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Effect of sprayer parameters and wind speed on spray retention and soil deposits of pesticides: Case of artichoke cultivar

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Abstract: Irrational use of chemical method for crop protection, presents increasingly serious risks for human health and the environment. Droplet size and meteorological parameters are key factors to both environmental contamination and pest control efficacy. The objective of this study is to assess the impact of the nozzle use parameters, the operating pressure and the wind speed on droplet foliage deposition (retention) and soil deposition (losses), when treating artichoke. Several combinations were tested in a wind tunnel and in the field, under Mediterranean microclimatic conditions, using a fluorescent dye as a substitute for pesticide. Multiple regression models were built from tunnel data to predict foliage deposition and soil deposits, with determination coefficients of 0.96. Thus, models are able to simulate pesticide deposition on artichoke leaves and soil deposition, depending on sprayer parameters and wind speed. Foliage deposition and soil deposits rates ranged from 30 to 52% and 26 to 57% respectively for anti-drift nozzle. For conventional nozzle, rates varied from 20 to 38% and 31 to 62%. To improve retention and reduce spray losses, it is recommended to choose a medium droplet size when using an anti-drift nozzle, in conjunction with medium nozzle size, medium pressure and reduced wind speed.

Keywords: droplets deposition; droplet size; meteorological factors; nozzle size; nozzle type; pressure

The inappropriate use of pesticides might result in significant losses of active ingredients that could be hazardous to health, the environment and farmers' income. These losses are predominantly due to the large amounts of spray being transferred to the environment, to the soil in particular, during the application. While spraying, the fine droplets are carried by the wind (drift), while the larger droplets are deposited on the ground due to run-off on the foliage. Researchers have conducted several studies on droplets behavior on leaf surfaces to understand better the process of droplet deposits on soil. All these studies have confirmed the diversity and complexity of the factors governing pesticide losses on the soil. Wang et al. (2018) explained that droplet adhesion is a function of interactions between active ingredients in the spray before and during droplet impact along with leaf surface characteristics and droplet properties, mainly the size and the velocity. Spray droplet size is arguably one of the most important factors in controlling particle behavior in terms of both environmental contamination and

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efficacy during pesticide application. When combined with inadequate weather conditions, droplet size can contribute to pesticide deposition on plants and their deposits on the soil, resulting in increased soil contamination and reduced efficacy (De Oliveira 2018). Yao et al. (2014) reviewed droplet size effects on wheat leaf wettability and spray retention. They concluded that droplet size affects directly the spray deposition on the target, explaining that smaller droplet size generates a good contact at the impaction site, allowing for high retention efficiency. Ozkan (2016) reported that, a droplet size smaller than 100 μm reduces ground contamination by increasing droplet retention on the foliage. However, when the droplet size decreases, the spray becomes more sensitive to the wind speed (Teske et al. 2002).

Sprayer parameters have a direct effect on the spray characteristics, especially on droplet size (Teske et al. 2002). Accordingly, they might have a definite impact on droplet deposition on leaves (D_f) and pesticide deposits in the soil (D_s) during spraying. Allagui (2019) showed that droplet size is largely determined by the nozzle type (*NT*), the nozzle size (*S*) and the operating pressure (*P*). She found that for a given nozzle type, within a droplet size range; increasing *S* and decreasing *P* while spraying systematically reduce D_f and favor D_s. In their turn, Nuyttens et al. (2007) found that, larger orifice produced larger droplets. Moreover, they reported that air induction nozzle produces large droplets and presumably resulting in a D_s increase. In practice, the droplet size is defined by the volume diameter (in μm) below which lies the size of 50% of the total sample volume, commonly known as volume median diameter (VMD) and providing information on the droplet spectra of the total sample volume. Differences in droplet spectra and deposition pattern can be observed with higher VMD when compared to the lower ones: the higher the VMD is, the larger the droplets size will be (Allagui 2019). Consequently, droplets with a low VMD (smaller than 200 μm) are more susceptible to drift, while those with a high VMD (greater than 400 μm) are more likely to run off on the leaves (Ozkan 2016). In order to reduce soil deposits, it is a common practice to increase the VMD in the spray by selecting a different nozzle, reducing the liquid pressure or increasing the spray nozzle size (Creech et al. 2015).

To understand the pesticide deposition process and to predict D_f and D_s, researchers have been following different approaches. Allagui et al. (2018) cited extensive research that has been focused on understanding the spray movement near the plant area. They reported that various computational models were developed to simulate the droplets deposition process (Forster et al. 2005; Dorr et al. 2014). However, the aforementioned models are complex due to diverse factors that govern the droplet deposition process, the reason why, several researchers have approached the problem differently. These, have considered different retention process including, all at once, a spray trajectory model, a droplet collision model, a run-off model and a plant canopy model. This approach can be either fully applied by modeling all the retention process (Mercer et al. 2007), or partially applied by choosing to model only two or three stages of this process (Forster et al. 2005; Dorr et al. 2014). In either case, the last stage consists of combining the developed models to estimate D_f and D_s deposits. To predict retention and soil deposits, statistical modeling has been used widely (Lammertyn et al. 2000; Li et al. 2020). Results of these studies have clearly proved that the regression analysis provided good assessments of the effects of physical sprayer parameters and meteorological factors on droplet deposition. The Spray Drift Working Group in the USA has developed the well-known "AgDRIFT" model to predict both plant canopy retention and post-spraying drift (Teske et al. 2002). In addition, AgDRIFT was partly based on an empirical model constructed from ground spraying observations. In our context, the Bayesian network approach (BNA), can be used to exploit the dependence relationships between local conditions in a model to conduct investigations for prediction and diagnostic analyses (Bonzanigo et al. 2016).

The purpose of this paper is to examine the impact of *NT*, *S*, *P* and the wind speed (*WS)* on pesticide deposition on artichoke leaves as well as soil deposits in order to evaluate how these parameters affect the environmental efficacy and phytosanitary treatment efficacy. We developed multiple regression and BNA models to assess relationships between the four parameters mentioned above and deposition rates (D_f and D_s) during the artichoke treatment in Tunisia, under Mediterranean conditions, and also to determine recommendations to follow in order to achieve the best results (Ni et al. 2011). The models were tested by correlating D_f and D_s between experimental and predicted rates.

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MATERIAL AND METHODS

This study was conducted at the National Research Institute for Rural Engineering, Water and Forestry (INRGREF), North of Tunisia to evaluate pesticide deposition on foliage and soil deposits during the treatment of the artichoke across the *NT*, *S*, *P* and the *WS*.

In 2017, an experimental campaign was accomplished in a wind tunnel followed by another in 2018 under field conditions to measure droplet depositions on artichoke foliage (D_f) and those falling on the soil (D_s), in percentage of the application rate, using a two nozzle types, with different nozzle sizes and operating pressures. Data from the wind tunnel measurements were used to develop multiple regression models for predicting D_f and D_s. Results from these models were compared with those obtained experimentally, and with other researchers' results.

Wind tunnel tests setting. Tests were conducted in the INRGREF's wind tunnel between January 15 and March 9, 2017, during artichoke spraying season. At the time of the study, artichoke plants (Violet d'Hyères variety) were at the Germanium Federal Biological Research Centre for Agriculture and Forestry (BBCH) growth stage of 57–507. A boom equipped with pressurized liquid technology and a three nozzles boom was used (Figure 1). Two ISO flat-fan nozzle types of 110-degree (Albuz, France) were tested: a low-drift nozzle (*AD*) with air-induction technology and a conventional one (*CL*) for traditional Flat Fan. Each one was tested with sizes of 02, 03 and 05 (noted *S*02, *S*03 and *S*05 respectively). All combinations *NT-S*, were tested at three pressures of 3 bar (*P*3), 4 bar (*P*4) and 6 bar (*P*6), with a travel speed (*TS*) of 5 km/h and a spray width (*SW*) of 1.5 m. Depending on the combination *NT-S-P*, *TS* and *SW*, the application rate ranged from 64 to 234.4 L/ha. *NT*, *S* and *P* were selected based on the Tunisian farmers' standards. The boom was in movement and adjusted at 0.5 m above the plant; with a nozzle spacing of 0.5 m. The meteorological parameters were a constant temperature (T) of 25 °C, a constant humidity (RH) of 40% and three wind speeds of 2, 3 and 5 m/s (*WS*2, *WS*3 and *WS*5 respectively).

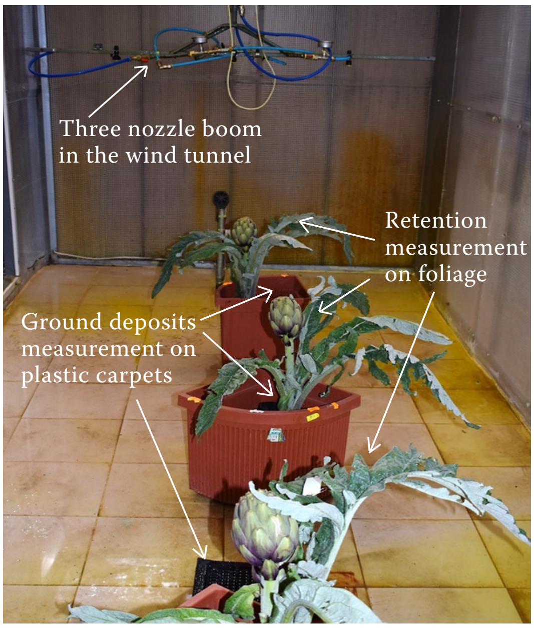

Figure 1. Measurement of deposition on foliage (D_f) and soil deposits (D_s) in the wind tunnel

Tests were performed by spraying the Brilliant Sulfo-Flavin tracer [BSF (Biovalley, France)] at a concentration of 1 g/L, as a substitute for pesticide (Gil et al. 2007; Allagui et al. 2018). To capture deposits, artichoke leaves acted as collectors for D_f, while small plastic carpets were used under the plant foliage for D_s(Bahrouni et al. 2008). The artichoke plants used in the wind tunnel were cut from the field the on day of the tests, and placed into plastic pots separately. Measurements were conducted by placing in a completely randomized design three pots under the wind tunnel boom in movement and three plastic carpets under the plant foliage, through the long axis of the spray cloud in a downward direction (Figure 1), with six replications, giving a total of 108 measurements. Fluorescent dye was extracted by rinsing each collector with a water volume of 1.5 L for plants foliage and 0.4 L for carpets (Allagui 2019) and the BSF concentration was later determined by fluorimetry. The wavelength used in fluorescence determination at emission and excitation were respectively of 500 and 455 nm. Deposits were calculated using the formula of Van de Zande et al. (2017), based on the average of the three rinsing solutions of each collector type and considering the leaf area index (LAI) of the plants.

Drifting was calculated to gain a comprehensive overview of the spray volume fate and to highlight any general losses during spraying. To this end, assuming that unmeasured amounts of spray correspond to losses by drift, and considering that the application rate per hectare (*Q*) corresponds to 100% of the spray, the drift rate (D_r) was obtained by calculating the difference between *Q* and total measured deposition [Equation (1)]:

$$D_r\,(\%) = 100 - \left(D_f + D_s\right) \tag{1}$$

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Multiple regression analysis and ANOVA were performed on the tunnel data using SPSS software (version 20). Deposition rates D_f and D_s, expressed in percentage of the application rate, were considered as the dependent variables (*Yi*) and their variation is considered to be significant when $P < 0.05$. The independent variables (*Xi*) assumed to influence D_f and D_s had been *NT*, *S*, *P* and *WS*. *NT* was noted as 1 for *AD* nozzle and 2 for *CL* nozzle. The experimental data set was used to test obtained models [Equations (2) and (3)], taking into account all variable effects.

D_f and D_s were also analyzed with BNA using Netica software (version 6.05) to highlight the causal links between all variables mentioned above. To be introduced to Netica, D_f and D_s should be classified as "low deposit", "medium deposit" and "high deposit". Thus, it was considered that the level of D_f and D_s was high for rates greater than 40%, it is medium in the range of 30–40% and low for rates below 30%.

The size of the droplets of the eighteen combinations selected (2*NT* × 3*S* × 3*P*) was previously analyzed in the INRAE Institute (Montpellier, France), using a Phase Doppler Analyze [PDA (Malvern Spraytec Laser: Malvern Instruments Ltd, USA)] according to the method of Nuyttens et al. (2007), to determine the VMD and the spray spectrum quality.

Field tests setting. Simplified field experiments were performed to consolidate the models validation using field data. The test plot was laid out in a strip system implemented in a mixed model (split-plot/crossed) in a randomized complete block with three replications.

All tests were conducted between January 16 and February 17, 2018, during artichoke spraying season, in accordance with the protocol and the sprayer parameters settings of wind tunnel experiments, except for the travel speed that ranged from 1.5 to 6 km/h while the application rate was kept constant at 200 L/ha. T, RH and *WS* were measured during each test, using a multifunction measuring instrument. The field parameters settings are presented in Table 1. Each combination was tested three times, which meant that a total of 54 measurements were carried out in the field.

RESULTS

Droplet size analysis. Droplet size data and spray quality of the combinations selected are presented in Table 2. The VMD varied from 273 to 409 μm for *AD*, and only from 154 to 230 μm for *CL*. According to the British Crop Protection Council

Table 1. Field tests parameters settings

Nozzle type	Nozzle size	Pressure (bar)	Practical travel speed (km/h)	Temperature (°C)	Relative humidity (%)	Wind speed (m/s)
Anti-Drift	02	3	1.5	19	42	2.4
		4	2.0	19	38	2.2
		6	2.5	19	35	2.2
	04	3	2.5	21	47	2.3
		4	3.0	20	50	2.0
		6	3.5	20	53	1.8
	05	3	4,0	22	47	2.4
		4	4.5	21	51	2.1
		6	6.0	20	55	1.7
Conventional	02	3	1.5	18	61	2.2
		4	2.0	18	61	2.0
		6	2.5	19	60	1.8
	04	3	2.5	19	58	1.0
		4	3.0	19	58	1.5
		6	3.5	20	55	1.9
	05	3	4.0	18	59	2.6
		4	4.5	19	58	2.8
		6	6.0	19	58	3.0

Application rate – 200 L/ha; spray width – 1.5 m

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Table 2. Volume median diameter (VMD) and spray quality for anti-drift (*AD*) and conventional (*CL*) nozzles, three nozzle sizes (*S*02, *S*03, *S*05) and three pressures (3, 4, 6 bar)

Nozzle size	Pressure (bar)	*AD*		*CL*	
		VMD (μm)	spray quality	VMD (μm)	spray quality
02	3	390	C	184	F
	4	338	C	170	F
	6	285	M	154	F
03	3	369	C	204	F
	4	324	C	183	F
	6	273	M	167	F
05	3	409	C	230	M
	4	324	C	209	M
	6	282	M	192	F

C – coarse; M – medium; F – fine

classification (Nuyttens et al. 2007), in general, *AD* corresponds to coarse spray, while *CL* to a fine spray.

As expected, results indicated that, for a given *NT*, increasing *P* results in a reduction of the VMD. Clear differences were found in VMD between the three pressures *P*3, *P*4 and *P*6. However, increases in VMD were found when changing *S* from *S*02 to *S*03 or from *S*03 to *S*05, but they were even more apparent with CL nozzle.

Artichoke deposits on the foliage and soil deposition. The average deposition rates of BSF measured in the wind tunnel and in the field from the various tested combinations are shown in Tables 2 and 3. The data show that, depending on the type of spray, there was a marked difference between the deposition distribution pattern of the *AD* and the *CL* nozzles compared to the application rate. In the wind tunnel, for coarse spray characterizing *AD*, the mean rate was 42% for D_f, fluctuating between 30 and 52%, while it was 41% for D_s with a fluctuation from 26 to 57% (Table 3). For fine spray produced by *CL*, D_f was only 30% and reached 47% for D_s, with a variation range of 20–38% and 31–62% respectively. Details indicated that D_f decreased with S and increased with *P* for all treatments. The opposite situation was observed for D_s which increased with S and decreased with *P*. On the other hand, increases of *WS* generated a lower D_f rate and a higher D_s rate with the different tested combinations.

Looking at Table 3, we can see clearly that the *AD*-*S*02 combination had a higher D_f compared to D_s. Opposite results were found with *AD*-*S*05,

Table 3. Deposition on foliage (D_f) and soil deposits (D_s) (%) of the application rate, in the wind tunnel for anti-drift (*AD*) and conventional (*CL*) nozzles, three nozzle sizes (*S*02, *S*03, *S*05), three pressures (3, 4 ,6 bar) and three wind speeds (*WS*) (2, 3, 5 m/s)

WS (m/s)	Pressure (bar)	*AD*									*CL*								
		*S*02			*S*03			*S*05			*S*02			*S*03			*S*05		
		D_f	D_s	D_r	D_f	D_s	D_r	D_f	D_s	D_r	D_f	D_s	D_r	D_f	D_s	D_r	D_f	D_s	D_r
2	3	43	36	21	43	42	15	40	49	11	34	40	26	30	48	22	26	58	16
	4	45	33	22	44	38	18	42	46	12	35	38	27	32	46	22	27	57	16
	6	52	26	22	50	31	19	46	40	14	38	31	31	36	38	26	31	51	18
3	3	41	37	22	39	45	16	35	53	12	33	41	26	29	49	22	24	59	17
	4	41	35	24	41	45	14	36	52	12	33	37	30	31	46	23	25	57	18
	6	49	27	24	46	34	20	40	45	15	35	32	33	33	40	27	29	52	19
5	3	37	41	22	35	49	16	30	57	13	31	43	26	26	52	22	20	62	18
	4	42	35	23	37	45	18	31	54	15	30	42	28	27	52	21	20	60	20
	6	44	31	25	41	38	21	35	49	16	32	34	34	29	43	28	24	56	20

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where D_s was less than D_f. A different situation was shown with *CL* nozzle where D_s were always greater than D_f. S03 occupied constantly an intermediate position for the two nozzle types.

Furthermore, it was also found that the larger the nozzle size was, the lower D_f and the higher D_s we had. This implies that medium droplets produced by *AD-S*02 and *AD-S*03 were better retained on artichoke leaves, compared to *AD-S*05, which gave coarse droplets (Table 2). This also indicates that, *AD* nozzle, spraying large droplets filled with air bubbles, were better at retaining droplets on leaves as compared to *CL* nozzle.

For the pressure, the only combination where $D_f > D_s$ was *AD-P*6 producing medium size droplets; for the five others combinations (*AD-P*3, *AD-P*4, *CL-P*3, *CL-P*4 and *CL-P*6) which gave coarse or fine droplets, $D_f < D_s$. This clearly confirms that the combinations producing either large or fine droplets favor spray losses, be it on the ground or in the air. Details presented in Table 3 show that for the different *NT-S* configurations, when *P* increased, D_f too, while D_s decreased. More differences between D_f and D_s rates were also observed when changing *WS*. Decreases in D_f and increases in D_s have been associated with *WS* increases for the different *NT-S-P* configurations. This was even more obvious when changing from 2 to 5 m/s with *AD-S*05-*P*6 and *CL-S*05-*P*6 combinations, where D_f was reduced by 11 and 7% respectively, while soil deposits increased by 9% and 5% respectively. Considering the 54 combinations tested in the wind tunnel, the largest D_f rate (52%) and the smallest D_s rate (26%) were given by *AD* nozzle associated wit h *S*02 at 6 bar and 2 m/s wind speed. Under our test conditions, the *CL-S*05-*P*3 combination at 5 m/s gave the lowest D_f (20%) and the highest D_s (62%). In general, these trends were also found with the field set data obtained from the 18 combinations tested under real conditions (Table 4).

As explained in the wind tunnel tests setting section, the D_r was calculated to have a comprehensive overview of the sprayed volume fate (mass balance). In comparison with measured values of D_f and D_s, this ratio had expected trends for the different configurations. Marked differences were found between the two nozzle types with a D_r range from 11 to 25% for *AD* and from 16 to 34% for *CL*. Obvious differences were also found in drift rates between the three sizes *S*02, *S*03 and *S*05, the three pressures *P*3, *P*4 and *P*6 and the three wind speeds *WS*2, *WS*3 and *WS*5. Lowest drift rates were obtained with the largest nozzle size *S*05 (respectively ranges of 11–16% and 16–20%), the smallest pressure *P*3 (respectively ranges of 11–22% and 16–26%) and the wind speed of 2 m/s (respectively ranges of 11–22% and 16–31%). The greatest D_r rate (34%) was found with the *CL* nozzle combined with *S*02, at a pressure of 6 bar and a wind speed of 5 m/s. These results agree with several other research findings (Creech et al. 2015; Ozkan 2016; Peters et al. 2017).

According to all the previous results, the three sprayer parameters (*NT*, *S*, *P*) and *WS* had an impact on both leaf deposits and ground loss rates.

Modeling Artichoke deposits on leaves and soil deposition. The analysis of variance showed that D_f and D_s vary significantly (P < 0.05), for dependent variables *NT*, *P*, *S*, *WS*, and for the most of their interactions when taken in pairs (Table 5). However, the $S \times P \times WS$ and the $NT \times S \times P \times WS$ interactions were not significant (P > 0.05). D_f variations were not significant (P < 0.05) based on the interactions of $P \times S$ and $P \times WS \times NT$. In addition, D_s presented not significant variations (P > 0.05) according to $P \times WS$, $P \times S \times NT$ and $S \times WS \times NT$ interactions (Table 5). The multiple regression was carried out for both *AD* and *CL* nozzles from tunnel deposition data (Table 3). A set of 54 runs (2*NT* × 3*S* × 3*P* × 3*WS*) was used with 27 runs for the AD nozzle and 27 for the *CL* nozzle. Table 6 from the regression analysis showed

Table 4. Deposition on foliage (D_f) and soil deposits (D_s) (%) of the application rate, in the field for anti-drift (*AD*) and conventional (*CL*) nozzles, three nozzle sizes (*S*02, *S*03, *S*05) and three pressures (3, 4 ,6 bar)

Pressure (bar)	*AD*									*CL*								
	*S*02			*S*03			*S*05			*S*02			*S*03			*S*05		
	D_f	D_s	D_r	D_f	D_s	D_r	D_f	D_s	D_r	D_f	D_s	D_r	D_f	D_s	D_r	D_f	D_s	D_r
3	39	23	38	39	30	31	38	34	28	31	29	40	24	36	40	18	43	39
4	40	20	40	42	27	31	38	34	28	31	28	41	25	35	40	19	42	39
6	43	19	38	43	21	36	39	30	31	32	28	40	26	34	40	19	43	38

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Table 5. Interactive effects of dependent variables deposition on foliage (D_f) and soil deposits (D_s) with the independent variables *NT*, *WS*, *S* and *P*

Source	*P*-value*	
	D_f	D_s
P	0.000	0.000
S	0.000	0.000
WS	0.000	0.000
NT	0.000	0.000
P × *S*	0.419	0.000
P × *WS*	0.001	0.789
P × *NT*	0.000	0.003
S × *WS*	0.000	0.000
S × *NT*	0.000	0.000
WS × *NT*	0.000	0.000
P × *S* × *WS*	0.478	0.965
P × *S* × *NT*	0.000	0.406
P × *WS* × *NT*	0.113	0.000
S × *WS* × *NT*	0.002	0.053
P × *S* × *WS* × *NT*	0.416	0.337

*Significant at $P < 0.05$; *NT* – nozzle type; *WS* – wind speed; *S* – nozzle size; *P* – operating pressure

that the four independent variables predicted significantly the scores of the dependent variables (D_f and D_s): $P < 0.05$. As reported by the standard regression analysis, the model's degree of explaining D_f and D_s variances was $R^2 = 0.961$ and $R^2 = 0.96$, respectively (Table 6). In light of these coefficients, it can be stated that the models predict the dependent variables well. The β absolute value designates the independent variables order of contribution to the models (Uyanik & Güler 2013).

According to Table 6, it was found that for the D_f model, *NT* had the highest contribution with the value of β = 0.74, followed respectively by *S* (β = 0.42), *WS* (β = 0.37) and *P* (β = 0.28). For the D_s model, *S* made the biggest contribution (β = 0.78), followed respectively by *P* (β = 0.41), *NT* (β = 0.31) and *WS* (β = 0.24).

The obtained regression models are shown in Equations (2 and 3):

$$D_f = 0.607 - 0.112\,NT - 0.025\,S + 0.017\,P - 0.022\,WS \quad (2)$$

$$D_s = 0.237 + 0.056\,NT + 0.058\,S - 0.031\,P + 0.018\,WS \quad (3)$$

Comparisons of models findings with measured data in the wind tunnel and in the field are shown in Figures 2 and 3 respectively. In general, the two models were in good agreement with the measured values, especially in the wind tunnel (Figure 2). However, they tended to over-predict D_f and D_s particularly with the field data (Figure 3).

Evaluation of D_f and D_s variations was carried out based on the Bayesian network approach (BNA) structure presented in Figure 4A. Results showed that the high deposit on the foliage presents only 32.4% of the total values, while the high deposit on the soil constitutes 50% (Figure 4B). These percentages represent the probabilities estimated by the Netica software based on the model data. By acting on Netica to assign the value 100% to high D_f and low D_s, the probabilities of the whole network will be updated (Figure 4C).

Table 6. Multiple linear regression models for the dependent variables deposition on foliage (D_f) and soil deposits (D_s)

Variable	A	SE	β	*t*-stat.	*P*-value
D_f model ($P = 0.00$; $R^2 = 0.961$)					
Intercept	0.607	0.007		91.891	0.000
Nozzle type (*NT*)	–0.112	0.002	–0.740	–51.270	0.000
Nozzle size (*S*)	–0.025	0.001	–0.418	–28.971	0.000
Operating pressure (*P*)	0.017	0.001	0.280	19.435	0.000
Wind speed (*WS*)	–0.022	0.001	–0.368	–25.474	0.000
D_s model ($P = 0.00$; $R^2 = 0.96$)					
Intercept	0.237	0.008		29.686	0.000
Nozzle type (*NT*)	0.056	0.003	0.306	21.248	0.000
Nozzle size (*S*)	0.058	0.001	0.782	54.240	0.000
Operating pressure (*P*)	–0.031	0.001	–0.415	–28.793	0.000
Wind speed (*WS*)	0.018	0.001	0.241	16.756	0.000

A – non-standardized coefficients; SE – standard error; β – standardized coefficients; *t*-stat – Student's statistical test value

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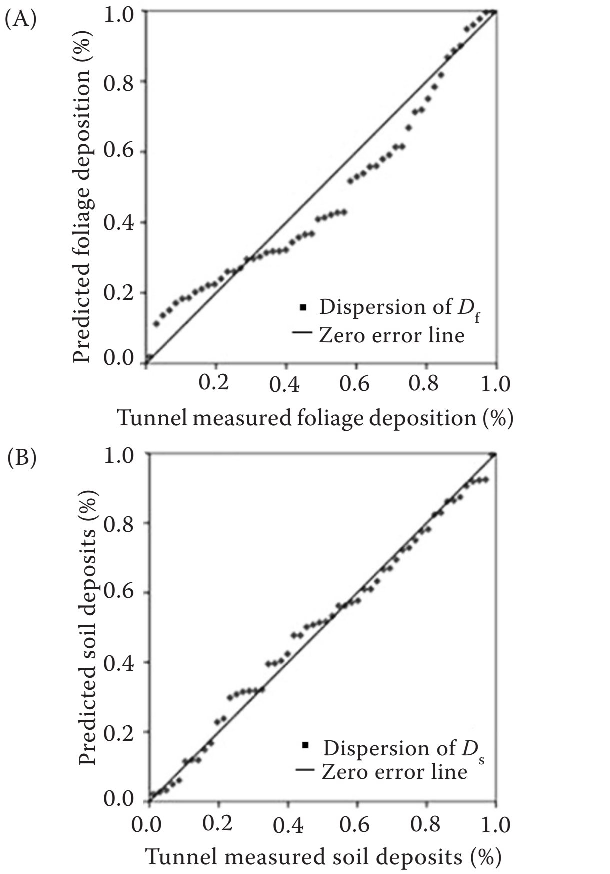

Figure 2. Comparison of models findings with tunnel measured data (A) foliage deposition (D_f) and (B) soil deposits (D_s)

DISCUSSION

As stated above, droplet size and spray quality are key factors to the spray fate control. In order to improve D_f and reduce D_s, the droplet size spectrum should be increased by selecting a different nozzle type (*NT*), reducing operating pressure (*P*) or increasing the nozzle size (*S*). Several other researchers obtained the same conclusions (Creech et al. 2015; Ferguson 2016) and some have even observed that the efficacy with coarser droplets is as good as with finer droplets (Shaw et al. 2000). However, the droplet size increase should not exceed 400 µm (medium spray quality) as a limit of droplet run-off on the foliage (Ozkan 2016).

Based on Tables 2, 3 and 4 data, changing *NT* was the most effective to increase droplet size to improve D_f as observed by Zhu et al. (2004). *AD* nozzle showed more flexibility in this regard, compared to *CL*. It gave large drops filled with air bubbles which exploded into fine droplets on leaves and adhered better (Peters et al. 2017). It was also observed that the proper nozzle size selection was important for satisfactory spray coverage on foliage. For a given *NT*, using smaller *S*, produced larger droplets improving D_f with lower loss potential, as found by Nuyttens et al. (2007). For their part, Womac and Bui (2002) found that the VMD was increased from 141 to 522 µm by decreasing

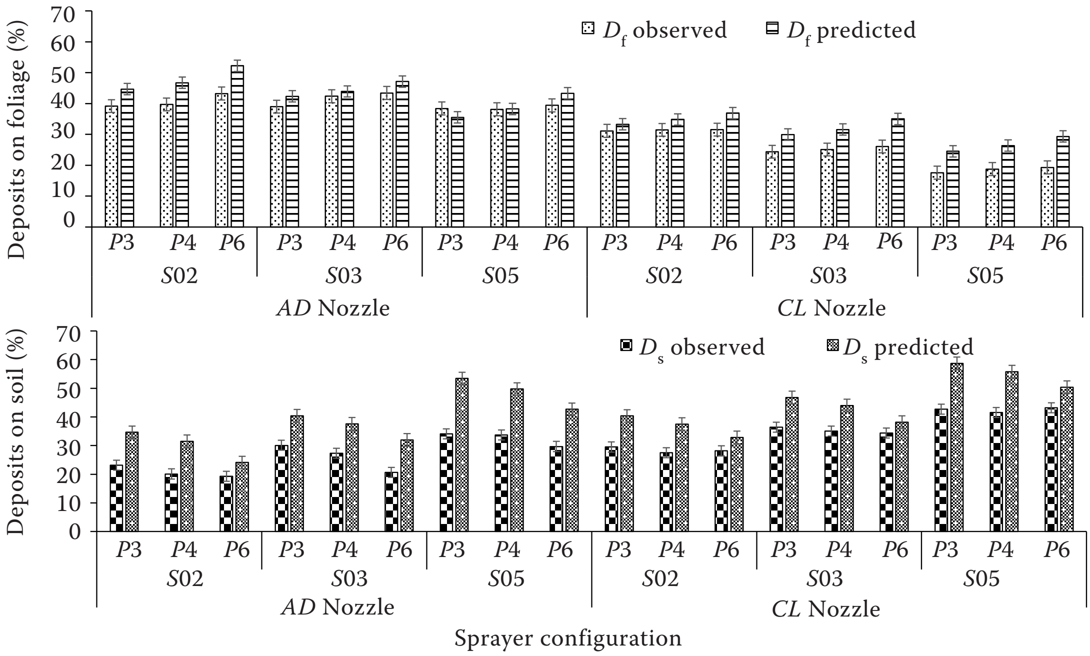

Figure 3. Comparison of models findings with measurements, using field data (A) foliage deposition (D_f) and (B) soil deposits (D_s)

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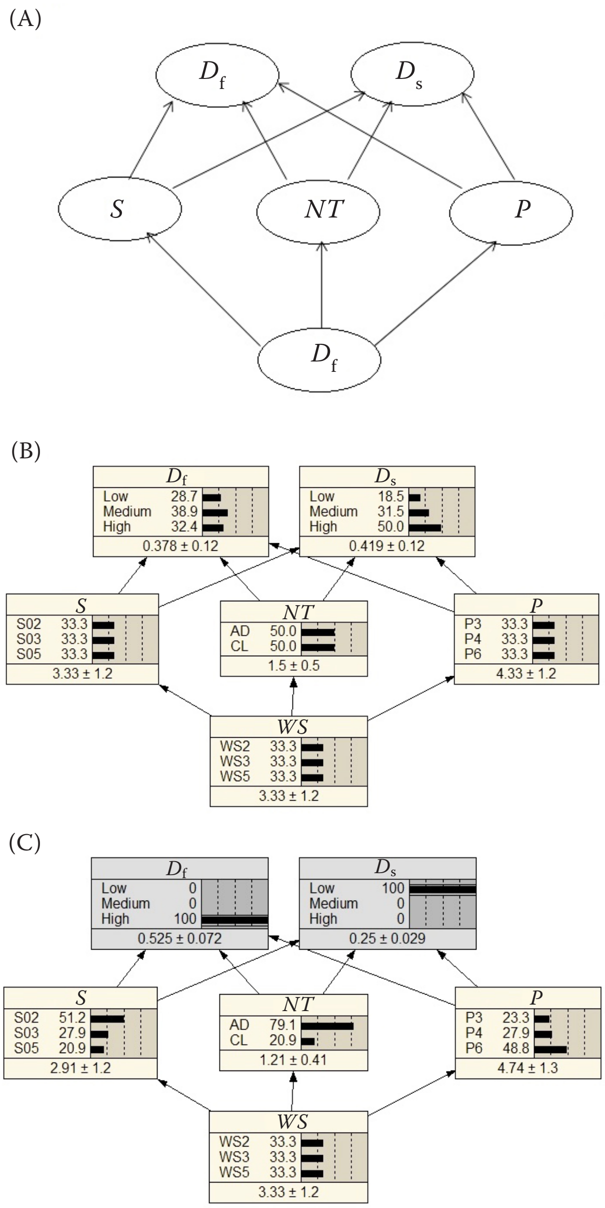

Figure 4. Application of Bayesian network for the analysis of deposits on leaves and soil deposition (A) Bayesian network structure considered, (B) the model after parameter learning in Netica and (C) prediction of the model when the evidence variables are deposits on th foliage (D_f) and deposits on the soil (D_s)

NT – nozzle type; *S* – nozzle size; *P* – operating pressure; *WS* – wind speed

the pressure from 4.2 to 1.4 bar. Our results tie in with these findings as they indicate that an increase in operating pressure leads to a greater proportion of the small droplets able to that adhere better to foliage and as a result, the potential for soil deposits is reduced.

On the other hand, Table 3 shows that in addition to sprayer parameters, wind speed affects significantly on foliage coverage. As droplets size decrease, they become increasingly sensitive to changes in wind speed. Teske et al. (2002) found also that wind speed, was a critical factor, impacting deposition and losses.

The obtained multiple regressions assess D_f and D_s through the Equations (2) and (3). The determination coefficients (R^2) were high enough to evidence the reliability of the statistical models for the data set assessed. The models' output from the wind tunnel and the field data indicate that the modelling approach adopted in this paper can be applied, according to the varying ranges of parameters tested in this study, to investigate the effect of *NT*, *S*, *P* and *WS* on D_f and D_s. It appears that the most influential factors turn out to be *NT*, *S* and *WS*, all determined to be significant at confidence level of 5%. However, *NT* had the highest contributions to deposition rate models. The two obtained models tended to reflect the measured data, but with a slight over-prediction, especially for the field measurements. This could be attributed to the limited number of the studied combinations. Thus, introducing other *NT*, other *S*, other *P* may be improv the predictive ability of the models. Regressions confirm that, as explained above and as shown by Zhu et al. (2004), using *AD* nozzle, associated with *S*02 and *P*6, is favorable to the increase in D_f and the decrease in D_s. This conclusion was confirmed when we compared obtained probabilities in the scenario proposed by BNA with those of the real scenario that highlight the parameters which need to be acted on in order to improve D_f and reduce D_s. Based on this comparison, it is recommended to promote the use of *AD*, with *S*02 and *P*6, regardless of the wind speed (Figure 4C).

CONCLUSION

Tests were conducted in a wind tunnel and under field conditions to assess pesticide deposition on artichoke leaves and droplet deposition on the soil, during spraying, based on several sprayer parameters and the wind speed. Tests were performed using two nozzle types (anti drift nozzle using air-induction technology and conventional nozzle), three nozzle sizes (02, 03 and 05), three pressures (3, 4 and 6 bar) and three wind speeds (2, 3 and 5 m/s).

Spray deposition is influenced mainly by the spray droplet size and wind speed, affecting droplet

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behavior upon contacting leaves. In practice, the wind speed is not controllable; therefore, the sprayer user can only act on the droplet size. Nozzle type, nozzle size and spraying pressure were found to be the important variables influencing sprayed droplet size. It was found that the anti-drift nozzle gave the best deposition on leaves and the lowest soil deposits. Similarly, retention decreased with nozzle size increase and increased with pressure decrease; however, soil deposits showed the opposite results.

The models developed within this paper, under our experimental conditions, can be further used to predict pesticide deposition on the foliage and those lost on the soil. Comparison with the results of others researches confirmed our approach. Improvement of these models may be through the expansion of the database by introducing other nozzle types, nozzle sizes and operating pressures.

REFERENCES

Allagui A. (2019): Caractérisation de l'efficacité agroenvironnementale des traitements phytosanitaires de l'artichaut pour une gestion respectueuse de l'environnement en Tunisie. [PhD. Thesis.] Sousse, University of Sousse.

Allagui A., Bahrouni H., M'Sadak Y. (2018): Deposition of pesticide to the soil and plant retention during crop spraying: The art state. Journal of Agricultural Science, 10: 104–115.

Bahrouni H., Sinfort C., Hamza E. (2008): Evaluation of pesticide losses during cereal crop spraying in Tunisian conditions. Journal of Agricultural Machinery Science, 4: 215–220.

Bonzanigo L., Giupponi C., Moussadek R. (2016): Conditions for the adoption of conservation agriculture in Central Morocco: An approach based on Bayesian network modelling. Italian Journal of Agronomy, 11: 24–34.

Creech C.F., Henry R.S., Fritz B.K., Kruger G.R. (2015): Influence of herbicide active ingredient, nozzle type, orifice size, spray pressure, and carrier volume rate on spray droplet size characteristics. Weed Technology, 29: 298–310.

De Oliveira A.R. (2018): The effect of physical application parameters on herbicide efficacy and droplet size. [PhD. Thesis.] Lincoln, University of Nebraska.

Dorr G.J., Kempthorne D.M., Mayo L.C., Forster W.A., Zabkiewicz J.A., McCue S.W., Belward J.A., Turner I., Hanan J. (2014): Towards a model of spray–canopy interactions: Interception, shatter, bounce and retention of droplets on horizontal leaves. Ecological Modelling, 290: 94–101.

Ferguson J.C. (2016): Towards the optimization of coarse sprays to reduce drift and improve efficacy in Australian cropping systems. [PhD. Thesis.] Brisbane, University of Queensland.

Forster W.A., Kimberley M.O., Zabkiewicz J.A. (2005): A universal spray droplet adhesion model. Transaction of The ASAE, 48: 1321–1330.

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: 2945–2957.

Lammertyn J., Aerts M., Verlinden B.E., Schotsmans W., Nicolai B.M. (2000): Logistic regression analysis of factors influencing core breakdown in 'Conference' pears. Postharvest Biology and Technology, 20: 25–37.

Li J., Cui H., Ma Y., Xun L., Li Z., Yang Z., Lu H. (2020): Orchard spray study: A prediction model of droplet deposition states on leaf surfaces. Agronomy, 10: 747. doi: 10.3390/agronomy10050747

Mercer G.N., Sweatman W.L., Elvin A., Caunce J., Fulford G., Harper G. (2007): Process driven models for spray retention in plants. In: Proceedings of the 2006 Mathematics-In-Industry Study Group. Wake G. (ed.) Wellington, Nov 2006: 57–85.

Ni Z., Phillips L.D., Hanna G.B. (2011): Exploring Bayesian belief networks using Netica. In: Athanasiou T., Darzi A. (eds): Evidence Synthesis in Healthcare. London, Springer-Verlag: 293–318.

Nuyttens D., Baetens K., De Schampheleire M., Sonck B. (2007): Effect of nozzle type, size and pressure on spray droplet characteristics. Biosystems Engineering, 97: 333–345.

Ozkan H.E. (2016): Effect of major variables on drift distances of spray droplets. Ohio State University Extension Service. Available at https://ohioline.osu.edu/factsheet/fabe-525

Peters T., Thostenson A., Nowatzki J., Hofman V., Wilson J. (2017): Selecting spray nozzles to reduce particle drift (AE1246). North Dakota State University Extension Service. Available at https://www.ag.ndsu.edu

Shaw D.R., Morris W.H., Webster E.P., Smith D.B. (2000): Effects of spray volume and droplet size on herbicide deposition and common cocklebur (*Xanthium strumarium*) control. Weed Technology, 14: 321–326.

Teske M.E., Bird S.L., Esterly D.M., Curbishley T.B., Ray S.L., Perry S.G. (2002): AgDRIFT: A model for estimating near-field spray drift from aerial applications. Environmental Toxicology and Chemistry, 21: 659–671.

Uyanik G.K., Güler N. (2013): A study on multiple linear regression analysis. Procedia-Social and Behavioral Sciences, 106: 234–240.

Van de Zande J.C., Butler Ellis C., Douzals J.P., Stallinga H., Van Velde P., Michielsen J.M.G.P. (2017): Spray drift reduction of the MagGrow spray system – Effect of magnetism, nozzle type, end nozzle and spray boom height. Wageningen, Wageningen University Research – WUR.

https://doi.org/10.17221/29/2021-PPS

Wang F., Hu Z., Abarca C., Fefer M., Liu J., Brook M.A., Pelton R.H. (2018): Factors influencing agricultural spray deposit structures on hydrophobic surfaces. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 553: 288–294.

Womac A.R., Bui J.S. (2002): Design and tests of a variable-flow fan nozzle. Transactions of the ASAE, 45: 287–295.

Yao C., Myung K., Wang N., Johnson A. (2014): Spray retention of crop protection agrochemicals on the plant surface. American Chemical Society Publications. In: Retention, Uptake, and Translocation of Agrochemicals in Plants. ACS Symposium Series, 1171: 1–22.

Zhu H., Dorner J.W., Rowland D.L., Derksen R.C., Ozkan H.E. (2004): Spray penetration into peanut canopies with hydraulic nozzle tips. Biosystems Engineering, 87: 275–283.

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