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Evaporation and coverage area of pesticide droplets on hairy and waxy leaves

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The fate of pesticide droplets on leaves is significantly influenced by the fine structures found on leaf surfaces. Evaporation times and the maximum coverage areas of single droplets (246, 343, 575, 762, and 886 μm) on hairy and waxy geranium leaf surfaces were determined under controlled conditions. Stereoscopic sequential images of the droplet evaporation processes were taken for five droplet sizes, three relative humidity (RH) conditions and 13 different sprays. The sprays were combinations of water, a non-ionic colloidal polymer drift retardant, an alkyl polyoxyethylene surfactant, a fungicide and three insecticides. The evaporation time and maximum coverage area of droplets were significantly changed by adding the surfactant or drift retardant to the sprays, but not by adding fungicide or insecticide. Droplet evaporation times on waxy leaves were longer than those on hairy leaves. Evaporation times increased exponentially as droplet diameter and RH increased with limited variability of regression coefficients independent of spray type and leaf surface. The maximum coverage area of droplets also increased exponentially as droplet diameter increased but it was not significantly affected by RH. On the waxy geranium leaf surfaces, the coverage area of pesticide droplets decreased throughout the evaporating process and at all RH conditions, while, on hairy leaf surfaces for the same size droplets, and at the same RH conditions, the coverage area continued to spread until evaporation was nearly completed. Given that the duration of evaporation time and the extent of the coverage area affect pesticide distribution on waxy or hairy leaves, recommendations for pesticide dosage and spray methods should be taken into account for different leaf surfaces to obtain the optimum biological effect and reduced pesticide use.

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1. Introduction

Sprayer operating conditions, the physical properties of the spray mixture, the fine structures of leaf surfaces, and the prevailing microclimate are all factors that can alter the efficacy and the efficiency of pesticide applications (Reichard *et al.*, 1986; Fox *et al.*, 1992). The hydrophilic or hydrophobic properties of leaf surfaces are usually characterised by droplet contact angle. If the value of the contact angle is less than 90° the surface is hydrophilic while if the value of the contact angle is greater than

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Nomenclature

A Maximum coverage area (mm^2)
a_0, a_1 and a_2 Regression coefficients for the evaporation time equation
b_0, and b_1 Regression coefficients for the maximum coverage area equation
T Evaporation time (s)
X Droplet diameter (μm)
Y Relative humidity (%)

90° the surface is hydrophobic (Haines *et al*., 1985; Brewer and Smith, 1997; Wagner *et al*., 2003). These characteristics depend on the type and amount of leaf wax, surface energy, roughness, and surface cleanliness (Adamson, 1990; Israelachvili, 1992; Journet *et al*., 2005).

Several studies have investigated the role of leaf surface microstructure in relation to pesticide or herbicide spread and absorption with scanning electron micrographs of leaf surfaces (Chachalis *et al*., 2001a, 2001b; Hatterman-Valenti *et al*., 2006). In general, the amount of wax and the spray droplet coverage has been found to be inversely related. Long-chain hydrocarbons are highly hydrophobic, whereas alcohols and acids are relatively hydrophilic. The density of trichomes (the fine outgrowths of hair on leaves) has been found to have a greater influence on droplet coverage than the trichome length because closely spaced trichomes appear to produce air pockets beneath the droplets that prevent leaf surface contact (Hess *et al*., 1974). The presence of a large number of glandular trichomes may result in increased micro-roughness and hence the greater spreading of droplets (McWhorter, 1993).

Spray additives such as non-ionic colloidal polymer drift retardants or alkyl polyoxyethylene surfactants are widely used in foliar applications to reduce spray drift and to increase leaf wetness. Drift retardants have been reported to increase deposition of pesticide on cotton leaf surfaces (Mulrooney, 2002). Spray deposition, adhesion, droplet coverage, and retention on leaves were found to be enhanced when non-ionic surfactants were added into spray mixtures (Nalewaja and Matysiak, 2000; Basu *et al*., 2002). With surfactants, Baur (2006) found that smaller droplets had improved retention and spread more efficiently on leaves than larger droplets. When surfactants are used, the foliar uptake of pesticides from droplets and the biological efficacy of the active ingredients were improved (Holloway and Silcox, 1985; Zabkiewicz *et al*., 1985; Holloway *et al*., 1992; Uhlig and Wissemeier, 2000; Brazee *et al*., 2004). Reports also indicated that surfactants altered the size of droplets produced in sprays (Ellis *et al*., 2001; Ramsdale and Messersmith, 2001; Stainier *et al*., 2006; Spanoghe *et al*., 2007). However, the amount of surfactants to be added to sprays should be carefully monitored because residue patterns of droplets on surfaces vary with the concentration of added surfactants (Pierce *et al*., 2008).

Relative humidity (RH) greatly influences droplet evaporation rate and deposition on targets (Yu *et al*., 2009). Vesala and Kukkonen (1992) found that regardless of the initial droplet size, the deposited mass fraction decreased as RH increased. Jung and Bhushan (2006) reported that the adhesion and friction between artificially induced rough surfaces and droplets increased with increasing RH.

Spray deposition and coverage are the two major components of spray performance. Although numerous studies have been reported on methods to maximise deposition and coverage of droplets on target surfaces, current application technologies are still highly inefficient. This can lead to excessive amounts of pesticides being applied with greater cost and with increased contamination of the environment. The amount of pesticides used could be reduced if spray coverage per litre used was increased.

Little research has been carried out on how droplets spread and how long the droplets last on target surfaces; i.e., the evaporation time of droplets on different types of leaves, which directly influences the morphology and absorption of active ingredients. Increasing the lifetimes of spray droplets on leaves increases the absorption and uptake of active ingredients (Knoche and Bukovac, 1994; Knoche *et al*., 2000). Also, longer lifetimes can prevent ingredients forming crystals. Once droplets completely evaporate, leaves may stop absorbing chemicals (Ramsey *et al*., 2005), and if the droplets do not spread out evenly on leaves chemical residues may be formed as large crystals. Crystals may be suspended and removed from their target site by wind further reducing chemical effectiveness. Therefore, information on the evaporation time and spreading area of pesticide droplets on plant leaf surfaces can assist pesticide formulators to develop better products that can maximise uptake by leaves. It can also help spray applicators to maximise efficacy and minimise chemical use by selecting optimal droplet sizes and chemical formulations for the specific crops under specific environmental conditions.

Droplet size, RH, leaf surface fine structure and spray formulation are well known factors that influence droplet evaporation and spread on leaves. However, quantitative information on the influences is lacking. The objective of this research was to determine effects of individual variables including surfactant, drift retardant, droplet size, and RH on the evaporation and maximum coverage area of single droplets deposited on waxy and hairy leaf surfaces, in an effort to further maximise pesticide spray application efficiency and reduce pesticide use. Experiments were conducted under the controlled conditions to avoid interferences among these variables that could not be controlled under the field conditions. The maximum coverage area of a droplet in this paper is defined as the observed maximum area of droplet deposition on the target surface.

2. Materials and methods

An investigation of droplet evaporation and coverage area on different target surfaces was conducted using a custom-built, experimental system. The system was constructed with a RH control unit, a target holding chamber, a stereoscope fitted with a high definition digital camera, and a single droplet generator (Zhu *et al.*, 2008). With this system, individual factors such as droplet diameter, RH, spray formulation and leaf surface structure were controlled separately.

The RH control unit was designed to generate air with a constant RH ranging from 10% to 90%. The target holding chamber was insulated from the environment and was used to position targets and single droplets in X–Y directions along the plane of the leaf surface. A stereoscope (Model SZX12, Olympus, Japan) and a digital camera (Insight Firewire© Model SZX-TB1, Olympus, Japan) were used to take sequential images of droplets at regular, timed intervals while evaporation proceeded. An imaging program (Spot, Diagnostic Instruments, Inc., Sterling Heights, MI, USA) was used to record and save the sequential images. Droplet evaporation time was measured from the total number of sequential images and intervals after the droplet was deposited. The maximum coverage area of droplets after spreading was measured with Polygonal Hand-trace Feature in ImagePro Plus (version 4.1, Media Cybernetics, Bethesda, MD, USA). The droplet generator was a microprocessor-based time mode, air-powered fluid dispenser (Model 2405, EFD Inc., East Providence, RI, USA) that could produce a single droplet with a diameter in the range 200–2000 μm. A detailed description of the system including the determination of droplet sizes was reported by Zhu *et al.* (2008).

This study examined two different surface leaves (hairy and waxy surfaces), three RH conditions (30, 60 and 90%), five droplet sizes (246, 343, 575, 762, and 886 μm) and 13 liquid sprays formed by combinations of three insecticides, a fungicide, a non-ionic colloidal polymer drift retardant, an alkyl polyoxyethylene surfactant, and distilled water. The droplet diameters used were in the range commonly used in pesticide spray applications to reduce drift potentials.

Details of the pesticide formulations, three insecticides, one fungicide, one drift retardant and one surfactant are listed in Table 1. These materials are examples of chemicals commonly used in foliar spray applications. Each of the materials contained a different active ingredient, and was presented either as a powder or liquid formulation. They were mixed with distilled water to form 13 sprays for the tests (Table 2). Surface tension and viscosity of the sprays were also reported in Table 2. The surface tension was measured with a Semiautomatic tensiometer (Model 21 Tensiomat®, Fisher Scientific, Park Lane, Pittsburgh, PA, USA), and viscosity was measured using a glass capillary viscometer (No. E335/150, Cannon Instrument Company, State College, PA, USA).

Plant species with different surface properties were selected from the *Pelargonium* collection of the Ornamental Plant Germplasm Centre (OPGC), Columbus, OH, USA. This collection provided an opportunity to select genetically related plant material with widely varying leaf phenotypes. A plant species that appeared to have waxy deposits and few hairs (*Pelargonium stenopetalum*; OPGC accession number 566) and a species with many hairs on the surface (*Pelargonium tomentosum*; OPGC accession number 521) were selected. A representative image of the surface structures of the two species is shown in Fig. 1. Trichome lengths and density were measured by analysing digital images of the leaf surface using a digital magnifying camera and 40× magnification (IPM Scope, Spectrum Technologies, Plainfield, IL, USA) and an imaging program (Assess, American Phytopathology Society, Madison, WI, USA). The abaxial side of freshly cut leaf samples (20 mm by 20 mm) was secured onto a glass plate with double-sided adhesive tape and then placed into an environmentally-controlled chamber for tests. For each measurement, only a single droplet was deposited on the leaf by direct contact. This was followed by the process of taking sequential images of the droplet spreading and evaporation process. The contact angle of a 343 μm diameter water droplet on the waxy leaf surface was 84.5°. When the drift retardant was added to the water it became 86°, but 30° when the surfactant was added into water. The contact angle of droplets on hairy leaf surfaces was not obtained because long hairs prevented measurement viewing angles for the measurement.

For comparison purposes in Section 3, data for hydrophilic and hydrophobic slide surfaces from previous work reported by Yu *et al.* (2009) are used. The hydrophilic surface used was a smooth wax-free glass microscope slide, and the

Table 1 – Formulation, active ingredient and concentration of chemicals used to form mixtures in tests

Chemicals	Trade name	Formulation	Active ingredient	Concentration[a]
Drift retardant	Strike zone[b]	Powder	100% Proprietary blend of poly-ammonium, phosphates, ammonium carboxylates, potassium phosphates, phosphoric acid.	$0.46\ \mathrm{mg\,l^{-1}}$
Surfactant	X-77[c]	Liquid	90% Alkyl polyoxyethylene and 10% constituents ineffective as adjuvants.	$7.52\ \mathrm{ml\,l^{-1}}$
Fungicide	Banner Max[d]	Powder	14.3% Propiconazole and 85.7% others.	$1.5\ \mathrm{g\,l^{-1}}$
Insecticide No. 1	Celero 16 WSG[e]	Powder	16% Clothianidin and 84% inert ingredients.	$0.23\ \mathrm{g\,l^{-1}}$
Insecticide No. 2	Marathon II[f]	Liquid	21.4% Imidacloprid and 78.6% others.	$0.13\ \mathrm{ml\,l^{-1}}$
Insecticide No. 3	Safari 20 SG[g]	Powder	20% Dinotefuran and 80% others.	$0.45\ \mathrm{g\,l^{-1}}$

[a] Concentration of the chemical in distilled water.
[b] From Helena Chemical Company, Collierville, TN, USA.
[c] From Loveland Industries Inc., Greeley, CO, USA.
[d] From Syngenta Crop Protection, Inc., Greensboro, NC, USA.
[e] From Arysta Lifescience North America Corporation, San Francisco, CA, USA.
[f] From Olympic Horticultural Products Company, Mainland, PA, USA.
[g] From Valent USA Corporation, Walnut Creek, CA, USA.

Table 2 – Surface tension and viscosity of spray mixtures used in tests. Standard deviations are presented in the parentheses

Spray No.	Spray type[a]	Surface tension (mN m^{-1})	Viscosity (mPa s)
1	Water only	71.7(0.3)	0.97(0.06)
2	Fungicide	67.8(0.1)	0.99(0.04)
3	Insecticide No. 1	69.3(0.4)	0.99(0.07)
4	Insecticide No. 2	64.3(0.2)	0.97(0.09)
5	Insecticide No. 3	68.3(0.2)	0.97(0.07)
6	Fungicide + drift retardant	68.4(0.1)	1.18(0.03)
7	Insecticide No. 1 + drift retardant	68.4(0.5)	1.13(0.06)
8	Insecticide No. 2 + drift retardant	68.2(0.2)	1.11(0.11)
9	Insecticide No. 3 + drift retardant	69.8(0.31)	1.17(0.05)
10	Fungicide + surfactant	39.7(0.2)	1.84(0.25)
11	Insecticide No. 1 + surfactant	35.5(0.1)	1.25(0.03)
12	Insecticide No. 2 + surfactant	39.1(0.4)	1.91(0.15)
13	Insecticide No. 3 + surfactant	40.6(0.1)	1.4(0.14)

a All sprays used water as the carrier.

hydrophobic surface was the same hydrophilic slide coated with a thin layer of transparent liquid wax.

The same group of data was first analysed using a one-way analysis of variance (ANOVA) to test null hypothesis that all treatments had equal means with Duncan's methods using ProStat version 3.8 (Poly Software International, Inc., Pearl River, NY, USA). If the null hypothesis was rejected, the multiple comparison procedure was used to determine differences among means. All differences were determined at the 0.05 level of significance.

3. Results and discussion

3.1. Leaf surface structures

No trichomes were present on the waxy geranium (*P. stenopetalum*) leaf surface, while the trichomes on the hairy geranium (*P. tomentosum*) leaf surface were in 4 different lengths. Surfaces designated as having short trichome lengths had an average length of 93 μm, those with lengths of 227 μm were designated as medium, those with 529 μm were designated long, and those with 1231 μm designated extremely long trichome. The average density of all hairs on this species was 400 trichomes per cm^2.

3.2. Evaporation time

At 0.05 level of significance, the type and concentration of pesticides (fungicide, insecticide No. 1, insecticide No. 2 and insecticide No. 3) did not significantly influence the evaporation time of droplets from sprays of water only, water mixed with drift retardant, or water mixed with surfactant. This trend was also true for the maximum droplet coverage area. Because of this matter, the results from the fungicide, insecticide No. 1, insecticide No. 2 and insecticide No. 3 were unified and simply defined as pesticide. Their droplet evaporation times and maximum coverage areas for each treatment were averaged as a group.

Alike to the results on hydrophilic, hydrophobic, and crabapple leaf surfaces reported by Yu *et al.* (2009), the evaporation time of droplets on hairy and waxy geranium leaf surfaces was greatly influenced by droplet size, RH and surfactant (Tables 3 and 4). The drift retardant also influenced the evaporation time, but the degree of influence was not as great as droplet size, RH and surfactant.

Fig. 2 illustrates the comparison of evaporation time of droplets containing water and insecticide No. 3 on hairy leaf, waxy leaf, hydrophilic surface, and hydrophobic surface for droplet sizes ranging from 246 μm to 886 μm at 60% RH. Among the four surfaces, droplets had the longest evaporation time on the hydrophobic surface, followed by waxy leaf, hydrophilic surface, and had the shortest evaporation time on the hairy leaf. For a 343 μm water droplet containing insecticide No. 3 at 60% RH, the evaporation time was 99 s on the hydrophobic surface, 80 s on the waxy leaf, 63 s on the hydrophilic surface, and 47 s on the hairy leaf. Droplet evaporation times for all sprays varied greatly with the fine structure of the target surface.

Evaporation time increased when the drift retardant was added to sprays, and decreased when the surfactant was added into the sprays. For example, the average evaporation

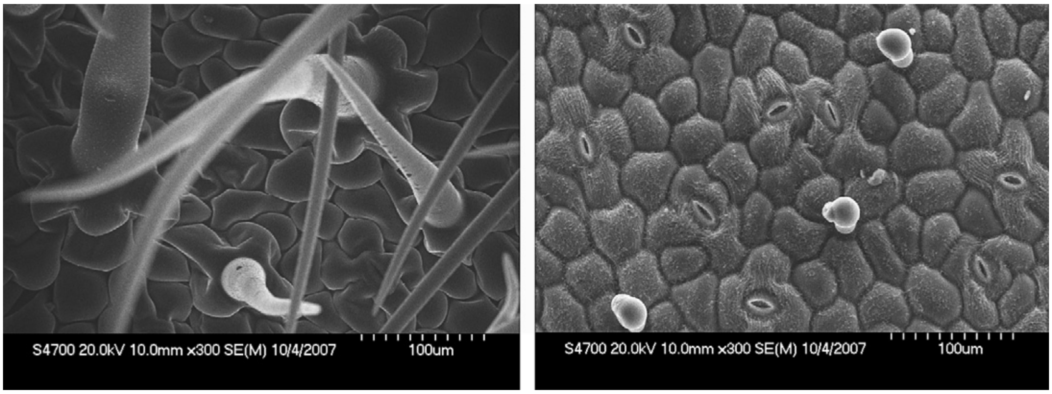


Fig. 1 – The fine-surface structures of hairy (left) and waxy (right) geranium leaves observed by Scanning Electronic Microscope with 300× magnification.

Table 3 – Mean evaporation time (s) of droplets containing different spray mixtures on hairy geranium leaf at three values of RH. Standard deviations are presented in the parentheses

Sprays[a]	RH (%)	Droplet diameter (μm)				
		246	343	575	762	886
Water only	30	12(1)	25(3)	73(13)	166(7)	277(12)
Water only	60	19(6)	41(10)	109(10)	220(9)	357(17)
Water only	90	40(3)	71(9)	157(12)	292(21)	480(58)
Pesticide[b]	30	15(3)	36(6)	83(8)	165(13)	280(19)
Pesticide	60	23(4)	48(7)	112(12)	212(12)	359(44)
Pesticide	90	42(8)	80(9)	157(19)	286(20)	444(31)
Pesticide + drift retardant	30	23(4)	49(10)	102(15)	196(25)	325(39)
Pesticide + drift retardant	60	35(5)	77(9)	149(23)	263(28)	423(31)
Pesticide + drift retardant	90	57(7)	107(10)	198(24)	333(20)	517(32)
Pesticide + surfactant	30	6(1)	14(2)	31(5)	58(10)	92(20)
Pesticide + surfactant	60	10(2)	21(4)	43(9)	81(8)	134(29)
Pesticide + surfactant	90	17(3)	39(5)	72(13)	123 (23)	199(32)

a All sprays used water as the carrier.
b Evaporation time for pesticide was averaged from values of fungicide, insecticide No. 1, insecticide No. 2 and insecticide No. 3.

time of 343 μm water droplets containing pesticides (Table 3) at 60% RH on the hairy geranium surface increased 60% (i.e., from 48 s to 77 s) after the drift retardant was added to the spray, but decreased 56% (i.e., from 48 s to 21 s) after the surfactant was added into the spray.

The relative percent change in evaporation time for droplets with either drift retardant or surfactant varied with the structure of the target surface. Fig. 3 shows relative percent increase in evaporation time of water droplets containing insecticide No. 3 on the hairy leaf, the waxy leaf, the hydrophilic surface, and the hydrophobic surface at 60% RH after drift retardant was added. Among the four surfaces, the hairy leaf had the highest relative percent increase in evaporation time and the waxy leaf had the lowest relative percent increase among droplet diameters ranging from 246 μm to 886 μm. For example, when droplet diameter increased from 246 μm to 886 μm, the relative percent increase in evaporation time due to the addition of the drift retardant into the water spray decreased from 73% to 22% on hairy leaf surfaces, and decreased from 21% to 10% on waxy leaf surfaces.

Similarly, Fig. 4 illustrates the relative percent reduction in evaporation time due to addition of the surfactant at 60% RH for different size droplets containing the mixture of water and insecticide No. 3 on the four different target surfaces. The relative percent reduction varied considerably with the type of target surfaces, but did not vary with droplet size. The average relative percentage reduction in evaporation time due to addition of the surfactant for the five droplet sizes was 57% on hairy leaf surface, while only 29% on waxy leaf, 23% on hydrophobic surface, and 25% on the hydrophilic surface. After a surfactant was added, the relative percent reduction of droplet evaporation time on hairy leaves was nearly twice as great as on waxy leaves.

Table 4 – Mean evaporation time (s) of droplets containing different spray mixtures on waxy geranium leaf at three values of RH. Standard deviations are presented in the parentheses

Sprays[a]	RH (%)	Droplet diameter (μm)				
		246	343	575	762	886
Water only	30	23(2)	45(3)	99(6)	196(3)	315(12)
Water only	60	35(7)	64(5)	156(4)	302(12)	448(21)
Water only	90	58(8)	116(16)	249(8)	500(9)	768(32)
Pesticide[b]	30	26(3)	52(6)	105(7)	201(10)	337(22)
Pesticide	60	40(9)	72(9)	150(15)	275(15)	453(37)
Pesticide	90	64(6)	115(13)	235(16)	441(26)	734(22)
Pesticide + drift retardant	30	34(3)	71(4)	133(8)	242(10)	395(21)
Pesticide + drift retardant	60	50(6)	92(6)	181(16)	315(20)	519(32)
Pesticide + drift retardant	90	91(10)	161(11)	294(31)	521(31)	835(38)
Pesticide + surfactant	30	13(2)	31(5)	65(7)	126(15)	242(17)
Pesticide + surfactant	60	26(3)	53(4)	111(6)	201(14)	324(31)
Pesticide + surfactant	90	42(6)	78(8)	165(15)	304(28)	490(35)

a All sprays used water as the carrier.
b Evaporation time for pesticide was averaged from values of fungicide, insecticide No. 1, insecticide No. 2 and insecticide No. 3.

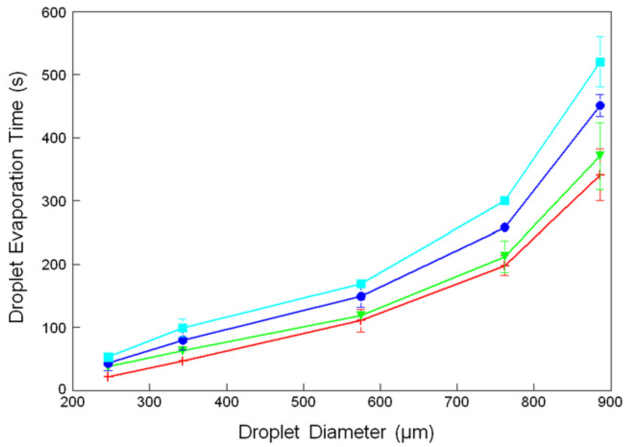


Fig. 2 – Evaporation time of different size droplets containing insecticide No. 3 on hairy leaf, hydrophilic surface, waxy leaf and hydrophobic surface at 60% RH. Data for droplet evaporation on hydrophilic and hydrophobic surfaces are from Yu *et al.* (2009). Error bars represent standard deviations around means (+ Hairy leaf, ▼ Hydrophilic surface, ● Waxy leaf, and ■ Hydrophobic surface).

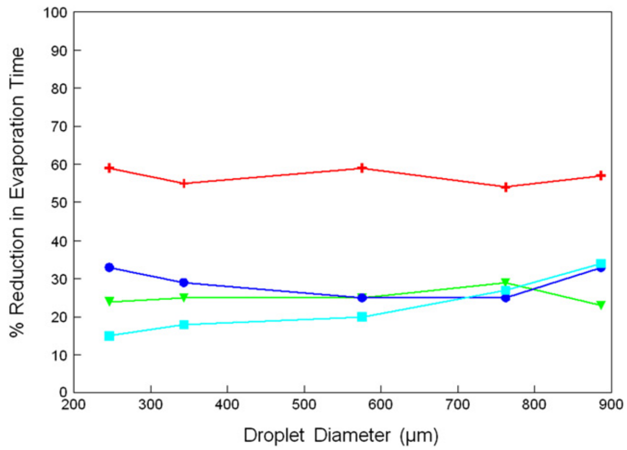


Fig. 4 – Relative percent reduction in evaporation time of different size droplets containing insecticide No. 3 on hairy leaf, hydrophilic surface, waxy leaf and hydrophobic surface at 60% RH after surfactant was added. Data for droplet evaporation on hydrophilic and hydrophobic surfaces are from Yu *et al.* (2009) (+ Hairy leaf, ▼ Hydrophilic surface, ● Waxy leaf, and ■ Hydrophobic surface).

The evaporation time increased as droplet size and RH increased (Tables 3 and 4), and their relationship could be expressed as an exponential function.

$$T = a_0 e^{a_1 X + a_2 Y} \tag{1}$$

Where, T is the evaporation time (s), X is droplet diameter (μm) and Y is RH (%). a_0, a_1 and a_2 are the regression coefficients, and their values for all the sprays on hairy and waxy leaves are shown in Table 5. The selection of the exponential function was based on the fact that the coefficient of determination (R^2) values for regression equations of the exponential function ranged from 0.97 to 0.99, which was higher than the ones for the reciprocal, logarithmic, power, and logistic growth curve functions. Interestingly, the values of a_1 and a_2 were consistent for all sprays and leaf type while the values of a_0 varied greatly with the leaf type and sprays containing pesticides, drift retardant, or surfactant. With the averaged values of a_1 and a_2 for all sprays and leaves shown in Table 5, Eq. (1) was simplified to:

$$T = a_0 e^{0.0038X + 0.0134Y} \tag{2}$$

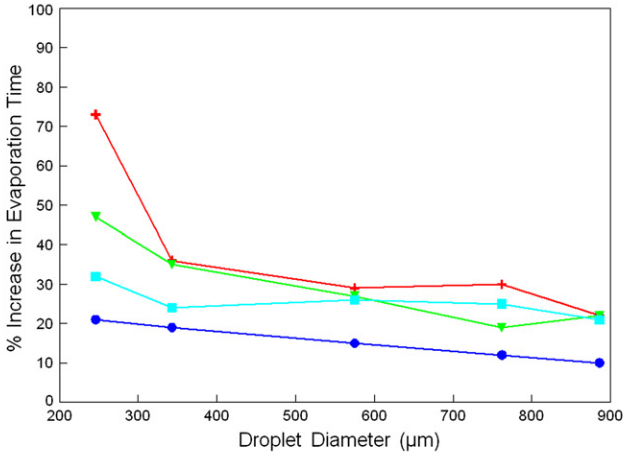


Fig. 3 – Percent increase in evaporation time increase of different size droplets containing insecticide No. 3 on hairy leaf, hydrophilic surface, waxy leaf and hydrophobic surface at 60% RH after drift retardant was added. Data for droplet evaporation on hydrophilic and hydrophobic surfaces are from Yu *et al.* (2009) (+ Hairy leaf, ▼ Hydrophilic surface, ● Waxy leaf, and ■ Hydrophobic surface).

On waxy leaves, the evaporation time of 343 μm water droplets containing the pesticide increased from 52 s to 115 s when RH increased from 30% to 90% (Table 4). Hence, it is important to include RH in allocation guidelines for applications such as formulation preparations and best pesticide management programmes to assure that a longer droplet evaporation time is incorporated for systemically active chemicals.

3.3. *Maximum deposit coverage area*

As mentioned before, the type of pesticides (fungicide, insecticide No. 1, insecticide No. 2 and insecticide No. 3) did not make a significant difference to the maximum coverage area. The maximum coverage areas of droplets of five different sizes containing different additive sprays on hairy and waxy leaves are presented in Tables 6 and 7. These data illustrate that maximum coverage area significantly increased after the surfactant was added to the sprays. For example, the maximum coverage area of 343 μm droplet

Table 5 – Regression coefficients for the exponential function $T = a_0 e^{a_1 X + a_2 Y}$ shown in Eq. (1) for different spray droplets on hairy and waxy leaf surfaces.[a] T – Evaporation time (s), X – droplet diameter (μm), Y – RH (%)

Sprays[b]	Hairy leaf			Waxy leaf		
	a_0	a_1	a_2	a_0	a_1	a_2
Water only	3.67	0.0043	0.0138	6.32	0.0039	0.0154
Fungicide	5.70	0.0039	0.0123	7.85	0.0038	0.0160
Insecticide No. 1	5.59	0.0040	0.0118	8.55	0.0037	0.0123
Insecticide No. 2	5.48	0.0040	0.0110	8.13	0.0038	0.0121
Insecticide No. 3	5.24	0.0040	0.0115	8.35	0.0036	0.0139
Fungicide + drift retardant	8.71	0.0035	0.0122	10.72	0.0034	0.0155
Insecticide No. 1 + drift retardant	9.52	0.0036	0.0109	11.72	0.0034	0.0137
Insecticide No. 2 + drift retardant	8.08	0.0036	0.0130	12.55	0.0034	0.0133
Insecticide No. 3 + drift retardant	9.01	0.0036	0.0104	11.35	0.0035	0.0122
Fungicide + surfactant	2.10	0.0036	0.0125	3.89	0.0038	0.0186
Insecticide No. 1 + surfactant	1.74	0.0038	0.0162	4.00	0.0038	0.0141
Insecticide No. 2 + surfactant	2.02	0.0038	0.0127	4.02	0.0041	0.0147
Insecticide No. 3 + surfactant	1.81	0.0040	0.0149	4.93	0.0038	0.0140
Average	5.28	0.0038	0.0126	7.88	0.0037	0.0143
CV (%)	54.6	6.1	13.1	39.2	5.9	12.6

[a] Coefficient of determination R^2 for all the regression equations was greater than 0.92.

[b] All sprays used water as the carrier.

containing insecticide No. 3 at 60% RH increased 4.2 times (from 0.422 mm^2 to 1.757 mm^2) on the hairy leaf and increased 5 times (from 0.249 mm^2 to 1.244 mm^2) on the waxy leaf after the surfactant was added. However, adding a drift retardant to the sprays did not change the maximum coverage area as much as a surfactant. In general, the maximum coverage area increased slightly when a drift retardant was added to the sprays. Similarly, changing RH did not change the maximum coverage area significantly ($p < 0.05$) because the maximum coverage area was reached shortly after deposition.

The maximum coverage area on hairy and waxy geranium leaf surfaces increased as droplet diameter increased for all the sprays and RH conditions (Tables 6 and 7). For the insecticide No. 3 solution on hairy leaves at 60% RH, the maximum droplet coverage area increased from 0.132 mm^2 to 2.591 mm^2 (or 19.6 times) when droplet diameter increased from 246 μm to 886 μm (or 3.6 times) or droplet volume increased 46.7 times. For the same range of droplet sizes, the maximum droplet coverage area increased from 0.156 mm^2 to 1.082 mm^2 (6.9 times) on waxy leaves. Similarly to evaporation time results reported above, the maximum droplet coverage area on both hairy and waxy leaves increased exponentially as droplet diameter increased.

$$A = b_0 e^{b_1 X} \tag{3}$$

Table 6 – Mean maximum deposition coverage area (mm^2) of droplets containing different mixtures on hairy geranium leaf at three values of RH. Standard deviations are presented in the parentheses

Sprays[a]	RH (%)	Droplet diameter (μm)				
		246	343	575	762	886
Water only	30	0.081(0.005)	0.150(0.033)	0.260(0.049)	0.537(0.054)	0.644(0.010)
Water only	60	0.092(0.020)	0.119(0.018)	0.226(0.044)	0.417(0.032)	0.714(0.018)
Water only	90	0.150(0.019)	0.227(0.027)	0.351(0.061)	0.661(0.170)	1.225(0.235)
Pesticide[b]	30	0.132(0.018)	0.185(0.028)	0.340(0.055)	0.635(0.062)	1.105(0.206)
Pesticide	60	0.126(0.025)	0.286(0.063)	0.517(0.085)	0.915(0.120)	1.524(0.266)
Pesticide	90	0.161(0.030)	0.232(0.036)	0.385(0.059)	0.684(0.070)	0.982(0.087)
Pesticide + drift retardant	30	0.143(0.020)	0.234(0.028)	0.436(0.079)	0.747(0.157)	0.946(0.142)
Pesticide + drift retardant	60	0.228(0.068)	0.357(0.054)	0.597(0.097)	1.205(0.152)	1.880(0.277)
Pesticide + drift retardant	90	0.161(0.025)	0.269(0.029)	0.486(0.062)	0.864(0.101)	1.201(0.197)
Pesticide + surfactant	30	0.778(0.254)	1.034(0.529)	2.321(0.818)	3.185(0.669)	6.337(2.122)
Pesticide + surfactant	60	1.275(0.210)	1.991(0.554)	2.846(0.770)	4.938(1.489)	6.856(2.113)
Pesticide + surfactant	90	1.272(0.266)	1.594(0.314)	3.157(0.670)	4.882(0.840)	7.605(1.215)

[a] All sprays used water as the carrier.

[b] Coverage area for pesticide was averaged from values of fungicide, insecticide No. 1, insecticide No. 2 and insecticide No. 3.

Table 7 – Mean maximum deposition coverage area (mm^2) of droplets containing different mixtures on waxy geranium leaf at three values of RH. Standard deviations are presented in the parentheses

Sprays[a]	RH (%)	Droplet diameter (μm)				
		246	343	575	762	886
Water only	30	0.123(0.012)	0.208(0.016)	0.363(0.019)	0.787(0.006)	1.198(0.019)
Water only	60	0.199(0.052)	0.230(0.027)	0.444(0.002)	1.052(0.123)	1.401(0.074)
Water only	90	0.119(0.014)	0.193(0.013)	0.405 (0.104)	0.647(0.056)	0.999(0.062)
Pesticide[b]	30	0.140(0.026)	0.256(0.036)	0.450(0.022)	0.778(0.072)	1.187(0.130)
Pesticide	60	0.165(0.033)	0.257(0.040)	0.536(0.052)	0.944(0.095)	1.373(0.114)
Pesticide	90	0.154(0.016)	0.264(0.066)	0.445(0.057)	0.805(0.071)	1.232(0.124)
Pesticide + drift retardant	30	0.172(0.016)	0.301(0.029)	0.610(0.036)	0.963(0.046)	1.4260.091)
Pesticide + drift retardant	60	0.196(0.031)	0.324(0.056)	0.607(0.065)	1.074(0.207)	1.406(0.184)
Pesticide + drift retardant	90	0.200(0.034)	0.348 (0.045)	0.630(0.065)	1.147(0.116)	1.700(0.145)
Pesticide + surfactant	30	0.477(0.035)	0.989(0.097)	2.005(0.119)	3.825(0.163)	5.846(0.389)
Pesticide + surfactant	60	0.692(0.127)	1.115(0.065)	2.136(0.111)	3.944(0.152)	5.606(0.376)
Pesticide + surfactant	90	0.544(0.117)	0.948(0.045)	1.769(0.095)	3.120 (0.248)	4.281(0.295)

a All sprays used water as the carrier.

b Coverage area for pesticide was averaged from values of fungicide, insecticide No. 1, insecticide No. 2 and insecticide No. 3.

Where, A is the maximum coverage area (mm^2), b_0 and b_1 are regression coefficients, and their values for all the sprays on hairy and waxy leaves are shown in Table 8. Alike to the values of a_0 and a_1 in Eq. (1), the value of b_0 varied with leaf type and spray, but b_1 was always consistent.

The maximum coverage area varied greatly with the type of fine structures of target surface (Tables 6 and 7). Among the four different target surfaces, droplets on hydrophilic surface had the greatest maximum coverage area and droplets on hairy leaf had the lowest coverage area (Fig. 5). For example, the maximum coverage area of a 343 μm droplet containing water and insecticide No. 3 at 60% RH was 0.664 mm^2 on the hydrophilic surface, 0.169 mm^2 on the hydrophobic surface, 0.212 mm^2 on the waxy leaf surface and 0.149 mm^2 on the hairy leaf surface. However, when the surfactant was added to the sprays, the maximum coverage area greatly increased. Within the range of relative humility from 30% to 90% and droplet diameter from 246 μm to 886 μm, the maximum coverage area increased 4.5–10.1 times on the hairy geranium leaf (calculated from Table 6) and 3.4–4.9 times on waxy geranium leaf (calculated from Table 7) after the surfactant was added to the spray.

For droplets containing surfactant, the evaporation process and the coverage pattern formation with time performed differently on hairy and waxy leaves. Compared to the droplet deposited on the waxy leaves (Fig. 6), the droplet coverage area spread greatly after it was deposited on the hairy leaves (Fig. 7). For example, the droplet coverage area

Table 8 – Regression coefficients for the exponential function shown in Eq. (3) for different spray droplets on hairy and waxy leaf surfaces. A is the maximum deposition coverage area (mm^2), and X is droplet diameter (μm)

Sprays[a]	Hairy leaf			Waxy leaf		
	b_0	b_1	r^2	b_0	b_1	R^2
Water only	0.050	0.0031	0.90	0.065	0.0033	0.96
Fungicide	0.067	0.0030	0.97	0.063	0.0030	0.95
Insecticide No. 1	0.056	0.0031	0.97	0.057	0.0032	0.93
Insecticide No. 2	0.052	0.0032	0.88	0.053	0.0033	0.97
Insecticide No. 3	0.067	0.0033	0.89	0.068	0.0032	0.97
Fungicide + drift retardant	0.086	0.0032	0.97	0.107	0.0029	0.95
Insecticide No. 1 + drift retardant	0.079	0.0031	0.93	0.072	0.0033	0.94
Insecticide No. 2 + drift retardant	0.086	0.0031	0.93	0.093	0.0031	0.91
Insecticide No. 3 + drift retardant	0.077	0.0032	0.87	0.078	0.0032	0.95
Fungicide + surfactant	0.529	0.0027	0.90	0.245	0.0033	0.95
Insecticide No. 1 + surfactant	0.567	0.0027	0.87	0.278	0.0031	0.90
Insecticide No. 2 + surfactant	0.550	0.0032	0.93	0.251	0.0036	0.93
Insecticide No. 3 + surfactant	0.598	0.0028	0.87	0.301	0.0034	0.95
Average	0.220	0.0031		0.133	0.0032	
CV (%)	107.6	6.5		72.1	5.5	

a All sprays used water as the carrier.

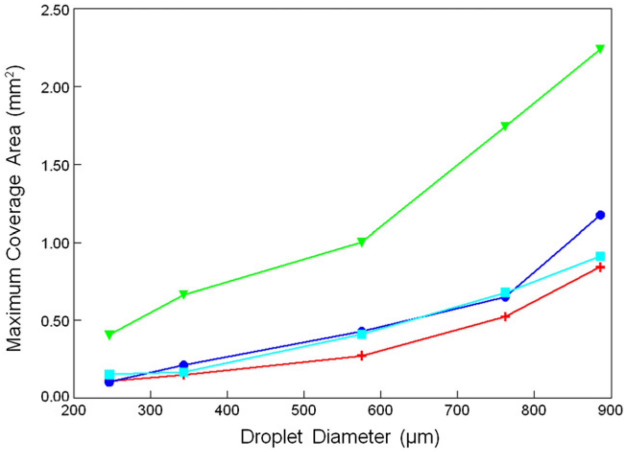
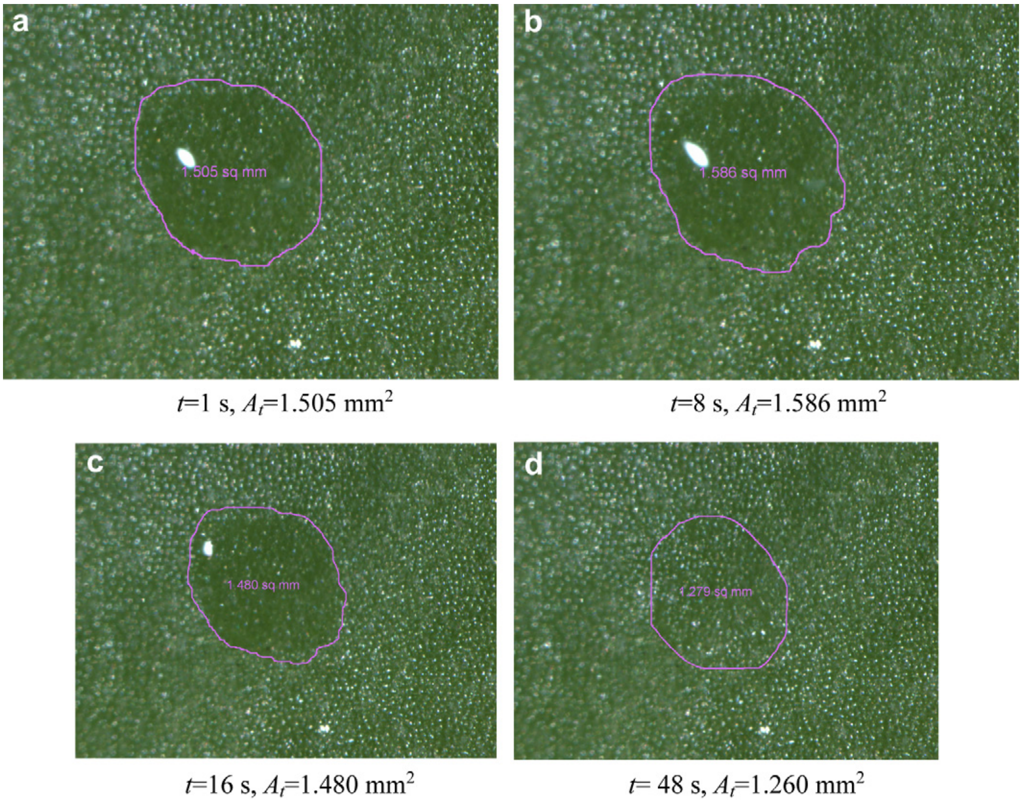


Fig. 5 – The maximum droplet coverage area of different size droplets containing insecticide No. 3 on hairy leaf, hydrophilic surface, waxy leaf and hydrophobic surface at 60% RH. Data for droplet evaporation on hydrophilic and hydrophobic surfaces are from Yu *et al.* (2009) (+ Hairy leaf, ▼ Hydrophilic surface, ● Waxy leaf, and ■ Hydrophobic surface).

increased from 1.505 mm^2 to 1.586 mm^2 at 7 s after deposition on the waxy leaves (only 0.081 mm^2 increase during 7 s), while the coverage area of the same-sized droplet increased from 0.637 mm^2 to 1.681 mm^2 at 7 s (1.044 mm^2 increase during 7 s) after deposition on the hairy leaves. The droplet coverage area became 2.381 mm^2 (or 4.7-time increase) at 20 s after deposition on the hairy leaves and then shrank to 0.226 mm^2 at 48 s before complete evaporation. The coverage area of a 343 μm water droplet containing insecticide No. 3 and the surfactant on the waxy leaf surface was 2.4 times the coverage area of the same-sized droplet on the hairy leaf surface when first deposited, but by the time the droplets completely evaporated, the droplet on the hairy leaves spread to cover an area 2.4 times larger than the area covered on the waxy leaves. Consequently, the addition of surfactant to the spray mixtures could enhance the performances of applications requiring adequate coverage on surfaces.

Droplets containing the surfactant spread rapidly and then evaporated rapidly after deposited on hairy leaves. Visual observation found that a droplet containing the surfactant penetrated between the hairs and spread along the path between hairs, perhaps through capillarity, after landing on the leaf surface. However, the same-sized droplet without surfactant stayed on top of the hairs and did not spread out readily.



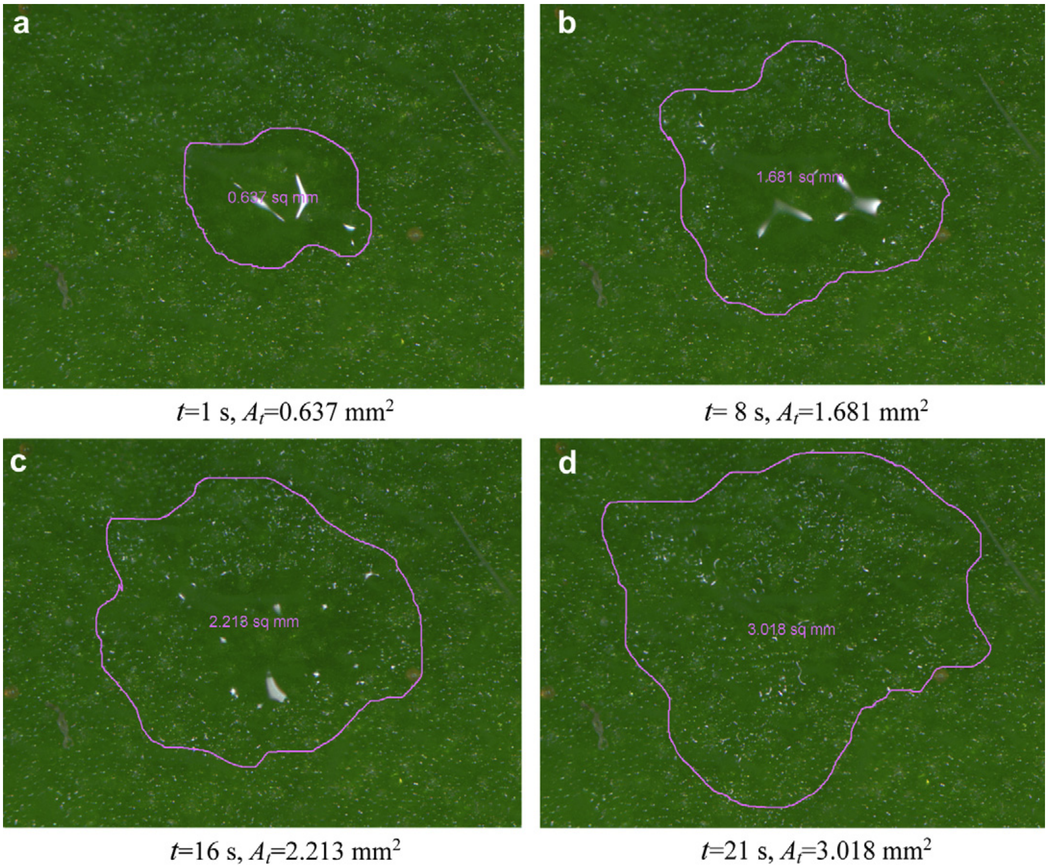
t=1 s, A_t=1.505 mm^2

t=8 s, A_t=1.586 mm^2

t=16 s, A_t=1.480 mm^2

t= 48 s, A_t=1.260 mm^2

Fig. 6 – Coverage area of a 343 μm droplet containing insecticide No. 3 + surfactant mixture at different times after deposited on waxy geranium leaf at 60% RH. t is the time after droplet is deposited on target surface, and A_t is the deposition coverage area on the target surface at the time t.



t=1 s, A_t=0.637 mm^2 t= 8 s, A_t=1.681 mm^2

t=16 s, A_t=2.213 mm^2 t=21 s, A_t=3.018 mm^2

Fig. 7 – Coverage area of a 343 μm droplet containing insecticide No. 3 + surfactant mixture at different times after deposited on hairy geranium leaf at 60% RH. *t* is the time after droplet is deposited on target surface, and A_t is the deposition coverage area on the target surface at the time *t*.

4. Conclusions

Droplet evaporation times were longer on the waxy geranium leaves than on the hairy geranium leaves for all droplet diameters, spray types and RH conditions. Addition of the alkyl polyoxyethylene surfactant to the spray significantly reduced the evaporation times of droplets on waxy and hairy leaves but the evaporation times were only slightly increased by the addition of the non-ionic colloidal polymer drift retardant. Addition of either the surfactant or the drift retardant to the spray affected the evaporation times of droplets on hairy leaves more than they did on waxy leaves.

Droplet evaporation times increased exponentially as droplet diameters and RH increased. For water droplets containing pesticides without additives on the waxy geranium leaf at 60% RH, the mean evaporation time increased from 40 s to 453 s when the droplet diameter increased from 246 μm to 886 μm. For the 343 μm water droplets containing pesticides on the waxy geranium leaf, the mean evaporation time increased from 52 s to 115 s when RH increased from 30% to 90%.

Adding the surfactant increased the maximum coverage area 4.5–10.1 times on the hairy leaves and 3.4–4.1 times on the waxy leaves under the conditions in this study. For the same size droplets without the surfactant, the maximum coverage area on waxy leaves was greater than on hairy leaves but the result was quite the opposite for droplets with the surfactant. On hairy leaves droplets containing the surfactant continued to spread until they nearly evaporated, demonstrating a different behaviour from similarly treated droplets on waxy leaves.

The maximum coverage areas increased exponentially as droplet diameters increased; however, the coverage area was not significantly affected by the addition of insecticide, fungicide or drift retardant, or the change in RH.

Droplet size, leaf surface structures (waxy or hairy), and addition of the surfactant greatly influenced evaporation time and maximum coverage area, suggesting that these factors are critical for the development of future spray strategies to improve efficacy and efficiency of foliar pesticide applications.

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