Evaporation and Deposition Coverage Area of Droplets Containing Insecticides and Spray Additives on Hydrophilic, Hydrophobic, and Crabapple Leaf Surfaces

Y. Yu, H. Zhu, H. E. Ozkan, R. C. Derksen, C. R. Krause

Abstract. *The efficiency of foliar spray applications is influenced by the evaporation and residual pattern of pesticide droplets on targets. Evaporation time and maximal coverage area of a single droplet from 246 to 886 μm in size at relative humidity (RH) ranging from 30% to 90% were measured with sequential images under controlled conditions. Droplets were placed on targets inside an environmentally controlled chamber under a stereoscope and a high-definition digital camera. The spray mixtures used to form droplets included different combinations of water, a nonionic colloidal polymer drift retardant, an alkyl polyoxyethylene surfactant, and two commercially available insecticides. The droplet evaporation was investigated on crabapple leaf surfaces, and hydrophilic and hydrophobic glass slide surfaces. Adding surfactant into spray mixtures greatly increased droplet coverage area on the surfaces, while droplet evaporation time was greatly reduced. For a 343 μm droplet on a crabapple leaf at 60% RH, the evaporation time decreased from 70 to 50 s and the maximal coverage area increased from 0.366 to 0.890 mm^2 after the surfactant was added into the spray mixture containing water and insecticide. Adding the drift retardant into the spray mixture slightly increased the droplet evaporation time and decreased the droplet coverage area. In addition, changing the target surface from the hydrophilic slide to the hydrophobic slide greatly increased the droplet coverage area and reduced the droplet evaporation time. Increasing RH increased the droplet evaporation time greatly but did not change the coverage area. The droplet evaporation time and coverage area increased exponentially as the droplet size increased. Therefore, droplet size, surface characteristics of the target (waxy or non-waxy), RH, and chemical composition of the spray mixture (water alone, pesticide, additives) should be included as important factors that can affect the efficacy and efficiency of pesticide applications.*

Keywords. *Drift retardant, Droplet size, Evaporation time, Pesticide formulation, Residual pattern, Spray efficiency, Surfactant.*

Reduction of pesticide use has been emphasized as an important goal by the public for many years due to potential risks to human health and the environment. However, significant progress toward that goal has not been achieved during the past decade. In the U.S., an estimated 216.6 × 10^6 kg of pesticide active ingredients were used for crop protection in 1991, while that amount increased to 224.3 × 10^6 kg in 2004 (Osteen and Livingston, 2006). To realize greater pest control efficiency with less pesticide use, the combined effects of application system performance, formulation of pest-control agents, plant surface fine structure, and microclimate conditions must be recognized and researched. Ignoring any these factors can cause excessive pesticide use.

Droplet size is typically recognized as one of the most important parameters influencing pest control. Droplets should be large enough to deposit on the target after some evaporation during transportation, but they should also be small enough to provide sufficient pesticide coverage on the target (Reichard et al., 1977). Using large droplets can reduce drift potential, but it can also reduce the control efficiency, resulting in excessive pesticide use (Wilson et al., 1963; Smith et al., 1975).

Numerous field experiments have reported that spray performance and spread factor were enhanced when non-ionic surfactants were added (Zabkiewicz et al., 1985; Holloway et al., 1992; Nalewaja and Matysiak, 2000; Uhlig and Wissemeier, 2000; Basu et al., 2002; Spanoghe et al., 2007). Surfactant added to foliar sprays improved chemical coverage on leaves, removed air films between spray and leaf surfaces, and reduced surface tension on leaves (Holloway and Silcox, 1985; Zabkiewicz et al., 1985; Holloway et al., 1992). Droplet adhesion, spreading area, and retention on leaf surfaces can also be increased by adding surfactants into spray tank mixtures (Basu et al., 2002). Herbicide application rates

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could be significantly reduced by adding nonionic surfactant into spray mixtures (Ramsdale and Messersmith, 2001).

Spray drift retardants were reported to reduce spray drift in many laboratory and field studies (Bouse et al., 1988; Salyani and Cromwell, 1992; Smith, 1993; Ozkan et al., 1993; VanGessel and Johnson, 2000, 2005; Miller et al., 2001). This technique has been recommended as an alternative method to reduce drift for field applications when other methods are unavailable. Although some drift retardants lost their effectiveness after recirculation through sprayer pumps (Bouse et al., 1988; Reichard et al., 1996), Zhu et al. (1997), after investigating various polymer compositions with a range of molecular weights, anionicities, and concentrations, reported that the drift retardant with the active ingredient xanthan gum maintained great resistance to breakdown due to shear.

When droplets are delivered to the targets, they experience the process of spreading and evaporation (Bukovac et al., 1995). The process varies with droplet size, leaf surface fine structure, physical properties of formulation, and weather conditions. To achieve an equal active ingredient on targets with a limited amount of spray, the surface-to-volume of droplets should be maximized. In many cases, systemic pesticide droplets are required to stay on the targets long enough for plants to absorb chemical ingredients; however, longer evaporation times may require larger droplets, which can cause runoff and lower the application efficiency.

Reactions of chemicals on leaf surfaces are dependent upon the droplet coverage pattern on intended target areas and the length of time that spray droplets remain on the target (Brazee et al., 2004). Knowing the evaporation time and deposit pattern of pesticide droplets on targets can assist better utilization of pest control agents to increase foliar application efficiency. However, previous research has mostly focused on droplet evaporation during the transportation of droplets from the atomizer to the target or droplet evaporation for other industrial uses such as pharmaceuticals (Picknett and Bexon, 1977; Cooper et al., 1983; Baines and James, 1994; Westin et al., 1998), but not for agro-chemical droplets on leaves. Reactions of ingredients of agro-chemicals on plant leaf surfaces are significantly different from those in other industries.

It is a fact that droplet coverage pattern and evaporation time on intended targets vary with the amount of additives, droplet size, fine structure of plant surfaces, and relative humidity conditions. It is unclear how spray additives such as nonionic colloidal polymer drift retardant or an alkyl polyoxyethylene surfactant affect the droplet evaporation and spreading process in foliar applications and how they react on different types of leaves under varied relative humidity conditions. Little literature is available on exact values of deposit coverage area and evaporation time of droplets on leaf surfaces for foliar agro-chemical spray applications.

The objective of this research was to investigate the effects of spray mixture additive, droplet size, and RH on the evaporation time and coverage area of droplets deposited on a hydrophilic surface, a hydrophobic surface, and crabapple leaves in an effort to provide useful information for spray applicators, pesticide formulators, and sprayer manufacturers to maximize the pesticide spray application efficiency and minimize pesticide use.

Materials and Methods

Investigation of droplet evaporation and deposit coverage area on different target surfaces was conducted with a custom-built, experimental system. The system was constructed with an RH control unit, a target holding chamber, a stereoscope with a high-definition digital camera, and a droplet generator (fig. 1). A brief description of the system follows, and detailed information was reported by Zhu et al. (2008).

The custom-designed RH control unit could generate air with a constant RH ranging from 10% to 90%. The target holding chamber was a rectangular box with an internal capacity of 0.56 L and was used to position targets and single droplets in X-Y directions. The chamber was completely insulated from the environment, and its internal air humidity was controlled by the RH control unit. The stereoscope (model SZX12, Olympus, Japan) and an Insight Firewire digital camera (model SZX-TB1, Olympus) were mounted vertically above the glass on the top of the chamber to take sequential images of droplets while the evaporation process was taking place. An imaging program (Spot, Diagnostic Instruments, Inc., Sterling Heights, Mich.) was used to record and save the sequential images in a computer.

After a droplet was deposited on a target surface, it spread out on the surface and evaporated. Droplet evaporation time was measured from the total number of sequential images and intervals after the droplet was deposited. The maximal coverage area (or wetted area) of the droplet after spreading was measured with ImageProPlus' polygonal hand-trace feature (version 4.1, Media Cybernetics, Bethesda, Md.). The standard area of each pixel grid for the area measurement ranged from 1.3×10^{-6} to 8.6×10^{-6} mm^2 depending on the amplification used to record images. The program was calibrated with a focal length of a Zeiss 0.01 mm micrometer slide.

The droplet generator was a microprocessor-based timed mode, air-powered fluid dispenser (model 2405, EFD, Inc., East Providence, R.I.) that could produce a single droplet with a diameter down to 200 μm and up to 2,000 μm. For each replication, only one droplet was discharged on the target inside the RH controlled chamber. Detailed information about determination of the diameter of a single droplet produced by the droplet generator was given by Zhu et al. (2008).

The variables used for the study of droplet evaporation time and the maximal droplet coverage area on targets were: three different target surfaces (hydrophilic slide, hydrophobic slide, and crabapple leaf), three RH conditions (30%, 60%, and 90%), five droplet sizes (246, 343, 575, 762, and 886 μm), and seven liquid mixtures. The first mixture was distilled water only. The second mixture was distilled water and a liquid formulation Imidacloprid insecticide (Marathon II, Olympic Horticultural Products Co., Mainland, Pa.). The third mixture was the second mixture with an addition of a nonionic colloidal polymer drift retardant (Strike Zone WDG, Helena Chemical Co., Collierville, Tenn). The fourth mixture was the second mixture with an addition of an alkyl polyoxyethylene surfactant (X-77, Loveland Industries, Inc., Greeley, Colo.). The fifth mixture was distilled water and a powder formulation Dinotefuran insecticide (Safari 20 SG, Valent USA Corp., Walnut Creek, Cal.). The sixth mixture was the

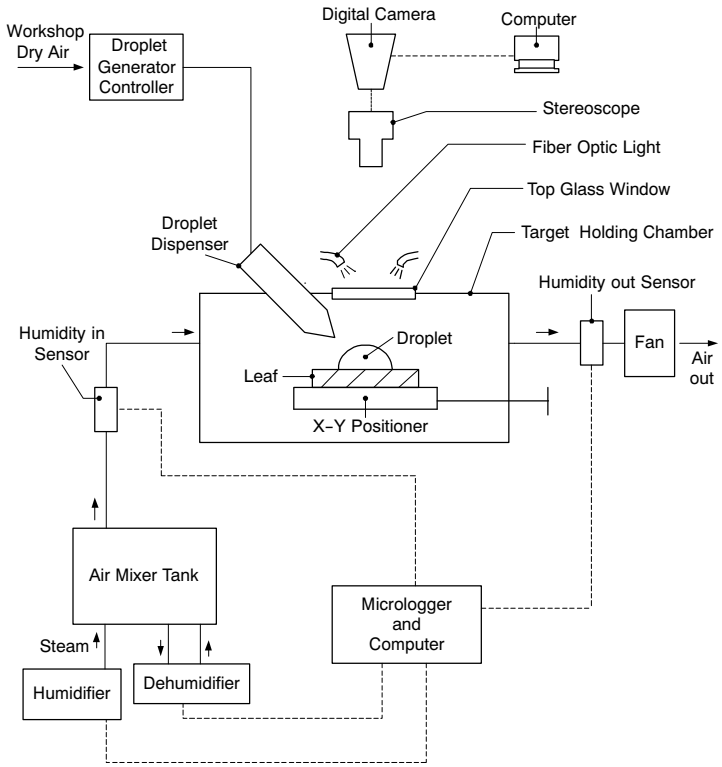


Figure 1. Schematic of the experimental setup for investigation of droplet evaporation process in a controlled environmental chamber.

Table 1. Formulation, active ingredient and concentration of chemicals used to form sprays with water for droplet evaporation and coverage area tests.

Chemicals	Trade Name	Formulation	Active Ingredient	Concentration[a]
Drift retardant	Strike Zone WDG	Powder	100% proprietary blend of poly-ammonium, phosphates, ammonium carboxylates, potassium phosphates, and phosphoric acid.	0.46 mg/L
Surfactant	X-77	Liquid	90% alkyl polyoxyethylene and 10% constituents ineffective as adjuvant.	7.52 mL/L
Insecticide#1	Marathon II	Liquid	21.4% Imidacloprid and 78.6% others	0.13 mL/L
Insecticide#2	Safari 20 SG	Powder	20% Dinotefuran and 80% others	0.45 g/L

[a] Concentration of the chemical in distilled water to form sprays.

Table 2. Surface tension, viscosity, and contact angle of 343 µm droplets on hydrophilic, hydrophobic, and crabapple leaf surfaces for sprays used in tests.

Item No.	Sprays[a]	Surface Tension (mN/m)	Viscosity (mPa·s)	Contact Angle (degree)		
				Hydrophilic	Hydrophobic	Crabapple
1	Water only	71.7	0.97	41.7	92.3	65.2
2	Insecticide#1	64.3	0.97	40.8	91.8	64.3
3	Insecticide#1 + Drift retardant	68.2	1.11	32.2	90.6	71.9
4	Insecticide#1 + Surfactant	39.1	1.91	22.9	43.5	16.1
5	Insecticide#2	68.3	0.97	36.8	89.9	58.4
6	Insecticide#2 + Drift retardant	69.8	1.17	32.6	90.4	48.3
7	Insecticide#2 + Surfactant	40.6	1.40	13.8	31.3	23.4

[a] All sprays used water as the carrier.

fifth mixture with an addition of the drift retardant. The seventh mixture was the fifth mixture with an addition of the surfactant. The formulation, percent active ingredient, and concentration of the insecticide, drift retardant, and surfactant are listed in table 1. Surface tension of the seven mixtures (table 2) was measured with a Fisher Semiautomatic Model 21 Tensiomat tensiometer (Fisher Scientific, Waltham, Mass.), and viscosity of the seven mixtures (table 2) was measured with a No. E335/150 glass capillary viscometer (Cannon Instrument Co., State College, Pa.).

The hydrophilic slide was a smooth, wax-free glass microscope slide that was used, cleaned with acetone, and stored in methanol until used again. The hydrophobic slide was the same hydrophilic slide but coated with a thin layer of transparent liquid wax (Rain·X, Sopus Products, Houston, Tex.). These slide treatments were selected for the tests

because they covered a wide range of contact angles of droplets on numerous fine structures of leaf surfaces. Contact angles of 343 μm droplets with different mixtures on the hydrophilic slide, the hydrophobic slide, and crabapple leaf surface are listed in table 2. The contact angle was determined with Image J software (National Institute of Mental Health, Bethesda, Md.) using the method described by Chachalis et al. (2001) by measuring the side-view images taken from the stereomicroscope.

One droplet was deposited on the target surface inside the chamber each time. Tests were conducted at an ambient temperature of 22°C, and each treatment was repeated three times.

Data were analyzed by one-way ANOVA at the 0.05 level of significance, and regression equations were developed with the SAS Enterprise Guide program (SAS Institute, Inc., Cary, N.C.). An exponential function, $Y = ae^{bX}$ ($a > 0, b > 0$), was selected for regression equations of evaporation time (Y) or maximal coverage area (Y) with droplet size (X) in this study. The selection was based on the fact that r^2 values for regression equations of the exponential function ranged from 0.97 to 0.99, which was higher than those for reciprocal function, logarithmic function, power function, and logistic growth curve function.

Results and Discussion

There was no significant difference ($p < 0.05$) in evaporation time of droplets on each hydrophilic surface, hydrophobic surface, or crabapple leaf between mixture 2 (water + insecticide#1) and mixture 5 (water + insecticide#2) (fig. 2). This result was true for the two insecticides added into drift retardant mixtures (mixtures 3 and 6) and surfactant mixtures (mixtures 4 and 7). That is, the effect of the two different insecticides on droplet evaporation time was not significantly different, or adding either liquid insecticide#1 or powder insecticide#2 into spray mixtures would have the same evaporation time. However, similar results were not found for droplet coverage area on each of the three surfaces, although the significance of difference between two insecticides was very weak at $p < 0.05$. Because of this, mixtures containing insecticide#1 and insecticide#2 for each treatment were grouped as an insecticide when reporting droplet evaporation times, but not for reporting droplet coverage area on the three target surfaces.

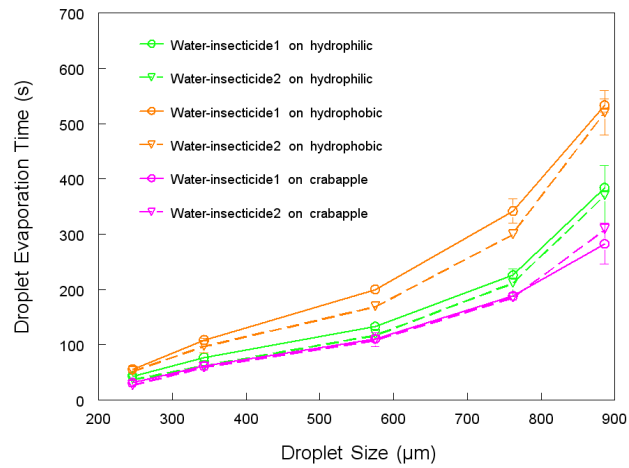


Figure 2. Comparison of evaporation time of droplets between insecticide#1 and insecticide#2 on hydrophilic, hydrophobic, and crabapple leaf surfaces at 60% RH.

Droplet Evaporation Time

Tables 3, 4, and 5 illustrate the evaporation times for five droplet sizes of different mixtures on the hydrophilic, hydrophobic, and crabapple leaf surfaces, respectively. The mean evaporation time of droplets was significantly increased by adding the drift retardant into the mixtures containing water and insecticides, or significantly decreased by adding the surfactant into the mixtures. For example, the evaporation time of 343 μm droplets containing insecticides at 60% RH on the hydrophilic surface increased about 30% (from 70 to 91 s) after drift retardant was added into spray mixtures (table 3), while it decreased about 29% (from 70 to 50 s) after surfactant was added into spray mixtures. For the same size droplets at a given RH condition, water-only droplets had a slightly higher evaporation time than insecticide droplets on the three surfaces. The formulation of insecticides generally contains a very small portion of surfactants. Among all four mixture groups, droplets containing the drift retardant had the longest evaporation time on all surfaces at all RH conditions, while droplets

Table 3. Mean evaporation time (s) of droplets on hydrophilic surfaces for different sprays at three relative humidities (RH).[a] Standard deviations are presented in parentheses.

Sprays[b]	RH (%)	Droplet Diameter (μm)				
		246	343	575	762	886
Water only	30	31 (5)	51 (3)	88 (11)	154 (12)	237 (5)
	60	42 (4)	78 (7)	131 (5)	220 (3)	397 (12)
	90	57 (5)	116 (5)	239 (23)	408 (47)	667 (17)
Insecticide	30	30 (2)	45 (0)	83 (0)	141 (1)	231 (6)
	60	41 (3)	70 (10)	126 (10)	219 (10)	377 (9)
	90	62 (0)	114 (16)	184 (23)	304 (31)	513 (43)
Insecticide + Drift retardant	30	39 (1)	61 (3)	103 (7)	179 (13)	296 (31)
	60	54 (2)	91 (7)	153 (5)	269 (23)	460 (25)
	90	77 (4)	146 (18)	247 (49)	407 (67)	664 (140)
Insecticide + Surfactant	30	17 (1)	29 (1)	50 (1)	90 (2)	160 (6)
	60	28 (2)	50 (5)	87 (9)	157 (8)	270 (18)
	90	40 (6)	68 (3)	120 (7)	198 (6)	332 (32)

[a] Mean evaporation time was calculated from both insecticides #1 and #2.
[b] All sprays used water as the carrier.

Table 4. Mean evaporation time (s) of droplets on hydrophobic surfaces for different sprays at three relative humidities (RH).[a] Standard deviations are presented in parentheses.

Sprays[b]	RH (%)	Droplet Diameter (μm)				
		246	343	575	762	886
Water only	30	40 (5)	77 (4)	139 (10)	250 (18)	389 (17)
	60	60 (2)	123 (3)	217 (8)	382 (19)	589 (36)
	90	96 (6)	186 (5)	321 (16)	518 (18)	765 (28)
Insecticide	30	39 (5)	68 (4)	127 (8)	226 (11)	391 (21)
	60	54 (2)	104 (7)	185 (22)	321 (30)	527 (9)
	90	92 (12)	161 (18)	267 (29)	442 (20)	693 (15)
Insecticide + Drift retardant	30	49 (1)	88 (12)	153 (18)	266 (21)	442 (23)
	60	69 (6)	130 (8)	226 (13)	397 (24)	613 (21)
	90	126 (4)	214 (5)	350 (20)	572 (33)	876 (44)
Insecticide + Surfactant	30	30 (2)	52 (4)	94 (3)	162 (7)	262 (12)
	60	42 (3)	77 (6)	129 (5)	219 (3)	343 (21)
	90	63 (1)	121 (6)	207 (9)	343 (21)	519 (29)

[a] Mean evaporation time was calculated from both insecticides #1 and #2.
[b] All sprays used water as the carrier.

Table 5. Mean evaporation time (s) of droplets on crabapple leaf surfaces for different sprays at three relative humidities (RH).[a] Standard deviations are presented in parentheses.

Sprays[b]	RH (%)	Droplet Diameter (μm)				
		246	343	575	762	886
Water only	30	17 (1)	37 (4)	76 (5)	138 (5)	234 (6)
	60	30 (4)	65 (14)	128 (4)	228 (6)	360 (32)
	90	48 (1)	87 (10)	161 (12)	304 (19)	475 (5)
Insecticide	30	20 (2)	44 (3)	86 (5)	153 (11)	248 (23)
	60	32 (4)	65 (5)	122 (14)	209 (26)	325 (36)
	90	44 (4)	86 (8)	167 (14)	287 (19)	440 (35)
Insecticide + Drift retardant	30	28 (3)	54 (1)	99 (4)	178 (6)	284 (16)
	60	41 (5)	79 (8)	144 (20)	242 (28)	381 (53)
	90	54 (4)	107 (16)	203 (24)	335 (25)	511 (37)
Insecticide + Surfactant	30	11 (6)	27 (7)	53 (12)	89 (24)	133 (37)
	60	23 (4)	49 (7)	95 (13)	162 (31)	246 (52)
	90	34 (3)	66 (6)	128 (18)	214 (34)	337 (57)

[a] Mean evaporation time was calculated from both insecticides #1 and #2.
[b] All sprays used water as the carrier.

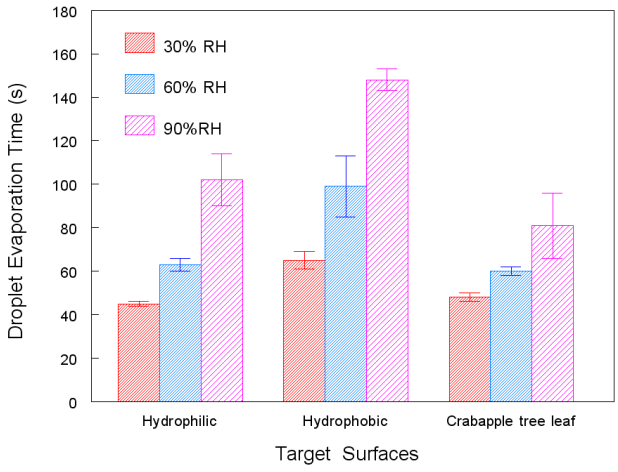


Figure 3. Evaporation time of a 343 μm droplet containing water and insecticide#2 on hydrophilic, hydrophobic, and crabapple leaf surfaces at three RH conditions.

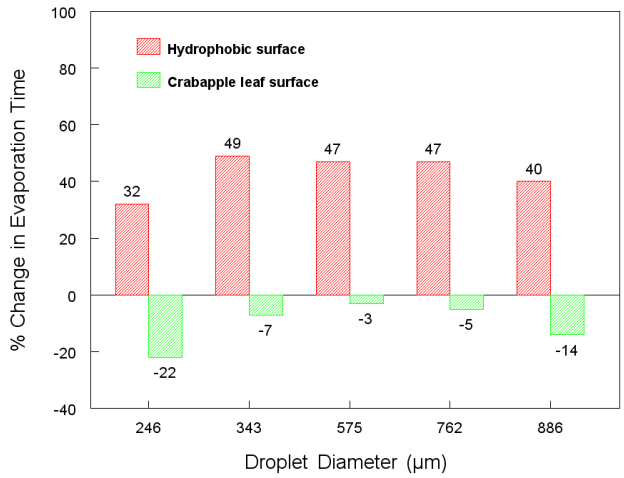


Figure 4. Relative percent increase or decrease of evaporation time for droplets containing water and insecticides at 60% RH on hydrophobic or crabapple leaf surfaces compared to the evaporation time on the hydrophilic surface.

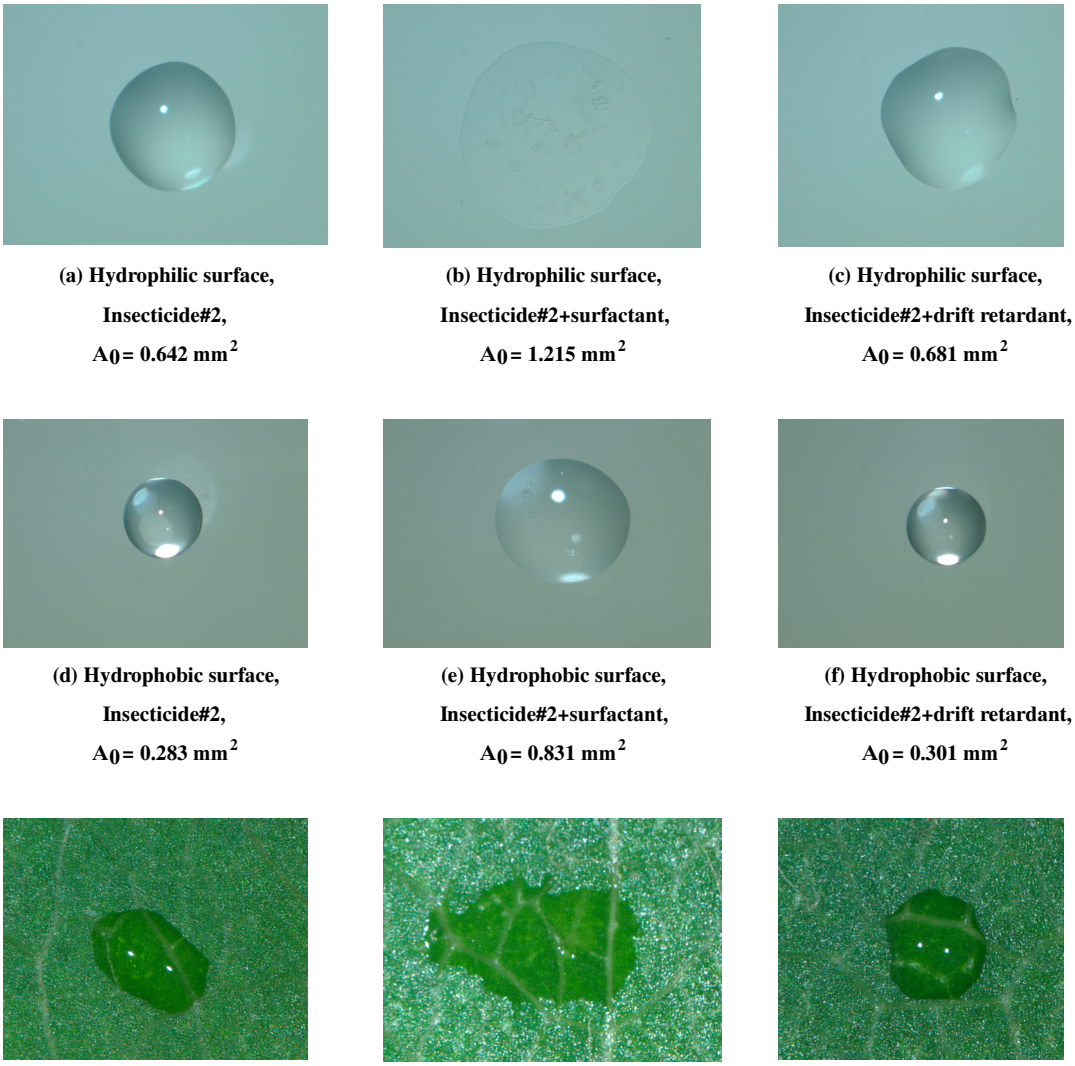
containing the surfactant had the shortest evaporation time. The polymer in the drift retardant may reduce the thermal exchange rate between the air and droplets.

The evaporation time of droplets increased as RH increased for the droplets on the hydrophilic surface (table 3), hydrophobic surface (table 4), and crabapple leaf surface

Table 6. Evaporation time of droplets with different sprays on hydrophilic, hydrophobic, and crabapple leaf surfaces as the exponential function of droplet diameter at three relative humidities (RH).[a]

Sprays[b]	RH (%)	Hydrophilic	Hydrophobic	Crabapple Leaf
Water only	30	$Y = 18.7e^{0.0026X}$	$Y = 24.1e^{0.0029X}$	$Y = 8.1e^{0.0038X}$
	60	$Y = 24.8e^{0.0028X}$	$Y = 36.8e^{0.0029X}$	$Y = 15.2e^{0.0036X}$
	90	$Y = 33.1e^{0.0031X}$	$Y = 62.8e^{0.0026X}$	$Y = 23.3e^{0.0034X}$
Insecticide	30	$Y = 14.7e^{0.0031X}$	$Y = 18.6e^{0.0034X}$	$Y = 10.1e^{0.0036X}$
	60	$Y = 20.1e^{0.0032X}$	$Y = 27.8e^{0.0033X}$	$Y = 16.8e^{0.0034X}$
	90	$Y = 33.6e^{0.003X}$	$Y = 50.3e^{0.0029X}$	$Y = 22.7e^{0.0034X}$
Insecticide + Drift retardant	30	$Y = 19.7e^{0.003X}$	$Y = 25.0e^{0.0032X}$	$Y = 14.1e^{0.0034X}$
	60	$Y = 27.1e^{0.0031X}$	$Y = 36.4e^{0.0032X}$	$Y = 21.7e^{0.0032X}$
	90	$Y = 41.8e^{0.0031X}$	$Y = 70.2e^{0.0028X}$	$Y = 29.0e^{0.0033X}$
Insecticide + Surfactant	30	$Y = 8.2e^{0.0033X}$	$Y = 15.2e^{0.0032X}$	$Y = 6.0e^{0.0036X}$
	60	$Y = 13.8e^{0.0033X}$	$Y = 22.7e^{0.0030X}$	$Y = 12.2e^{0.0034X}$
	90	$Y = 20.6e^{0.0031X}$	$Y = 35.1e^{0.0031X}$	$Y = 17.6e^{0.0034X}$

[a] Y = evaporation time (s), and X = droplet diameter (μm). The range of r^2 for all the exponential functions was between 0.96 and 0.99.
[b] All sprays used water as the carrier.



(a) Hydrophilic surface, Insecticide#2, A_0 = 0.642 mm^2

(b) Hydrophilic surface, Insecticide#2+surfactant, A_0 = 1.215 mm^2

(c) Hydrophilic surface, Insecticide#2+drift retardant, A_0 = 0.681 mm^2

(d) Hydrophobic surface, Insecticide#2, A_0 = 0.283 mm^2

(e) Hydrophobic surface, Insecticide#2+surfactant, A_0 = 0.831 mm^2

(f) Hydrophobic surface, Insecticide#2+drift retardant, A_0 = 0.301 mm^2

(g) Crabapple leaf surface, Insecticide#2, A_0 = 0.495 mm^2

(h) Crabapple leaf surface, Insecticide#2+surfactant, A_0 = 1.103 mm^2

(i) Crabapple leaf surface, Iinsecticide#2+drift retardant, A_0 = 0.499mm^2

Figure 5. Deposition patterns of a 343 μm droplet on hydrophilic, hydrophobic, and crabapple leaf surfaces with three different mixtures containing insecticide#2, surfactant, or drift retardant at 60% RH, respectively. All mixtures were formulated with distilled water as the carrier. A_0 is the maximal coverage area of a droplet on the target surface after deposition.

(table 5). For example, when RH increased from 30% to 90%, the evaporation time of 343 μm droplets containing water and insecticides on the hydrophilic surface increased about 153% (from 45 to 114 s), about 137% (from 68 to 161 s) on hydrophobic surfaces, and about 95% (from 44 to 86 s) on crabapple tree leaf surfaces respectively (fig. 3).

The evaporation time of droplets were also greatly influenced by target surface types (tables 3, 4, and 5). Figure 4 illustrates the relative percent increase or decrease in evaporation time for different size droplets containing water and insecticides without additives at 60% RH when the droplets deposited on the hydrophobic surface or crabapple leaf surface, compared to the hydrophilic surface. Among the three target surfaces, for the same size droplets at a given RH condition, the droplets on the hydrophobic surface had the longest evaporation time, while droplets on crabapple leaf surfaces had the shortest evaporation time. Compared to the evaporation time on the hydrophilic surface, the evaporation time of a 343 μm water-insecticide droplet on the hydrophobic surface at 60% RH relatively increased by 49%, and relatively decreased by 7% on the crabapple tree leaf surface (fig. 4). The reason that droplets on crabapple leaves had shorter evaporation time might be that the thermal conductivity of crabapple leaves was higher than the hydrophilic and hydrophobic slides.

The evaporation time of droplets on the hydrophilic surface (table 3), hydrophobic surface (table 4), and crabapple leaf (table 5) increased as droplet diameter increased for all RH conditions. For the droplets containing water and insecticides on the hydrophilic surface at 60% RH, the evaporation time increased from 41 to 377 s (or 9.2 times) when droplet diameter increased from 246 to 886 μm (or 3.6 times). For the same size droplets, the evaporation time increased from 54 to 527 s (9.8 times) on the hydrophobic surfaces and increased from 32 to 325 s (10.2 times) on the crabapple leaf. The relationship between droplet diameter and evaporation time on the three target surfaces followed the exponential function for all RH conditions (table 6).

Maximal Droplet Deposition Coverage Area

The maximal deposition pattern and coverage area of a droplet on different target surfaces varied greatly with the spray mixture formulation (fig. 5). Tables 7, 8, and 9 show the maximal coverage areas of five size droplets with different mixtures and three RH conditions on the hydrophilic surface, hydrophobic surface, and crabapple leaf, respectively. In comparison to the droplet evaporation time, the maximal coverage area of droplets increased when the surfactant was added into mixtures of water and insecticides (fig. 6). For example, the average maximal coverage areas of all five size droplets containing insecticide#2 on the crabapple leaf surface at 60% RH increased about 97% after the surfactant was added into spray mixtures (fig. 6). The area of a 246, 343, 575, 762, or 886 μm droplets projected on a surface before deposition is 0.048, 0.092, 0.260, 0.456, and 0.617 mm^2, respectively. The maximal coverage areas of droplets containing the surfactant were 5 to 22 times larger than the projection areas. Adding the surfactant into the mixtures greatly reduced the mixture surface tension (table 2), resulting in additional spread of droplets on target surfaces. Hence, the surface-to-volume ratio of droplets greatly increased by using the surfactant.

In comparison to the effect of the surfactant, the maximal coverage area of droplets was not strongly affected by adding the drift retardant or/and insecticides into water. In some cases, the maximal coverage area of droplets containing the drift retardant and/or insecticides was larger than those droplets containing water only, but the results were reversed in some other cases (tables 7, 8, and 9). For example, for all

Table 7. Mean maximal deposition coverage area (mm^2) of droplets with different sprays on hydrophilic surface at three relative humidities (RH). Standard deviations are presented in parentheses.

Sprays[a]	RH (%)	Droplet Diameter (μm)				
		246	343	575	762	886
Water only	30	0.541 (0.085)	0.835 (0.120)	1.667 (0.102)	2.33 (0.044)	3.177 (0.443)
	60	0.653 (0.063)	0.842 (0.073)	1.348 (0.011)	2.372 (0.580)	3.224 (0.128)
	90	0.217 (0.028)	0.517 (0.050)	0.880 (0.065)	1.576 (0.136)	2.195 (0.159)
Insecticide#1	30	0.434 (0.057)	0.541 (0.067)	1.116 (0.134)	1.780 (0.156)	2.121 (0.271)
	60	0.455 (0.020)	0.613 (0.051)	1.198 (0.077)	1.911 (0.097)	2.680 (0.189)
	90	0.594 (0.027)	0.954 (0.060)	1.572 (0.065)	2.608 (0.248)	4.044 (0.237)
Insecticide#1 + Drift retardant	30	0.522 (0.064)	0.760 (0.026)	1.113 (0.047)	2.033 (0.052)	2.738 (0.125)
	60	0.424 (0.077)	0.670 (0.160)	1.068 (0.168)	1.753 (0.163)	2.519 (0.141)
	90	0.885 (0.078)	1.166 (0.140)	1.901 (0.134)	3.12 (0.159)	4.700 (0.123)
Insecticide#1 + Surfactant	30	0.788 (0.236)	1.251 (0.163)	1.955 (0.231)	2.936 (0.306)	3.885 (0.405)
	60	1.066 (0.079)	1.353 (0.124)	2.060 (0.173)	3.465 (0.232)	4.659 (0.256)
	90	0.789 (0.026)	1.484 (0.040)	2.344 (0.150)	3.638 (0.048)	5.148 (0.106)
Insecticide#2	30	0.406 (0.016)	0.664 (0.059)	1.001 (0.132)	1.743 (0.392)	2.240 (0.213)
	60	0.414 (0.053)	0.576 (0.100)	0.978 (0.082)	1.775 (0.105)	2.189 (0.190)
	90	0.542 (0.045)	0.688 (0.073)	1.127 (0.011)	1.840 (0.025)	2.792 (0.304)
Insecticide#2 + Drift retardant	30	0.515 (0.044)	0.755 (0.061)	1.206 (0.045)	1.806 (0.207)	3.270 (0.267)
	60	0.595 (0.086)	0.827 (0.059)	1.219 (0.099)	2.020 (0.362)	3.486 (0.243)
	90	0.333 (0.025)	0.565 (0.049)	0.864 (0.097)	1.474 (0.135)	1.934 (0.136)
Insecticide#2 + Surfactant	30	0.731 (0.132)	1.383 (0.032)	2.235 (0.169)	3.258 (0.125)	5.667 (0.411)
	60	1.047 (0.039)	1.217 (0.047)	2.352 (0.058)	3.730 (0.410)	5.285 (0.481)
	90	0.892 (0.106)	1.525 (0.253)	2.251 (0.099)	4.324 (0.281)	5.241 (0.427)

[a] All sprays used water as the carrier.

Table 8. Mean maximal deposition coverage area (mm^2) of droplets with different sprays on hydrophobic surface at three relative humidities (RH). Standard deviations are presented in parentheses.

Sprays[a]	RH (%)	Droplet Diameter (μm)				
		246	343	575	762	886
Water only	30	0.105 (0.012)	0.188 (0.012)	0.372 (0.033)	0.653 (0.015)	1.026 (0.137)
	60	0.109 (0.005)	0.192 (0.006)	0.445 (0.029)	0.704 (0.031)	0.975 (0.012)
	90	0.089 (0.009)	0.133 (0.009)	0.351 (0.004)	0.693 (0.025)	0.864 (0.022)
Insecticide#1	30	0.114 (0.016)	0.186 (0.011)	0.341 (0.019)	0.667 (0.034)	1.080 (0.053)
	60	0.114 (0.015)	0.196 (0.007)	0.333 (0.015)	0.691 (0.019)	0.921 (0.009)
	90	0.116 (0.005)	0.173 (0.006)	0.383 (0.019)	0.708 (0.014)	0.943 (0.012)
Insecticide#1 + Drift retardant	30	0.207 (0.024)	0.399 (0.042)	0.645 (0.014)	1.116 (0.037)	1.585 (0.071)
	60	0.152 (0.010)	0.324 (0.026)	0.536 (0.008)	1.019 (0.034)	1.327 (0.056)
	90	0.223 (0.018)	0.352 (0.005)	0.598 (0.007)	1.074 (0.030)	1.695 (0.141)
Insecticide#1 + Surfactant	30	0.332 (0.026)	0.426 (0.045)	0.890 (0.136)	1.495 (0.131)	2.119 (0.432)
	60	0.464 (0.050)	0.780 (0.012)	1.340 (0.053)	2.348 (0.094)	3.291 (0.063)
	90	0.383 (0.022)	0.665 (0.013)	1.049 (0.062)	1.846 (0.047)	2.578 (0.071)
Insecticide#2	30	0.153 (0.019)	0.169 (0.122)	0.411 (0.013)	0.680 (0.024)	0.913 (0.011)
	60	0.193 (0.018)	0.275 (0.027)	0.372 (0.011)	0.653 (0.018)	0.987 (0.028)
	90	0.158 (0.004)	0.239 (0.037)	0.426 (0.008)	0.766 (0.037)	1.170 (0.049)
Insecticide#2 + Drift retardant	30	0.167 (0.032)	0.275 (0.033)	0.528 (0.054)	0.912 (0.028)	1.212 (0.041)
	60	0.221 (0.026)	0.335 (0.071)	0.548 (0.048)	0.852 (0.049)	1.250 (0.067)
	90	0.210 (0.021)	0.308 (0.019)	0.545 (0.038)	1.015 (0.026)	1.503 (0.118)
Insecticide#2 + Surfactant	30	0.286 (0.031)	0.606 (0.099)	0.989 (0.095)	1.429 (0.271)	2.729 (0.501)
	60	0.470 (0.017)	0.854 (0.034)	1.432 (0.025)	2.353 (0.160)	3.547 (0.207)
	90	0.406 (0.032)	0.669 (0.033)	1.202 (0.145)	1.964 (0.176)	2.800 (0.098)

[a] All sprays used water as the carrier.

Table 9. Mean maximal deposition coverage area (mm^2) of droplets with different sprays on crabapple leaf surface at three relative humidities. Standard deviations are presented in parentheses.

Sprays[a]	RH (%)	Droplet Diameter (μm)				
		246	343	575	762	886
Water only	30	0.232 (0.061)	0.422 (0.072)	0.480 (0.085)	0.989 (0.053)	1.440 (0.127)
	60	0.226 (0.015)	0.326 (0.028)	0.716 (0.075)	0.931 (0.031)	1.406 (0.393)
	90	0.242 (0.038)	0.323 (0.087)	0.591 (0.092)	1.009 (0.158)	1.398 (0.077)
Insecticide#1	30	0.202 (0.036)	0.338 (0.062)	0.636 (0.099)	1.111 (0.032)	1.856 (0.065)
	60	0.305 (0.014)	0.366 (0.082)	0.628 (0.171)	1.373 (0.240)	1.889 (0.301)
	90	0.198 (0.036)	0.400 (0.058)	0.613 (0.128)	0.975 (0.064)	1.496 (0.161)
Insecticide#1 + Drift retardant	30	0.254 (0.041)	0.405 (0.046)	0.634 (0.02)	1.466 (0.082)	2.025 (0.079)
	60	0.225 (0.049)	0.361 (0.015)	0.646 (0.021)	1.096 (0.023)	1.580 (0.116)
	90	0.392 (0.075)	0.538 (0.002)	0.938 (0.006)	1.590 (0.166)	2.414 (0.075)
Insecticide#1 + Surfactant	30	0.744 (0.085)	1.291 (0.494)	1.926 (0.244)	3.420 (0.375)	4.530 (1.630)
	60	0.821 (0.078)	0.890 (0.181)	2.007 (0.070)	4.305 (0.608)	5.157 (0.557)
	90	0.461 (0.068)	1.102 (0.322)	2.007 (0.203)	3.025 (0.403)	4.883 (0.127)
Insecticide#2	30	0.297 (0.048)	0.466 (0.063)	0.845 (0.057)	1.506 (0.074)	2.374 (0.255)
	60	0.262 (0.072)	0.491 (0.038)	0.658 (0.074)	1.398 (0.049)	1.914 (0.132)
	90	0.234 (0.006)	0.362 (0.032)	0.637 (0.047)	1.180 (0.048)	1.928 (0.176)
Insecticide#2 + Drift retardant	30	0.271 (0.048)	0.511 (0.019)	0.855 (0.091)	1.556 (0.033)	2.283 (0.100)
	60	0.247 (0.047)	0.491 (0.013)	0.708 (0.093)	1.443 (0.032)	1.888 (0.103)
	90	0.300 (0.010)	0.494 (0.035)	0.774 (0.091)	1.470 (0.065)	2.117 (0.033)
Insecticide#2 + Surfactant	30	0.465 (0.078)	0.907 (0.077)	1.215 (0.179)	2.749 (0.144)	3.542 (0.616)
	60	0.465 (0.078)	0.907 (0.077)	1.215 (0.179)	2.749 (0.144)	3.542 (0.616)
	90	0.436 (0.090)	0.753 (0.075)	1.362 (0.237)	2.328 (0.428)	3.470 (0.660)

[a] All sprays used water as the carrier.

three RH conditions and five droplet sizes, 14 out of 15 droplets containing water, insecticide#2, and drift retardant had larger coverage areas on the crabapple leaf than the droplets containing water only, while on the hydrophilic surface this ratio became 4 out of 15. Compared to the water + insecticide#2 droplets, the relative percentage change of maximal droplet coverage area ranged between −6% and 3% after the drift retardant was added, which is much lower than the relative percentage change between 78% and 96% after the surfactant was added (fig. 6). The inconsistence of target surfaces might be the reason for the change in maximal coverage area after the drift retardant was added, since the surface tension of these mixtures was very close (table 2).

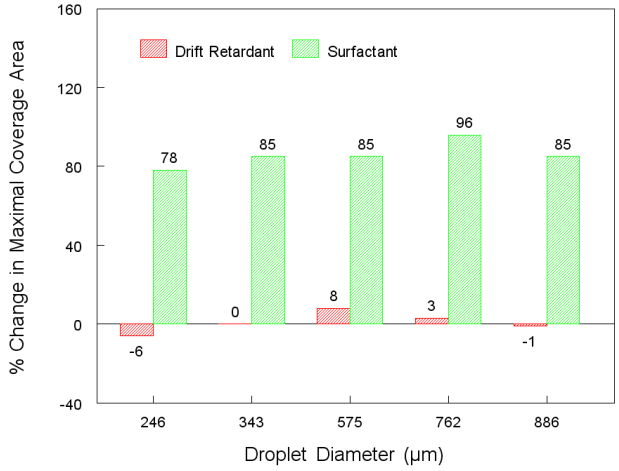


Figure 6. Relative percent increase or decrease of maximal droplet coverage area on crabapple leaf surface after surfactant or drift retardant was added into the mixture of water and insecticide#2 at 60% RH.

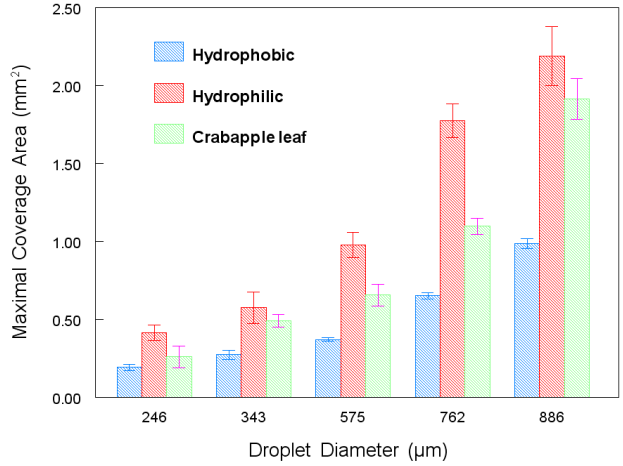


Figure 7. Maximal coverage areas of droplets containing water and insecticide#2 on hydrophilic, hydrophobic, and crabapple leaf surfaces at 60% RH.

Table 10. The maximal deposition coverage area of droplets with different sprays on hydrophilic, hydrophobic, and crabapple leaf surfaces as the exponential function of droplet diameter at three relative humidity conditions (RH).[a]

Sprays[b]	RH (%)	Hydrophilic	Hydrophobic	Crabapple leaf
Water only	30	$Y = 0.31e^{0.0027X}$	$Y = 0.05e^{0.0033X}$	$Y = 0.14e^{0.0026X}$
	60	$Y = 0.35e^{0.0025X}$	$Y = 0.06e^{0.0033X}$	$Y = 0.13e^{0.0028X}$
	90	$Y = 0.13e^{0.0033X}$	$Y = 0.038e^{0.0037X}$	$Y = 0.12e^{0.0027X}$
Insecticide#1	30	$Y = 0.232e^{0.0026X}$	$Y = 0.053e^{0.0037X}$	$Y = 0.098e^{0.0033X}$
	60	$Y = 0.237e^{0.0028X}$	$Y = 0.058e^{0.0032X}$	$Y = 0.137e^{0.0029X}$
	90	$Y = 0.322e^{0.0028X}$	$Y = 0.055e^{0.0033X}$	$Y = 0.119e^{0.0028X}$
Insecticide#1 + Drift retardant	30	$Y = 0.292e^{0.0025X}$	$Y = 0.118e^{0.003X}$	$Y = 0.121e^{0.0032X}$
	60	$Y = 0.242e^{0.0026X}$	$Y = 0.086e^{0.0032X}$	$Y = 0.12e^{0.0029X}$
	90	$Y = 0.472e^{0.0025X}$	$Y = 0.113e^{0.003X}$	$Y = 0.2e^{0.0028X}$
Insecticide#1 + Surfactant	30	$Y = 0.495e^{0.0024X}$	$Y = 0.16e^{0.0029X}$	$Y = 0.438e^{0.0027X}$
	60	$Y = 0.601e^{0.0023X}$	$Y = 0.251e^{0.0029X}$	$Y = 0.344e^{0.0031X}$
	90	$Y = 0.486e^{0.0027X}$	$Y = 0.216e^{0.0028X}$	$Y = 0.269e^{0.0033X}$
Insecticide#2	30	$Y = 0.241e^{0.0026X}$	$Y = 0.07e^{0.003X}$	$Y = 0.146e^{0.0031X}$
	60	$Y = 0.224e^{0.0026X}$	$Y = 0.109e^{0.0024X}$	$Y = 0.151e^{0.0027X}$
	90	$Y = 0.287e^{0.0025X}$	$Y = 0.216e^{0.0028X}$	$Y = 0.112e^{0.0032X}$
Insecticide#2 + Drift retardant	30	$Y = 0.277e^{0.0027X}$	$Y = 0.089e^{0.003X}$	$Y = 0.146e^{0.0031X}$
	60	$Y = 0.314e^{0.0026X}$	$Y = 0.126e^{0.0026X}$	$Y = 0.151e^{0.0027X}$
	90	$Y = 0.199e^{0.0026X}$	$Y = 0.103e^{0.003X}$	$Y = 0.158e^{0.0029X}$
Insecticide#2 + Surfactant	30	$Y = 0.424e^{0.0029X}$	$Y = 0.164e^{0.0031X}$	$Y = 0.256e^{0.003X}$
	60	$Y = 0.531e^{0.0026X}$	$Y = 0.263e^{0.003X}$	$Y = 0.309e^{0.0028X}$
	90	$Y = 0.52e^{0.0027X}$	$Y = 0.223e^{0.0029X}$	$Y = 0.23e^{0.0031X}$

[a] Y = maximal droplet deposition coverage area (mm^2), and X = droplet diameter (μm).
The range of r^2 for all the exponential functions was between 0.93 and 0.99.
[b] All sprays used water as the carrier.

Similar to the effect of the drift retardant on the maximal coverage area of droplets, the data in tables 7, 8, and 9 also illustrate that the RH did not influence the maximal droplet coverage areas for all droplets on three different surfaces. In some cases, lower RH had larger maximal coverage areas, but the result was reversed in some other cases. The variation might be caused by the inconsistence of fine structures of each target surface.

The maximal droplet coverage area was greatly influenced by the type of target surface (tables 7, 8, and 9). Among the three target surfaces, the hydrophobic surface had the highest resistance to the droplet spreading, while the resistance from the hydrophilic surface was the lowest. Thus, the maximal coverage areas of droplets on the hydrophilic surface are larger than that on other two surfaces. For example, at 60% RH, the maximal droplet coverage area of a 343 μm droplet containing water and insecticide#2 was 0.576 mm^2 on the hydrophilic surface, 0.491 mm^2 on the crabapple leaf, and 0.275 mm^2 on the hydrophobic surface (fig. 7).

The maximal droplet coverage area of a droplet on all three surfaces increased as droplet diameter increased for all RH conditions (tables 7, 8, and 9). For the droplets containing insecticide#2 on the hydrophilic surface at 60% RH, the maximal droplet coverage area increased from 0.414 to 2.189 mm^2 (or 5.3 times) when droplet diameter increased from 246 to 886 μm (or 3.6 times). For the same droplets, the maximal droplet coverage area increased from 0.193 to

0.987 mm^2 (5.1 times) on the hydrophobic surface and increased from 0.262 to 1.914 mm^2 (7.3 times) on the crabapple tree leaf surface. Similar to the results for droplet evaporation time, the maximal droplet coverage area was also represented by an exponential function of droplet diameter for all three RH conditions, three target surfaces, and spray mixtures (table 10).

Conclusions

- Adding the commercially available Imidacloprid or Dinotefuran insecticide into water at the label-recommended rate slightly reduced the evaporation time of droplets and slightly increased the maximal droplet coverage area on hydrophilic, hydrophobic, and crabapple leaf surfaces.
- Adding the surfactant into spray mixtures resulted in a large decrease in droplet evaporation time and a large increase in maximal droplet coverage area, while adding drift retardant into the spray mixtures slightly increased droplet evaporation time but did not change the maximal coverage area.
- Among the three target surfaces, the droplets had the longest evaporation time and smallest coverage area on the hydrophobic surface, while droplets had the shortest evaporation time on the crabapple leaf surface and the largest coverage area on the hydrophilic surface.
- Increasing RH greatly increased droplet evaporation time, but maximal droplet coverage area on targets was not influenced by the change in RH.
- Increasing droplet diameter increased both droplet evaporation time and coverage area exponentially.
- The information about droplet evaporation and coverage area on hydrophilic and hydrophobic surfaces could be used as references for a wide range of fine-structure leaf surfaces. Further studies will focus on the evaporation and coverage area of droplets containing different mixture contents on hairy and waxy leaf surfaces.

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