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A Laboratory System for Nozzle Spray Analysis

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Droplet spray spectrum is one of the most important factors affecting the biological efficacy of a phytosanitary treatment and water sensitive papers (WSP) are one of the most widely used tools to asses spray coverage. Aim of this study is to present a low cost laboratory test bench, suitably designed to analyse nozzle sprays according to the procedure established by ISO 5682-1 and to allow studying the correlation between spray features and WSP surface coverage. The test bench consists of a transportable trolley carrying a 70 L tank, a diaphragm pump driven by an electric motor, and a spray boom applied to a mobile support that moves along two slides placed above and parallel to the plane of the trolley, in such a way the distance between target and nozzle is 0.5 m. According to the procedure established by ISO 5682-1, the nozzle under test sprays a mixture with water-soluble dye (Poinceau Red) above Petri dishes containing silicon oil. The images of the drops trapped into the oil are acquired by using a high resolution (24 Mpixel) DSLR camera and then analysed with image analysis software. Moreover, spraying at the same time Petri dishes and WSPs, the data coming from the drops inside the Petri dishes can be correlated to those coming from the image analysis of WSPs.

To better asses the WSP behaviour, this paper also reports the results of some simulations of WSPs when sprayed with drops of assigned drop size distribution (log-normal) and volume median diameter ranging from 125 μm (fine spray) to 475 μm (coarse spray). The simulations showed that the overlap between stains is independent from spray features and that the unitary deposit (μL cm^{-2}) is highly correlated to the percentage of covered surface by means of second order equations whose coefficients depends on volume median diameter of drops.

1. Introduction

Spray deposit and superficial coverage, ensuring the correct amount of active substance on the target while minimizing the off target losses, play a fundamental role on the environment and human health impact (Balsari et al., 2005; Friso et al., 2015). In fact, the correct deposit assures the lethal dose on the target, whereas greater superficial coverage increases the probability of contact between pest and pesticide. Deposit assessment usually involves the use of a tracer to be added to the spray mixture (Pergher, 2001; Pascuzzi and Cerruto, 2015; Pascuzzi et al., 2016), whereas superficial coverage measurement involves the use of artificial targets as Water Sensitive Papers (WSP) (Pezzi and Rondelli, 2000; Salyani et al., 2013). Deposit and coverage are influenced by many factors (active substance, adjuvants, sprayer setting, nozzle types, environmental conditions, etc.), but one of the most important is the spray spectrum (Matthews, 2004; Nuyttens et al., 2007; Hewitt, 2008). In fact, small droplets are capable of drifting inside the canopy and to reach the target, but, if they become too small, they are more subjected to drift and evaporation. On the other hand, large droplets are heavier, are not usually deflected by air movement, their redistribution within the canopy is limited, and they are more prone to roll off onto the ground, so increasing the environmental impact.

There are many drop size analysers available on the market nowadays, most of which use optical imaging, laser diffraction and phase Doppler to characterise sprays (Lad et al., 2011; Nuyttens et al., 2006). This paper deals with a low-cost laboratory test bench, built at the Section of Mechanics and Mechanisation of the Department of Agricoltura, Alimentazione e Ambiente (Di3A). It allows the characterisation of the nozzle sprays according to the procedure established by ISO 5682-1 (ISO, 1996). Furthermore, since WSPs are a very practical tool used in field to quickly assess superficial coverage, spot irregularities in the spray application (overlap, over- and under-dosing), correct off-target losses, and used in sprayer workshops during sprayer inspection, the test bench allows correlating spray drop features, spray deposit and superficial coverage. To better understand the parameters affecting the correlations, WSP behaviour was also simulated under some simplifying hypotheses.

2. The test bench

The test bench, built at the Section of Mechanics and Mechanisation of the Di3A to analyse nozzle sprays according to the procedure established by ISO 5682-1, consists of a transportable trolley carrying a 70 L tank, a diaphragm pump driven by a 230 V AC electric motor, and a spray boom carrying one multiple nozzle holder. The main hydraulic components are connected as shown in Figure 1, that also shows a picture of the bench and a particular of the image acquisition system; the circuit was equipped with two lines: high pressure line (up to 3 MPa) and low pressure line (to operate up to 0.6–0.7 MPa). The two lines are manually selectable according to the needs by acting on appropriate manual ball valves; the required pressure value may be adjusted by acting on the corresponding manual pressure regulator.
The spray boom is applied to a mobile support that moves along two slides placed above and parallel to the plane of the trolley, at a distance of about 0.6 m. Travel speed and the acceleration and deceleration ramps of the mobile support are imposed by a closed-loop position/speed controller by using a 300 ppr rotary quadrature optical encoder, applied to a 240 W, 24 V DC brushed motor. Maximum speed for the mobile support is 1.5 m s^{-1}. Fluid pressure at the nozzle end and flow rate are both measured in real-time by means of suitable transducers.

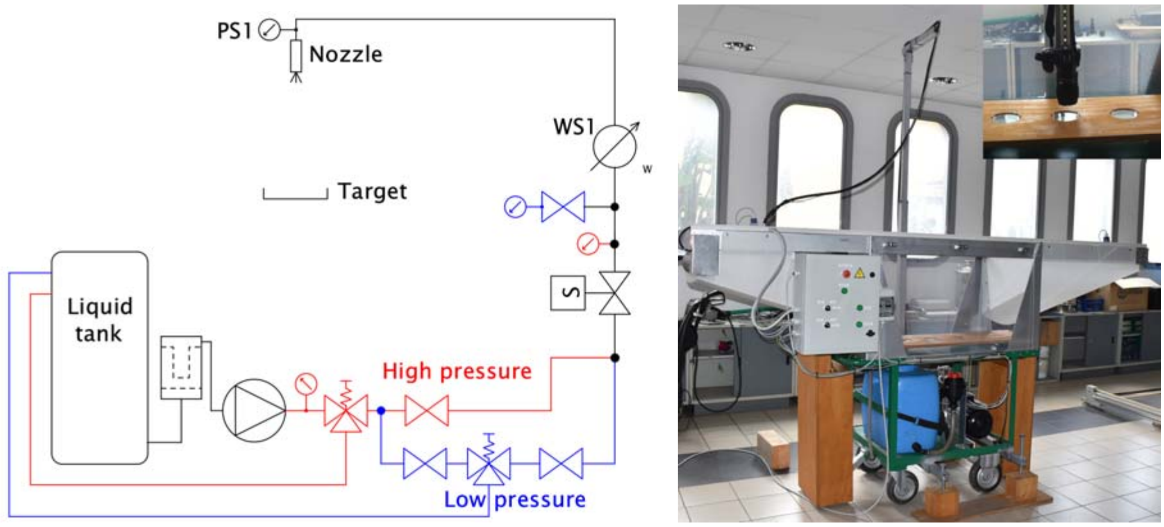

Figure 1: Block diagram of the hydraulic components (PS1: pressure sensor; WS1: water flux sensor; S: solenoid valve); on the right a picture of the test bench with a particular of the acquisition system.

In Figure 2 a block diagram of the system control architecture is shown. In this scheme, four main blocks can be highlighted. The first is composed by three Ethernet devices that allow to gain access to in-field sensors data. Two are general purpose Digital Input/Output (DIO) and Analog Input/Output (AIO) with Ethernet interface devices that allow to actuate valve S commands, to read flux information from sensor WS1 by counting sensor pulse frequency and to read pressure information from pressure sensor PS1 on a 4–20 mA current loop line. The third device is a serial device server that allows sending commands and receiving data to/from the power amplifier that drives the DC motor. The second block is composed by a four-quadrant regenerative power amplifier for the 240 W – 24 V DC motor with RS-232 interface and speed/position PID closed loop capability, using the above described encoder. A specific power supply subsystem able to tackle with high regeneration current, due to the very steep deceleration ramp, has been designed. The third block is composed by a standard WiFi access-point that allows wireless connection with standard interfaces as Windows PC or Android Tablet / Smartphone. The fourth block is finally the user interface that runs on a PC or on a Tablet. This software was specifically designed in order to allow the user to set and tune the system parameters (as PID closed-loop gains) and read in real-time any data from the system, as pressure and flux information, actuate the valve, set the spray boom speed and acceleration / deceleration ramps and so on. For sensors data and speed measurement, specific real-time graphs are provided. The software allows to save all log data on a standard ASCII comma separated values file format, that can be easily elaborated by any math software (Matlab, Excel, R and so on).

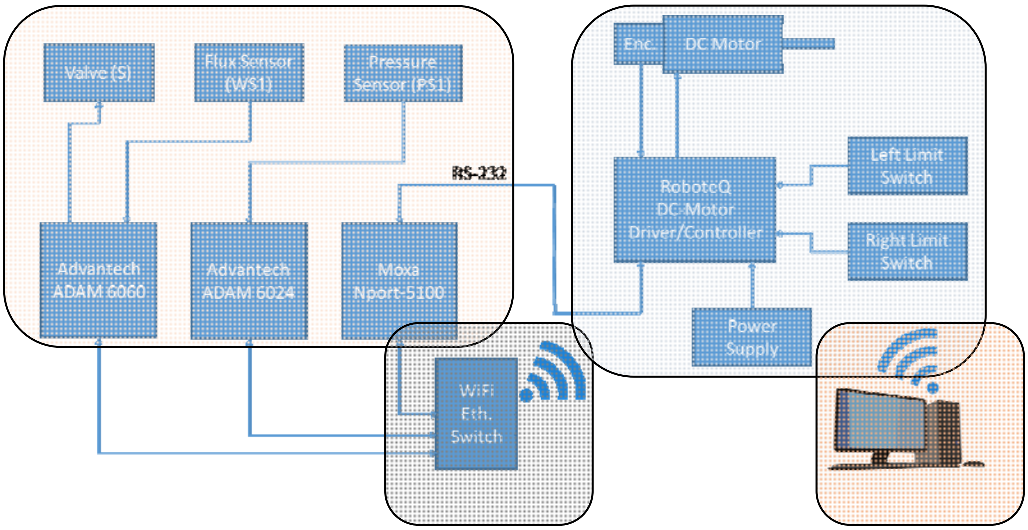

Figure 2: Block diagram of the electronic control system.

According to ISO 5682-1, the nozzle under test sprays the test liquid (clean water with the addition of a soluble colouring agent like Poinceau Red) above Petri dishes containing silicon oil of appropriate cinematic viscosity. To eliminate the effects of vibration produced by pump, motors and movement of the mobile support, Petri dishes are placed on a supplementary table, distinct and isolated from the trolley at a distance of about 0.5 m from the nozzle. The images of the drops trapped into the oil are acquired by using a high-resolution (24 Mpixel) DSLR camera equipped with a macro lens and then analysed using the ImageJ software. To acquire the images always under the same conditions, the camera is applied to a frame that is positioned on the bench at prefixed position with respect to each target.
The image analysis allows measuring the spray drop diameters and then all the spray features. Moreover, spraying at the same time Petri dishes and WSPs, the data coming from the drops inside the Petri dishes can be correlated to those coming from the image analysis of WSPs.

3. Simulation of water sensitive papers

Pulverisation of droplets sprayed from a nozzle can be described providing a suitable drop diameter Probability Distribution Function (PDF). One of the most used PDF is the log-normal (Babinsky and Sojka, 2002), according to which the number of drops as a function of their diameter D is (Eq(1)):

$$f_0(D) = \frac{1}{\sqrt{2\pi}\sigma D} e^{-\frac{(\ln D - \ln\mu)^2}{2\sigma^2}}, \tag{1}$$

being μ and σ the scale and location parameters, respectively, that are analytically correlated to Arithmetic Mean Diameter (AMD) and Coefficient of Variation (CV) of drop diameters by equations Eq(2) and Eq(3):

$$\mu = \frac{\mathrm{AMD}}{\sqrt{1+\mathrm{CV}^2}}, \tag{2}$$

$$\sigma^2 = \ln(1+\mathrm{CV}^2). \tag{3}$$

Known the distribution of the number of drops (Eq(1)), it is also possible to calculate the distribution of the volume of drops as a function of their diameters and then the Volume Median Diameter (VMD) according to Eq(4):

$$\mathrm{VMD} = \mu \cdot e^{3\sigma^2} = \mathrm{AMD} \cdot \left(1+\mathrm{CV}^2\right)^{5/2}. \tag{4}$$

Simulations were carried out keeping CV (80 %) and σ (0.70) constant and considering VMD values ranging from 125 to 400 μm with step of 25 μm, in such a way to generate sprays classified as Fine, Medium and Coarse according to the ASABE S572.1 standard (ASABE, 2009). The values chosen for the simulations were those reported in Table 1.

Table 1: Parameters chosen for water sensitive paper simulations

Spray quality	VMD, μm	AMD, μm	μ, μm
Fine	125	36	28
	150	44	34
	175	51	40
	200	58	45
	225	65	51
Medium	250	73	57
	275	80	62
	300	87	68
	325	94	74
Coarse	350	102	79
	375	109	85
	400	116	91

To simulate the images of the water sensitive papers, two main simplifying hypotheses were assumed:
1. each stain was considered as a circle whose diameter D_s (μm) was related to the drop diameter D (μm) by the Eq(5) (QInstruments, 2013):

$$D_s = 0.938 \cdot D^{1.143} . \quad (5)$$

2. the stains were allocated randomly on each image.
The images (2 cm × 7 cm) were produced with a resolution of 1200 dpi, enough to detect stains with diameter of 24 μm; the reference values of percentage of covered surface S* (without considering overlaps between stains) ranged from 5 % to 95 % with step of 10 %. Each test condition (CV, VMD, and reference covered surface *S**) was replicated three times, resulting in 360 images. These simulated images were considered as effective WSP images and then they were analysed by means of the image processing software ImageJ (Abramoff et al., 2004). The percentage of covered surface measured with the ImageJ was correlated with the reference data (covered surface and unitary deposit) used to produce the images, so to analyse the trends at varying spray and image features. All simulations, statistical analyses and graphical representations were carried out by using the R software (R Development Core Team, 2012).

4. Results and discussion

Figure 3 reports an example of the images simulated, obtained considering a Medium spray (VMD = 249 μm) and a reference percentage of covered surface *S** = 35 %. The unitary deposit due to the drops used to generate the image was 1.19 μL cm^{-2}.

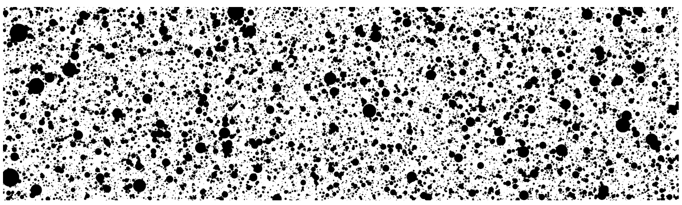

Figure 3: Example of image of water sensitive paper simulated.

The reference percentage of covered surface *S**, used to produce the images, and the measured one S_m, provided by the ImageJ software, were linked by the Eq(6):

$$S^* = 100.845 \ln \frac{100}{100 - S_m} - 0.011 , \quad (6)$$

characterised by a highly significant coefficient of determination R^2 = 0.9998. The regression equation was independent from the VMD values, confirming the results of previous researches on this topic (Cerruto et al., 2013; Cerruto et al., 2016), obtained considering sprays with different features. Perhaps this result is independent of spray features, but may depend on other assumptions of the model (circularity of the stains, for example) that will be investigated in further studies. The graphical representation is reported in Figure 4.

From Eq(6) it follows that when the percentage of covered surface increases towards 100 %, the reference one tends to infinity asymptotically. This means that high values of percentage of covered surface on WSPs imply a very high degree of overlap between stains, which could be indicative of run-off and then of high environmental impact. According to Eq(6), when S^* ranged from 5 % to 95 %, S_m ranged from 4.8 % to 61.0 % and then the overlap ranged from 0.2 % to 34.0 %.

The reference unitary deposit d_s (µL cm^{-2}) was linked to the measured percentage of covered surface S_m (%) as reported in Figure 5 at varying the volume median diameter VMD (µm) of the drops.

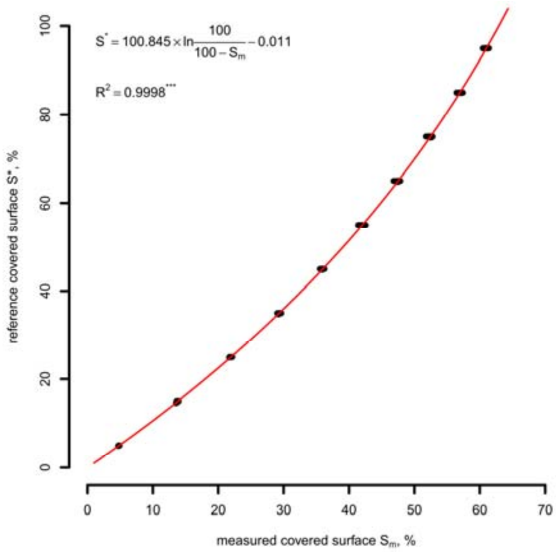

Figure 4: Correlation between measured (S_m) and reference (S^*) percentage of covered surface.

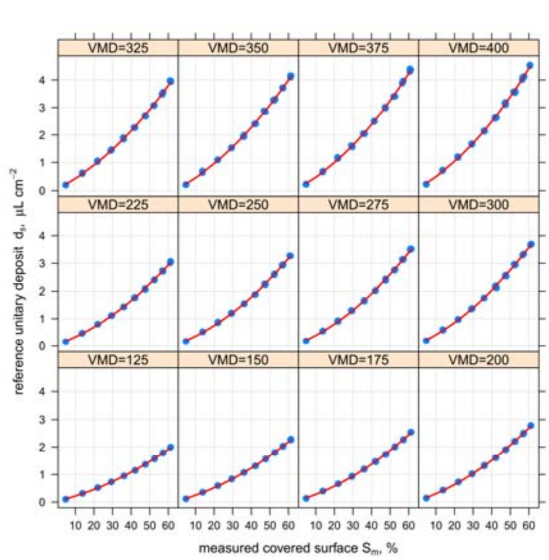

Figure 5: Correlation between measured percentage of covered surface (S_m) and reference unitary deposit (d_s) at varying volume median diameter VMD (µm) of the drops.

All trends were well explained by quadratic relations (Eq(7)) of the form:

$$d_s = a + b \cdot S_m + c \cdot S_m^2 \,, \tag{7}$$

with d_s measured in µL cm^{-2} and S_m in percent and with the coefficients a, b and c depending upon VMD values. The coefficients of determination R^2 were highly significant and ranged from 0.9991 to 0.9996. This result suggests that the unitary deposit could be estimated by reading the percentage of covered surface on WSP and knowing the VMD of the spray.

5. Conclusions and perspectives

The paper deals with the development of a low-cost laboratory test bench suitable to analyse nozzle sprays according to the ISO 5682-1 procedure. Preliminary tests have shown its usefulness under several aspects:

- Measuring all drop diameters, the test bench makes it possible to calculate all drop volumes and then the unitary deposit (µL cm^{-2}).
- Knowing the drop diameters, it also allows to calculate the drop diameter probability distribution function at varying nozzle features and test conditions and then to adjust the model used to simulate the behaviour of water sensitive papers, highlighting the parameters that most affect the unitary deposit (volume median diameter, arithmetic mean diameter, probability distribution function, coefficient of variation, and so on).

- Spraying at the same time Petri dishes with silicon oil and water sensitive papers, the test bench allows to correlate the data extracted from WSP analysis (mainly superficial coverage) to spray features and unitary deposit.
- Finally, spraying at the same time water sensitive papers and natural targets (fruits, leaves) the test bench allows to correlate the unitary deposit on targets with superficial coverage on WSP, the two parameters that most affect the efficacy of a pesticide application. If the correlation will be significant, the WSP analysis alone will allow the estimation of the deposit, so simplifying the measurement procedure (no necessity of tracer to be added to the mixture).

Measurements will be carried out at varying nozzle type and test conditions, allowing the detection of the operative conditions that assures the required deposition.

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