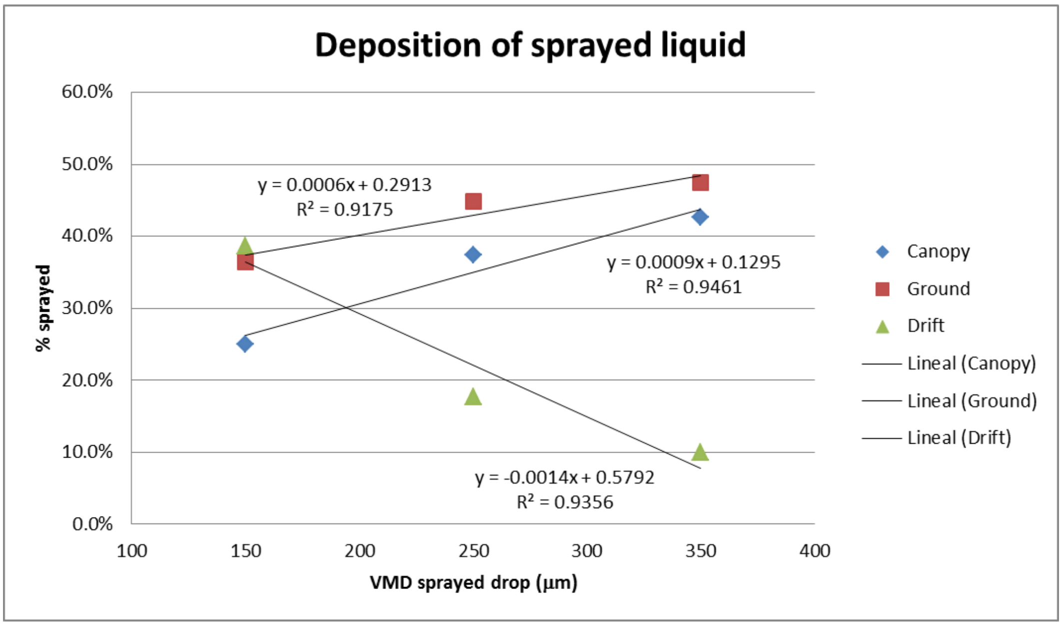

Figure 10: Correlation between mean droplet diameter and distribution of liquid (crop, soil and drift).

Other treatment improvement pathways

The CFD models performed obtain a large amount of data whose analysis can be used to improve the efficiency of treatment in other ways. For example, the amount of liquid sprayed into the crop from each nozzle can be known. If we analyse, for example, the highest efficiency simulation, which theoretically achieves a value of 63 %, and calculate the individual efficiency of the 16 nozzles, data shown in Table 1 are obtained.

Table 1: Calculated efficiency of the 16 nozzles. Settings: droplet size 350 µm, forward speed 1.25 m/s, air velocity 30 m/s.

Nozzle	Efficiency
right_nozzle_1	48%
right_nozzle_2	59%
right_nozzle_3	91%
right_nozzle_4	87%
right_nozzle_5	87%
right_nozzle_6	66%
right_nozzle_7	47%
right_nozzle_8	25%
left_nozzle_1	48%
left_nozzle_2	59%
left_nozzle_3	89%
left_nozzle_4	86%
left_nozzle_5	85%
left_nozzle_6	66%
left_nozzle_7	42%
left_nozzle_8	25%

It is quickly seen that under the proposed treatment conditions, with the dimensions of the expected vine hedge, the number 8 nozzles (the lowest position of each duct) have a very low efficiency. If we simply propose to annul them, the efficiency of the treatment raises to 69%, losing only 5% of liquid with respect to that previously reached in the crop, which would be easily compensable by decreasing the speed of displacement to 5%, if necessary. Analysing data of table 1, it could even be proposed to modify the angle of the nozzles 1, 2, 6 and 7, since their poor efficiency compared to nozzles 3, 4 and 5.

Conclusions

Simple CFD models of air-assisted sprayers performance, although do not show all the complexity of a treatment, supply useful conclusions in a short time at a lower cost compared to real experiments.

For the sprayer model studied, a wrong configuration can produce very low efficiencies. In the case of treating vineyards in an advanced vegetative state, the basic recommendations for the user would be:

- To configure the machine to provide as much air as possible.
- To perform the treatment at the lowest forward speed.
- To work with droplets as large as possible, always within the tolerable limit with the objective of the treatment.

The fight against drift, must be made mainly from the correct choice of nozzles, because in this type of machine, is the fundamental factor, not having hardly influence the flow of air, against what might be thought initially. The tunnel-type spray configuration may be responsible for this phenomenon.

Treatments carried out at high forward speeds reduce the efficiency and would have to be compensated with higher air flows.

The relative position between the nozzles and the hedge of the crop must be analysed to avoid, if necessary, inefficient nozzles. In the case of the geometry of the vineyard studied, the lower nozzle of each spray duct should be eliminated.

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