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PULSED-JET MICROSPRAY APPLICATIONS FOR HIGH SPATIAL RESOLUTION OF DEPOSITION ON BIOLOGICAL TARGETS

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In agricultural spraying, where discrete targets and nontargets are present in a localized region, high spatial resolution of liquid deposition is essential for selective treatment. Microspraying with small jets can provide high resolution in spray dose and position. Pulsed microspray jets were created with various orifice sizes and duration of liquid emission and deposited with various orifice-to-target distances. Formulations included surfactants that increase area covered onto plant surfaces for increased herbicide efficacy, and polymers to inhibit splash during deposition. Kromekote[®] cards were used as the deposition target. Image analysis measured deposition area and centimeter-scale splashing, i.e., "microdrift" from the pulsed jets. Liquid properties were measured; Reynolds (Re), Weber (We), and Ohnesorge (Oh) numbers were calculated. Formulations containing polyethylene oxide polymer were more effective at reducing microdrift than polyacrylamide polymer, and silicone surfactant increased spreading compared to an oil-based surfactant.

INTRODUCTION

In agricultural spraying, effective use of spray adjuvants to alter liquid properties can minimize spray drift, worker hazards, and surface-water contamination through irrigation or runoff. Uniform deposition of small, concentrated droplets can provide higher biological efficacy than large, dilute droplets [1-3]. Improved spray technology has increased our ability to dispense dose volumes precisely, on the order of microliters, onto specific target locations. Selective applications within 1 cm are a completely new scale of accuracy and precision in agricultural chemical treatment. Spray applications can aim the initial deposit toward weed surfaces that are only slightly displaced from adjacent crop plants. A precise postemergent treatment system, coupled with an effective adjuvant, may allow nonselective herbicides to be used for weed control. Nonselective herbicides are those that can kill the crop as well as the target weeds. In specialty and organic cropping systems, nonselective, postemergent herbicides may be the only effective option for chemical weed control.

Figure 1 shows a typical scene from a commercial processing tomato field, where a grassy weed grows in close proximity to a tomato plant. These weeds can significantly reduce crop yield, since they are highly competitive with the crop plants for water, light, and nutrients. The position of the weed within the crop row makes mechanical removal difficult. Machine vision inspection systems have been developed to distinguish and locate weeds in scenes similar to that shown in Fig. 1 [4-6]. However, once the weed targets are located, the challenge is to deposit an effective or lethal dose of herbicide solution exclusively on the weed while preventing damage to the adjacent crop plant.

Adjuvants can significantly increase the physical transport of chemical across a leaf surface after initial droplet deposition. The surfactant Silwet-L77 was found to improve

NOMENCLATURE

D	orifice diameter, m
DS_{50}	distance within which 50% of microdrift stains occurred from primary stain center, m
L	nozzle length, m
Oh	Ohnesorge number $[= (We)^{1/2}/Re]$
PS	primary stain area, m^2
PS/V	primary stain area/volume applied, m^{-1}
Re	Reynolds number $[= (U\rho D)/\mu]$
TS	total stain area, m^2
U	steady-state velocity, m/s
V	volume, L
We	Weber number $[= U^2 \rho D/\sigma]$
μ	viscosity, Pa s
μD	microdrift, m^2
μDf	fraction of microdrift area versus total stain area $(= \mu D/TS)$
ρ	density, kg/m^3
σ	surface tension, N/m

droplet spread by a factor of 100 on Johnsongrass leaves, while other materials have shown improvement by up to a factor of 500 [7]. Deposition analysis of pesticide formulations, spray diluents, and petroleum sprays to estimate deposition area, spray droplet size, and extent of area covered using water-sensitive cards, oil-sensitive paper, and Kromekote cards has been conducted for a number of years [8–10]. These studies used the ratio of deposit

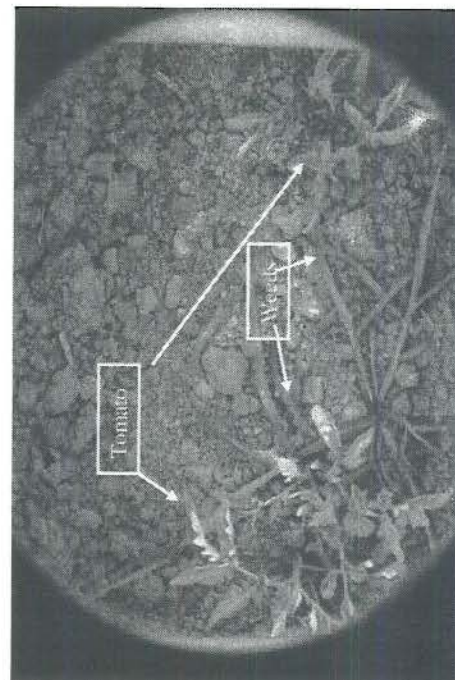


Fig. 1 Image of young tomato plants and weeds showing proximity and need to minimize splashing.

stain size to spray droplet size to estimate spread factors in agricultural field settings to determine spray cloud coverage and potential drift over treatment sites. One of the main drawbacks with using stain size estimates is the effect of overlap, that is, multiple drops impinging over the same area or in close proximity so that application rates are difficult to predict. Current digital imaging technology has enhanced the ability to estimate deposition stain sizes that are representative of measured areal empirical results. Results presented in the current study are concerned with extent of microdrift, represented as deposit outside the target area, that can occur during specific application conditions using pulsed jets.

One aspect that is of concern in the current research is the effect, or result, of liquid jet impingement onto foliar surfaces and the extent of coverage and production of splash from the target that might deposit liquid on adjacent nontargets (crops). Prior work has considered droplet impacts on foliar and artificial surfaces [11–13]. The physical nature of leaf surfaces as well as age of the leaf can influence wettability of the surface [11], and this may in part be due to the microroughness on leaf surfaces due to acicular crystals from straight-chain paraffins, alcohols, etc., in addition to the extent of leaf wetness during an application of liquid material [12, 13]. Single droplet impacts onto solid flat surfaces have been interpreted recently from visual results of deposit that exhibit prompt splash, corona splash, receding breakup, partial rebound, and rebound based on liquid properties, surface, and velocity of droplet [14]. Although these results do not apply directly to the current study, observations presented by these researchers will be discussed in light of the effects seen in the current research.

Previous work [15] has considered the effect of splatter on flat solid surfaces due to liquid jet impingement. This work showed that the We number and the dimensionless number representing the ratio of nozzle-to-target distance/nozzle orifice diameter described the mass fraction of jet splattered. Additionally, the results indicated that surface tension did not affect splattering. The experimental setup for the reported work described a timed continuous jet stream used to measure flow rates in addition to the volume of splatter, thus enabling an estimate of mass splattered. These measurements were inherently different than those in the current study, which used a discrete volume of a liquid jet impinging onto a flat surface. However, several concepts and results presented in the cited work are comparable to the current study.

Previous work on robotic machine vision for pest control strategies in commercial fields for cotton and processing tomatoes has been reported [4–6]. Based on work presented by these researchers, a system that allows centimeter-scale application of herbicides will likely include an image-based crop/weed discrimination system to inspect the seed line from the vertical direction to locate and distinguish weeds and crop, and a precision dosing system to simultaneously and exclusively apply any number of pest control agents to crop targets, weed targets, or combinations.

GOAL AND OBJECTIVES

The present work was done to establish liquid properties and jet conditions that could be used in a field setting to adequately wet targets (weeds) and minimize splash onto adjacent crop plants. This work was not done solely to establish nondimensional mathematical models, but rather to determine conditions over a finite range of parametric conditions that could be used to establish operational criteria for use in an applied field equipment setting.

To that end, biological efficacy depends on a precise target area covered when microliter volumes are applied on a centimeter scale. Additionally, minimization of splash, or microdrift, to avoid undesired phytotoxic damage to the adjacent crop is a critical constraint in the current work. Based on these criteria, the objectives of this research were:

1. Determine the volume dose per pulse for a centimeter-scale "spot" sprayer under different pulse durations of liquid jet emission, spray liquid adjuvants, and orifice diameters
2. Quantify the deposition area and centimeter-scale splashing (microdrift) using Kromekote™ card targets for different spray adjuvant formulations, different jet conditions, and different orifice-to-target distances
3. Establish liquid properties that may provide effective weed control in addition to protecting adjacent crops by minimizing microdrift

EXPERIMENTAL DESIGN

The herbicide rate used in this study was 0.75% v/v glyphosphate (Rodeo™ Monsanto Co.) and was added to all tested formulations except the water reference liquid [physical parameters for water in this test are a temperature range of 19–23°C, pH range of 7.6–8.4, and hardness range of 70–590 (ppm as CaCO₃)]. Glyphosphate (or glyphosate) is a common, nonselective, postemergent herbicide used in agricultural, landscape, homeowner, and right-of-way weed control. The spray adjuvants used were a silicone surfactant at 0.25% v/v (Silwet-L77, Loveland Industries, Inc.) and an emulsified oil-based adjuvant at 5% v/v (Herbimax, Loveland Industries, Inc.). The polymers that were added to formulations were a polyethylene oxide polymer (Polyox WSR N-60K, 2,000,000 MW, Union Carbide) at 0.03% v/v and polyacrylamide polymer (Target LC, > 20,000,000 MW, Loveland Industries, Inc.) at 0.05% v/v. The diluent for all formulations was municipal water. Liquid parameters for diluent, herbicide, surfactant, and polymer mixtures are given in Table 1 (the following abbreviations are used for formulations in all tables and figures: W = water, S = 0.25% Silwet L-77, SPEO = 0.25% Silwet L-77 with 0.03% polyethylene polymer (PEO), STLC = 0.25% Silwet L-77 with 0.05% polyacrylamide

Table 1. Physical Properties of Liquid Formulations and Dimensionless Flow Numbers for 70-kPa Liquid Supply Pressure and Two Orifice Sizes*

Formulation	ρ (kg/m ³)	μ (mPa·s)	σ (N/m)	Orifice diameter = 0.508 mm				Orifice diameter = 1.194 mm			
				U (m/s)	Re	We	Oh × 10 ³	U (m/s)	Re	We	Oh × 10 ³
W	998.9	1.078	0.0723	6.621	3117	308	5.628	7.997	8848	1055	3.671
S	999.8	1.116	0.0263	6.414	2919	794	9.656	7.526	8050	2571	6.298
SPEO	999.6	1.395	0.0263	6.242	2272	752	12.07	6.745	5771	2065	7.874
STLC	1000.4	2.980	0.0278	6.230	1062	710	25.07	7.344	2944	2317	16.35
H	986.5	1.019	0.0338	6.621	3256	650	7.830	7.648	8840	2038	5.107
HPEO	988.2	1.317	0.0337	6.472	2467	624	10.13	6.939	6217	1686	6.605
HTLC	990.3	2.805	0.0337	6.681	1198	666	21.54	7.847	3308	2160	14.05

* Physical properties were measured at 22°C. Jet velocities are for a steady-state condition integrated over a 10 s sample period.

polymer (TLC), H = 5% Herbimax, HPEO = 5% Herbimax with 0.03% PEO, HTLC = 5% Herbimax with 0.05% TLC).

Test parameters for the experiments were the liquids listed in the previous paragraph, jet orifice diameter, jet pulse duration, and orifice-to-target distance. The jet orifices were constructed of 16- and 21-gauge stainless steel hypodermic tubing, with 1.194 and 0.508 mm inside diameters, respectively. Liquid was supplied to the orifices at a constant 70 kPa pressure. Jet pulse durations were 6 and 20 ms. The liquid supply consisted of a pressurized plastic container. The sprayer generated pulses by using a direct-acting two-way DC solenoid valve with a Luer™ lock fitting close-coupled to the valve outlet [16]. All orifice tips were 12.7 mm long and attached to the solenoid valve at the Luer lock outlet. The 6- and 20-ms pulses refer to the duration of the electrical signal sent to the valve. Since the valves require approximately 3 ms to open or close, the 6-ms pulse time represented a transient condition for the jet. The 20-ms pulse represented substantially more steady-state time for the jet emission. The test conditions were selected based on typical and expected operating conditions for a vehicle-mounted automatic sprayer system [4–6] where a typical 10-ms spray jet emission is used and the resolution of the imaging system results in spray treatment cells with dimensions of 12.7 × 6.4 mm.

"One-shot" mass measurements were made by collecting the discharge from 6- and 20-ms pulses from the orifice with a Sartorius scale (model BP61, Sartorius AG) with a resolution of 0.1 mg and calibrated based on manufacturer recommendations. Several representative shots of liquid were collected, averaged, and converted to volume using the measured density of each formulation. The "one-shot" measurements are reported as the volumetric doses in Table 2. Steady-state flow rate measurements were made for each parametric condition and each formulation by collecting flow for a 10-s time frame. The steady-state values were used to calculate the velocity, Re, We, and Oh values in Table 1. Since the actual transient behavior of the pulsed jet emission and the resulting partial flow conditions were not measured directly in the study, the steady-state values represent maximum values.

For each parametric condition, the jet orifice was positioned at 5 and 20 cm above the target cards. These distances were chosen to represent the likely range of distances at which equipment might operate above the target level when deployed on a moving vehicle in the field. The spray targets were smooth Kromekote cards with a size of 21.6 cm × 27.9 cm. A spray colorant (Signal™ Precision Laboratories, Inc.) was added at 1.0% v/v to solutions for stain visualization on the Kromekote cards. After each deposition application, the cards were allowed to air-dry and then were scanned (Epson® Perfection 1200U Photo Scanner, Epson, Inc.) for conversion to digital images using Scion Image™ and subsequent numerical processing described in a previous publication [10]. After the digital images were collected, the stains produced by the spray deposition were quantified as follows. The total stain (TS) was defined as the total projected area covered by the deposition from the impacted jet. The primary stain (PS) area was defined as the area of the largest single contiguous stain produced by the jet impact. A relative index of the "spread" of the deposit was calculated as PS/TS, where PS was the volume of fluid emitted in the pulsed jet. The microdrift (μD) was defined as the difference between the TS and PS values; μD represented the "splash" or deposition not directly in contact with the PS. Similarly, the relative amount of microdrift in the total jet deposit was quantified by calculating the fractional microdrift, μD_f , as $\mu D/TS$. In addition to the deposition area covered, the extent of splash, or microdrift, was quantified by normalizing discrete microdrift

Table 2 Dispensed Volume and Deposition Results from Pulsed Jets of 6- and 20-ms Duration and 0.508- and 1.194-mm Diameters for Applications onto Kromekote Cards at 5-cm Orifice-to-Target Distance

Formulation	V _f (μL)	PS (cm ²)	TS (cm ²)	μD (cm ²)	PS/V _f (cm ⁻¹)	DS ₅₀ (cm)	μD ₅₀ (μL)
D = 0.508 mm, 6-ms pulse							
W	26.4	0.88	2.56	1.68	33	8.7	0.66
S	32.7	8.72	10.47	1.75	267	10.7	0.17
SPEO	35.1	9.66	9.66	0.00	276	0.0	0.00
STLC	28.6	12.61	12.61	0.00	441	0.0	0.00
H	25.3	1.35	5.03	3.68	53	9.4	0.73
HPEO	24.1	0.76	0.76	0.00	31	0.0	0.00
HTLC	36.0	1.75	3.33	1.58	48	8.5	0.47
D = 1.194 mm, 6-ms pulse							
W	128.6	5.01	6.28	1.27	39	2.1	0.20
S	123.4	37.39	39.39	2.00	303	9.9	0.05
SPEO	103.1	29.79	29.79	0.00	289	0.0	0.00
STLC	100.5	29.09	29.58	0.49	289	12.5	0.02
H	117.7	10.29	11.36	1.07	87	7.9	0.09
HPEO	104.0	5.44	5.44	0.00	52	0.0	0.00
HTLC	111.1	10.39	11.46	1.07	94	6.5	0.09
D = 0.508 mm, 20-ms pulse							
W	58.1	1.37	3.87	2.50	24	8.2	0.65
S	61.3	17.35	22.04	4.69	283	10.8	0.21
SPEO	49.2	18.13	18.13	0.00	369	0.0	0.00
STLC	47.8	15.30	15.30	0.00	320	0.0	0.00
H	60.0	2.42	11.62	9.21	40	9.7	0.79
HPEO	57.8	1.37	1.37	0.00	24	0.0	0.00
HTLC	62.0	2.87	6.43	3.57	46	9.0	0.56
D = 1.194 mm, 20-ms pulse							
W	280.9	7.33	8.12	0.79	26	8.7	0.10
S	290.5	68.08	71.25	3.18	234	12.1	0.05
SPEO	298.6	58.21	58.21	0.00	195	0.0	0.00
STLC	303.8	72.40	72.50	0.10	238	8.6	0.001
H	309.3	20.40	21.89	1.49	66	9.3	0.07
HPEO	277.4	10.23	10.23	0.00	37	0.0	0.00
HTLC	301.3	15.96	17.80	1.85	53	8.9	0.10

stains. Knowledge (from the software) of the coordinates of the centers of microdrift stains enabled the distance of the microdrift deposit from the center of the primary stain to be calculated. The technique was to accumulate the spray deposition between the outer boundary of the PS and the maximum distance outward of the microdrift deposition. When the accumulated μD was plotted against the distance from the maximum extent of μD inward toward the PS center, the result was analogous to the classic "spray drift" curves used in larger-scale agricultural field research. Several representative curves showing primary stains with microdrift, control of microdrift, and lack of microdrift control appear in Figs. 2-4. In addition to the results shown in the continuous curves, a DS_{50} value was calculated as the radial distance outward from the center of the primary stain within which 50% of the μD was contained.

In addition to the stain analysis, behavior of the jets impacting a leaf surface was visualized through a series of photographs during impacting events. A leaf sample of a waxy plant (*Dieters iridioides*) was positioned to create a horizontal surface 5 cm below a 0.508-mm orifice. Jet pulse time was extended to 100 ms. A digital camera (D1H, Nikon) was triggered at a sequence of time intervals after jet emission to provide a sequence of images of the jet impactation. Images were collected for the water (W), silicone surfactant solution (S), and surfactant + polyethylene oxide (SPEO) solution.

RESULTS AND DISCUSSION

The measured liquid properties and calculated dimensionless numbers Re , We , and Oh are shown in Table 1. The effects of the adjuncts were as expected. The relatively low concentrations of adjuncts produced negligible change ($<2\%$) in the mass density of the resulting solutions. Addition of the silicone surfactant to water and polymer solutions reduced surface tension to 0.027 N/m; similarly, addition of the oil-based surfactant reduced surface tension to 0.034 N/m. Addition of the polyethylene oxide and polyamide polymers increased shear viscosity to 1.35 and 2.85 mPa·s, respectively. Addition of PEO increased the viscosity of the Silwet and Herbimax adjuncts by 25% and 29%, respectively. Addition of TLC increased the viscosity of the Silwet and Herbimax adjuncts by 160% (recognize that these are static measurements under low shear viscosity and, as discussed below, deposition and impactation processes may be better explained with respect to dynamic surface tension and high shear rate measurements). The data indicate that steady-state velocities for the different formulations are relatively equivalent. For the small orifice, the largest difference in velocities was 0.45 m/s (7%), whereas for the larger-diameter orifice, the maximum difference in velocities was 1.25 m/s (16%). Re values for the 0.508-mm diameter orifice ranged from 1 to 3×10^3 , indicating that flows were laminar or transitional, while flows from the 1.194-mm orifice were proportionately higher and into the transitional - turbulent range [17].

Measured and calculated results from the tests are shown in Tables 2 and 3 for the 5- and 20-cm target-to-nozzle spacings, respectively. The emitted liquid volume (dose) per jet pulse was strongly dependent on pulse duration and orifice diameter and less affected by liquid formulation. For the 0.508-mm orifice, 6- and 20-ms pulses emitted volumes of the order of 30 and 55 μL , respectively. Since the emitted volumes for the 20-ms pulse were not proportionately larger than for the 6-ms pulses, it was hypothesized that the transient cycle (opening/closing) time of the valve was greater than the 6-ms electronic pulse. Since the valve is normally closed, the electrical solenoid opens the valve and the valve is subsequently closed by a mechanical spring. Additionally, the jet orifice tube, with a length/diameter ratio of 25, provided considerable resistance to flow in series with the metering valve. These effects would likely cause nonlinearity between the emitted volume and the valve pulse, especially at brief pulse durations. For the 1.194-mm orifice, 6- and 20-ms pulses emitted volumes of the order of 110 and 300 μL , respectively. With the 1.194-mm-diameter orifice, the overall resistance to flow downstream of the valve is less and the length/diameter ratio of the jet tube is less; consequently, the relationship between emitted volume and pulse duration was more proportional than with the smaller orifice.

Data in Tables 2 and 3 show several clear trends with respect to effects of orifice size, pulse duration, and orifice-to-target distance on deposition characteristics. Results for the

5-cm orifice-to-target distance showed that primary stain area increased greatly as orifice size and pulse duration increased; this was expected since the individual effects and combination of these effects resulted in greater volumes emitted per jet pulse. Calculation of the PS/V value normalized the area to the amount of liquid dispensed and allowed relative effects to be analyzed. The PS/V values varied over an order of magnitude and clearly illustrated the effectiveness of the silicone surfactant, even when the PEO and TLC polymers were present in the formulation. The oil-based surfactant was less effective, as observed, with lower PS/V values; however, this is consistent with the design objective of the liquid, which is to increase penetration of chemical into the plant rather than increasing spread of the deposit on the plant surface. Results for the 20-cm orifice-to-target distance showed similar trends to those from the 5-cm spacing. Microdrift increased as transit

Table 3 Dispensed Volumes and Deposition Results from Pulsed Jets of 6- and 20-ms Duration and 0.508- and 1.194-mm Diameters for Applications onto Kromekote Cards at 20-cm Orifice-to-Target Distance

Formulation	V (μ L)	PS (cm^2)	TS (cm^2)	μD (cm^2)	PS/V (cm^{-1})	DS_{50} (cm)	μDf
<i>D = 0.508 mm, 6-ms pulse</i>							
W	26.4	0.75	3.81	3.07	28	7.3	0.81
S	32.7	11.71	22.82	11.11	358	7.5	0.49
SPEO	35.1	12.73	12.73	0.00	363	0.0	0.00
STLC	28.6	9.57	9.61	0.03	335	5.7	0.003
H	25.3	1.37	6.51	5.15	54	7.9	0.79
HPEO	24.1	1.82	2.10	0.28	75	2.1	0.13
HTLC	36.0	2.00	4.35	2.35	55	6.6	0.54
<i>D = 1.194 mm, 6-ms pulse</i>							
W	128.6	3.96	10.33	6.37	31	7.4	0.62
S	123.4	29.33	39.16	9.83	238	10.1	0.25
SPEO	103.1	26.93	27.00	0.08	261	7.0	0.003
STLC	100.5	18.67	31.25	12.58	186	8.3	0.40
H	117.7	6.74	16.72	9.99	57	9.7	0.60
HPEO	104.0	5.29	6.06	0.77	51	2.5	0.13
HTLC	111.1	6.20	10.40	4.19	56	8.6	0.40
<i>D = 0.508 mm, 20-ms pulse</i>							
W	58.1	1.32	6.86	5.54	23	8.2	0.81
S	61.3	15.12	32.69	17.57	247	8.5	0.54
SPEO	49.2	16.25	16.25	0.00	331	0.0	0.00
STLC	47.8	11.18	11.29	0.11	234	2.4	0.01
H	60.0	2.10	14.03	11.93	35	8.4	0.85
HPEO	57.8	2.65	2.90	0.25	46	1.3	0.09
HTLC	62.0	3.08	9.77	6.69	50	9.1	0.69
<i>D = 1.194 mm, 20-ms pulse</i>							
W	280.9	10.60	20.96	10.36	38	7.0	0.49
S	290.5	58.98	82.89	23.91	203	10.8	0.29
SPEO	298.6	70.75	89.51	18.77	237	11.2	0.21
STLC	303.8	34.19	46.88	12.69	113	10.6	0.27
H	309.3	16.17	32.83	16.66	52	9.6	0.51
HPEO	277.4	14.59	20.12	5.53	53	6.1	0.27
HTLC	301.3	13.79	25.72	11.93	46	10.1	0.46

distance increased; however, no general trend was observed with primary stain size and increased transit distance.

No general trend was observed from the addition of PEO to the silicone surfactant (SPEO formulation) with respect to primary stain size. SPEO controlled microdrift completely in all cases, except for the extreme case of longest pulse duration, largest orifice diameter, and highest transit distance. HPEO controlled microdrift for all conditions at the 5-cm orifice-to-target distance, with minimal splashing at the 20-cm orifice-to-target distance, except for the extreme case. Also, HPEO decreased primary stain size at the 5-cm orifice-to-target distance; however, no trend was observed for the higher transit distance. STLC tended to control microdrift for all conditions except the extreme case, and tended to decrease primary stain size for the highest transit distance. HTLC showed microdrift for all conditions studied.

Inspection of the DS_{50} and the μD values provide insight into the potential damage that adjacent nontargets such as crop plants could suffer from the pulsed jet applications. The combination of DS_{50} and the μD indicates the amount of microdrift deposit and the distance of microdrift deposit from the target area. Based on these results, use of the silicone surfactant without any polymer would be undesirable, since significant volumes of liquid are displaced relatively significant distances away from the target deposit. Additionally, use of the large jet diameter and long pulse duration produced the greatest potential microdrift hazards to nontargets. Generally, the empirical results show that control of microdrift is not as evident with TLC as with PEO, especially with the oil-based surfactant. Based on these results (and possible implications discussed below), it is likely that PEO will be the preferred adjuvant to control microdrift in future field studies using the microspray system. However, weed control bioassay experiments must precede the final selection of the adjuvants, in order to confirm that they do not reduce efficacy to unacceptable levels.

Graphic representations of the actual deposit on cards and the microdrift results appear in Figs. 2–4, which show quantitative estimates of the distance microdrift occurs from the primary stain center. Figure 2 shows water and Silwet applications for 0.508-mm orifice diameter, 20-ms pulse duration, and 20-cm orifice-to-target distance. Immediately evident is the increased surface coverage by surfactant and extent of microdrift that occurred. Figure 3 shows SPEO and HPEO for the same application conditions as in Fig. 2. PEO is shown to control microdrift for both surfactants, however, SPEO shows complete control when compared to HPEO. Figure 4 shows the extreme conditions of 1.194-mm orifice diameter, 20-cm orifice-to-target distance, and 20-ms pulse duration, and the inability of PEO to control splashing. Figure 4 also illustrates the different characteristics of the microdrift when the polymers are added. In Fig. 2 the microdrift is observed as a high number of small, individual droplets, whereas in Fig. 4 the microdrift is seen as large contiguous ligaments and fractured ligaments.

Figures 5 and 6 show photographic images of exiting jet streams and resulting spreading, splashing, and onset of microdrift, in addition to jet stream characteristics at the end of an application for some of the test formulations. In Fig. 5, water is shown to accumulate on the surface prior to the end of the jet stream breaking off and producing droplets which promote splash and microdrift. This behavior is typical of a high-surface-tension liquid on a waxy leaf surface. Figure 5 also shows the effect of the silicone surfactant and the more extreme nature of microdrift production after the initial portion of the jet stream impinges on the surface. The lower surface tension leads to a greater tendency to form smaller droplets upon jet breakup [18], and this effect is evident in the microdrift

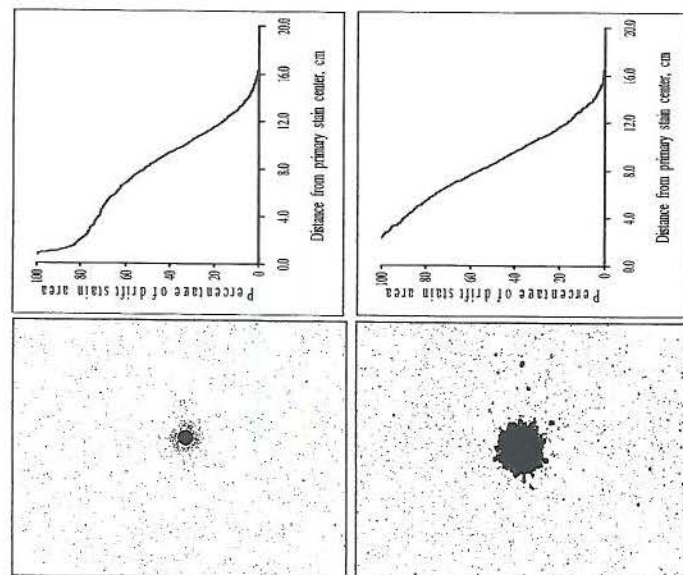


Fig. 2 Results showing primary stains and microdrift for W (top) and S (bottom) at 70-kPa liquid pressure, 0.508-mm D , 20-ms pulse duration, and 20-cm orifice-to-target distance.

results for the silicone surfactant presented in Tables 1 and 2 and previously in Fig. 2. Figure 6 shows images of the silicone surfactant with PEO polymer and the effect surfactant has by increasing spread of the deposit and effectiveness of polymer to control microdrift at the onset of the jet impinging on the surface. Additionally, the sinuous and beading nature of the jet stream during the end of an application can be observed. The lack of microdrift produced is due to polymer addition; there is less of a tendency to form small droplets on breakup [18] due to the dampened energy transfer during impactation and due to the increased extensional viscosity of the liquid. From these results, it is evident that an increase in viscosity overrides the tendency to form small droplets due to the lower surface tension during the initial jet impingement upon the surface. Additionally, the increased spreading of material (due to silicone surfactant) is not dampened to a great extent by addition of the polymer. Application of HTLC may have a slower exiting tail of the jet stream, leading to increased droplet and dripping production (especially in light of the Re numbers for these formulations). This effect is evident in Tables 2 and 3 with the μD term, where the increase in microdrift stain area is likely due to drops impinging on a wetted flat surface.

RESULTS IN RELATION TO PREVIOUS STUDIES

In an earlier study, Rioboo et al. [14] discussed and classified the effect of droplets applied to different surfaces. Also, the report discussed previous work and attempts to classify criteria for a splash/deposition limit by defining the dimensionless number K' ($We \cdot Oh^{-0.9}$). Although their results were for a single droplet, consideration of the dimensionless numbers presented in the present study (Table 1) for the small-orifice nozzle shows similar results for the splash/deposition limit criteria. Water on glass (with deposition) had a K' value of 5340, ethanol on glass had a K' value of 2080 (with corona splash), and water on PVC had a K' value of 1240. In the present study, with a discrete volume of a liquid jet impinging on Kromekote paper, set on a rigid surface, the K' value for SPEO was 4401 (deposition), for Silwet was 5080 (deposition with corona splash), and for water was 2446 (deposition and receding breakup). Obviously, the experimental techniques presented with these comparisons are different, and as the previous research [14] has indicated, there is an inherent complexity of interaction between the physical parameters describing liquids, and

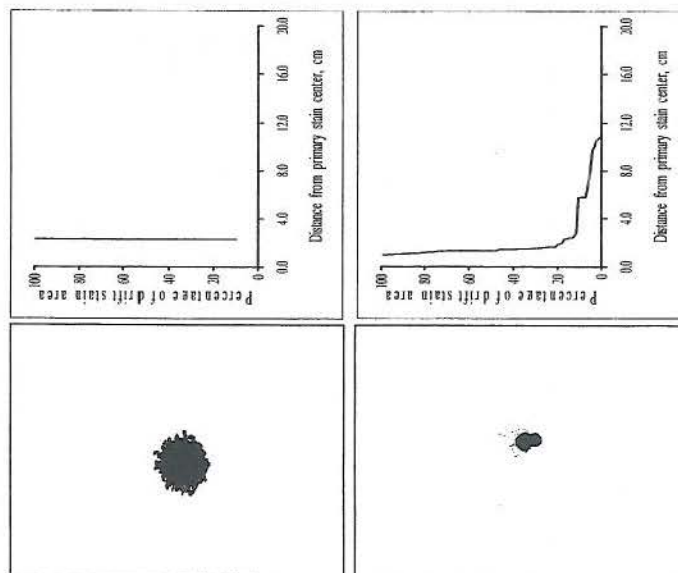


Fig. 3 Results showing primary stains and microdrift control due to polymer addition for SPEO (top) and HPEO (bottom) at 70-kPa liquid pressure, 0.508-mm D , 20-ms pulse duration, and 20-cm orifice-to-target distance.

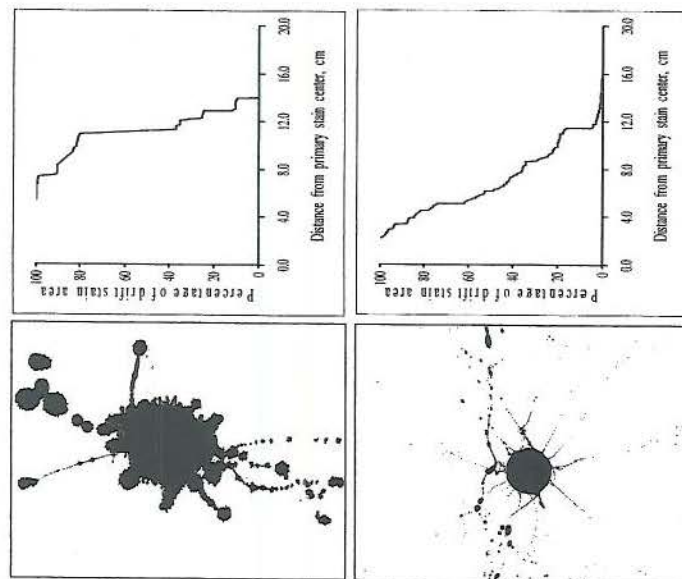


Fig. 4 Results showing primary stains and lack of microdrift control due to polymer addition for SPEO (top) and HPEO (bottom) at 70-kPa liquid pressure, 1.194-mm D , 20-ms pulse duration, and 20-cm orifice-to-target distance.

resulting deposition, splash, and wettability, in addition to basic deficiencies and an oversimplification that may exist in current models.

A model was developed to estimate splattering of turbulent liquid jets impacting on solid targets [15], based on the We number and nozzle-to-target distance. Although the work used a continuous stream impinging on a flat hard surface, the authors discussed several concepts that may explain some of the results observed in the current study. The present work observed microdrift with the liquid formulations containing TLC, and this may be due to disturbances from capillary instability. Also, Bhunia and Leinhard [15] report that traveling waves originate near the jet impingement point and travel outward on the liquid film (forming hydraulic jumps), and when the jet disturbances are sufficiently large, these waves can sharpen and break into droplets. Although it is not readily observable with the silicone surfactant in Fig. 5, Fig. 6 shows the formation of a traveling wave (or hydraulic jump); however, the effect of the PEO polymer addition prevents splash or microdrift from occurring. Since the experimental setups were relatively different and Bhunia and Leinhard [15] were using a continuous jet stream (as opposed to a discrete

volume of liquid jet), there was difficulty in comparing the present results with those reported based on We and nozzle-to-target distance. However, it is interesting to note that Bhunia and Leinhard found that the presence of surfactant did not alter splattering, whereas this study produced an opposite result. Considering the results (μD) presented in Tables 2 and 3, it appears, at first glance, as if surfactant does not increase microdrift (splash, splatter) when normalizing the μD term to the total stain area measured. However, the μD term is substantially larger in terms of splashed stain area outside of the primary

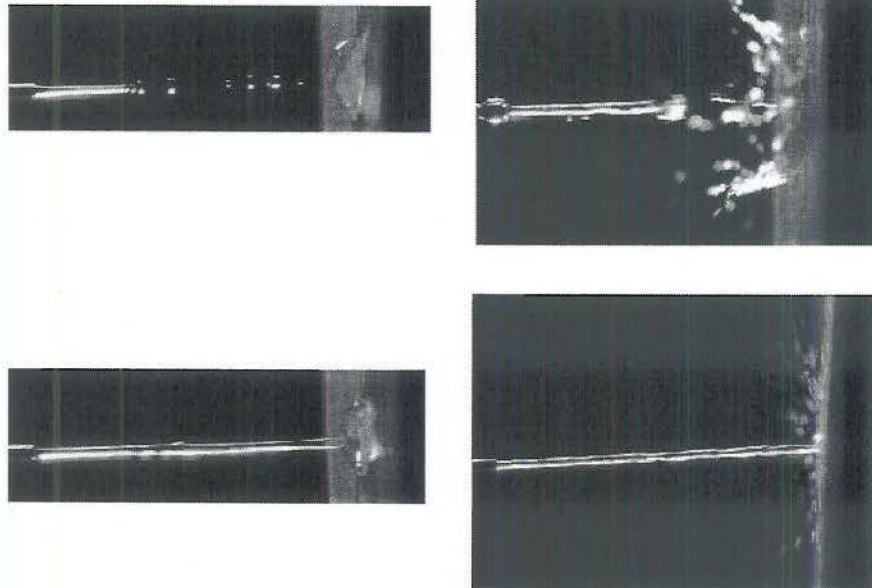


Fig. 5 Images of W (top) and S (bottom) showing differences of microdrift onset at 70-kPa liquid pressure, 0.508 mm orifice diameter, and 5-cm orifice-to-target distance.

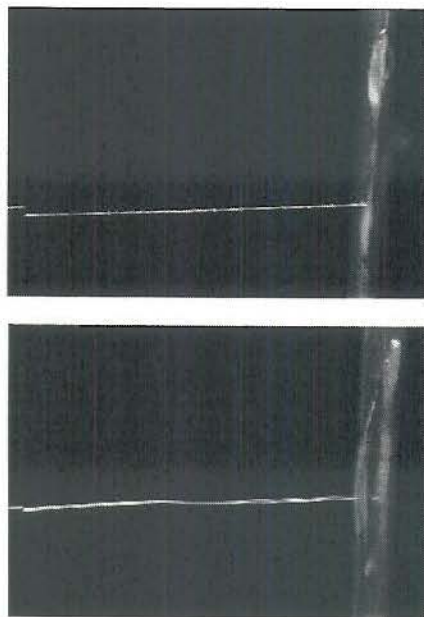
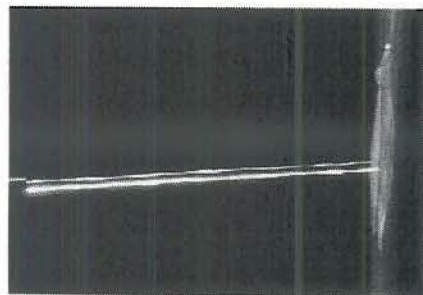


Fig. 6 Images of SPEO showing spreading (top), sinusous wave production along the jet (bottom left), and beading of jet stream at the end of an application (bottom right) at 70-kPa liquid pressure, 0.508-mm orifice diameter, and 5-cm orifice-to-target distance.

deposition area covered when compared to water. Bhunia and Leinhard additionally implied that their observations may be due to the fact that surfactant does not diffuse fast enough from the bulk fluid to the free surface (along the liquid jet stream) and this free surface remains unsaturated, or retains the surface tension of pure water. This may have been the case for their study (soap and water); however, one can speculate an alternative effect in view of the microdrift observed with the current study. It is possible that hydrogen

bonding of their surfactant to water slowed the rate of diffusion of surfactant to the free surface, thus preventing any splash occurring, whereas diffusion of surfactant, used in the present study, to the free jet surface occurs at a much faster rate, enabling the effect of a lower surface tension to be seen (Fig. 5, silicone surfactant) soon after jet impingement onto the surface.

Recent information has been found that may describe the impaction and deposition process with respect to additional physical properties of solution [19]. Impaction, spread, and splash under the operating parameters reported in this work occur within 20 ms. Surfactants can take a significant time to diffuse to the liquid-air surface to reach equilibrium concentration. As the two adjuvants studied in this work have similar surface tensions, yet have markedly different effects with respect to spreading and splash, the discrepancy may be better explained with dynamic surface tension measurements in light of the dimensionless quantity of PS/V (ratio of primary stain area to volume applied). Additionally, the similar viscosity values reported here are based on a low-shear-rate measurement method. The PEO solutions were able to control splash better than the TLC solutions, and this effect is not indicated by the measured viscosities we have reported. It is possible that the large differences in the deposition and splash in the results presented for the solutions here may be better explained by measuring extensional viscosity. Dexter [20] has presented a method for measuring extensional viscosity, in addition to reporting on the correlation of droplet size distribution with extensional viscosity. The results reported here may be further described based on extensional viscosity measurements, as the process of impaction and splash is an extensional or stretching process [19]. Differences in extensional viscosity may be much larger than differences in shear viscosity and could explain the large differences between the microdrift results reported.

As a means to classify the type of liquid jet stream observed in the current work, Lefebvre [21] has reported previous research to categorize spray atomization and reproduced the classification of modes of disintegration charts by other researchers. Based on these reproductions and data presented here (Table 1, Fig. 7), the liquid spray jet emissions reported for the 0.508-mm-diameter orifice and operating conditions can be categorized as sinusous wave breakup (or first wind-induced). This classification of modes of disintegration follows the jet-stream image results presented in Fig. 6 for the silicone surfactant and PEO polymer at the end of the exiting material. Results for the 1.194-mm diameter orifice and operating conditions are classified as wavelike breakup with air friction (or second wind-induced).

CONCLUSIONS

The results presented in this work show that addition of a polyethylene oxide polymer (PEO) and a polyacrylamide polymer (TLC) can effectively reduce microdrift from deposited pulsed jets for a spot sprayer system applying material at 5- and 20-cm transit distances. Primary stains of silicone surfactant were at least 5 times greater in area than those for water; however, the effect of microdrift does not warrant use of this material without addition of polymer. Addition of PEO and TLC to the silicone surfactant solution controlled microdrift in all cases except for the large (1.194-mm-diameter) jet orifice, longest pulse time (20 ms), and greatest transit distance (20 cm). Also, primary stains of both formulations measured were at least 5 times those for water, indicating that polymer

addition did not affect the spreading nature of silicone surfactant. Future studies will analyze the effect of extensional viscosity measurements on microdrift with respect to the different formulations considered in this work.

Primary stains of the oil-based penetrant and surfactant were comparable to water, and additionally, PEO added to Herbimax controlled the onset of microdrift much better than HTLC and Herbimax alone. The recommendations for field studies are to use PEO as the sole microdrift reduction agent, used in conjunction with Silwet L-77 and Herbimax, to directly target weed plants adjacent to high-value crops for the spot sprayer system.

The results presented in this work will enhance the ability to precisely target noxious weeds with a precision spraying system. Knowledge of the extent of areal coverage of a formulation *a priori*, and use of this information to apply a precision chemical dose over the specific area, will minimize chemical application in the environment, in addition to providing a cost savings for materials. As seen in Fig. 1, proximity of a weed to young tomato plants implies the need to minimize microdrift, in addition to precisely targeting chemicals to limit their deposition on bare soil.

These results are preliminary with respect to field application trials, and may be different in an actual field setting due to the plant nature of a leaf surface versus a hard surface. The logical next step in the process is to assess behavior in the field of formulations studied in this work. However, knowledge deduced from the presented results will enable several of the parametric conditions to be eliminated in future studies. That is, the dripping nature of an exiting jet due to polymer addition (HTLC) should not be used with a precision dosing system that is moving, due to the likelihood that material would be deposited off-target. Future field tests are warranted to ensure that physical applications are precisely and accurately deposited over a selected target with microdrift control, minimization of material applied to bare soil, with a high percentage of weed control and crop protection.

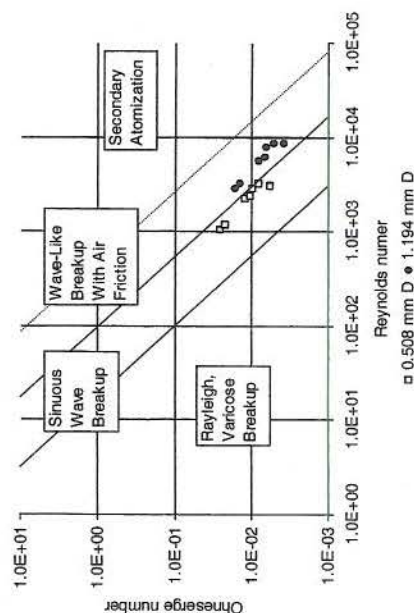


Fig. 7 Atomization regions based on Re and Oh numbers [from Ref. 8, Fig. 2-7] and conditions used in this experiment.

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