Efficacy of Selected Insecticides as Replacement for Neonicotinoids in Managing Sweetpotato Whitefly on Poinsettia

Gunbharpur Singh Gill¹ and Juang Horng Chong¹

ADDITIONAL INDEX WORDS. *Bemisia tabaci*, *Euphorbia pulcherrima*, floriculture, foliar spray, substrate drench

SUMMARY. Management of sweetpotato whitefly (*Bemisia tabaci*), one of the most economically important pests of poinsettia (*Euphorbia pulcherrima*), relies heavily on neonicotinoid insecticides. Growers are seeking insecticide alternatives to neonicotinoids due to market demands. Although several systemic and translaminar insecticides have been suggested as alternatives to neonicotinoids, no published study has simultaneously compared their efficacies against sweetpotato whiteflies. This study compared the efficacies of 10 systemic and translaminar alternative insecticides with those of two systemic neonicotinoids, when all products were applied as foliar spray (twice at 14 d) or substrate drench (once) against sweetpotato whiteflies on poinsettia plants. Sweetpotato whitefly nymph and adult densities were examined 2 weeks before the first application (pretreatment), and weekly after the application for 8 weeks. Results showed that insecticides varied greatly in their efficacy, particularly against adults, and that spray application provided more effective suppression of nymphs than drench application. Spray and drench applications of imidacloprid and dinotefuran were consistently the most effective against sweetpotato whitefly nymphs and adults. Among the neonicotinoid alternatives, cyantraniliprole was the most effective insecticide in reducing sweetpotato whitefly nymph densities by both spray and drench application methods, with efficacy comparable to those of imidacloprid and dinotefuran. Although less effective than cyantraniliprole, foliar sprays of afidopyropen, chlorantraniliprole, cyclaniliprole, flonicamid, flupyradifurone, pyrifluquinazon, spirotetramat, and sulfoxaflor + spinetoram were also effective against nymphs and could serve as partners in an insecticide rotation program.

Poinsettia (*Euphorbia pulcherrima*) is a major floricultural crop in North America. In 2019, 1193 operations produced close to 47 million

pots that valued nearly \$216 million in the United States (U.S. Department of Agriculture, National Agricultural Statistics Service, 2019). Whiteflies (Aleyrodidae), particularly sweetpotato whitefly (*Bemisia tabaci*), are the most economically important arthropod pests of poinsettia (Martin and Mound, 2007; Perring et al., 2018). Their presence is objectionable to consumers, and the removal of a large amount of sap and nutrients by a large population can also

retard the growth of poinsettia (Wang et al., 2017). Sweetpotato whiteflies also produce honeydew, which is an excellent substrate for the growth of black sooty mold (Byrne and Bellows, 1991). The presence of shiny, sticky honeydew and black sooty mold further reduces the marketability and value of a poinsettia crop.

Although a treatment threshold or tolerable sweetpotato whitefly density on poinsettia is poorly defined at retail outlets (Vafaie et al., 2020), most poinsettia growers operate under the assumption of “zero tolerance” for sweetpotato whitefly. Biological control programs using entomopathogenic fungi and parasitoids at various stages of a crop cycle were very successful in some studies (Buitenhuis et al., 2016; Krauter et al., 2017; Stevens et al., 2000; Van Driesche et al., 1999); however, sweetpotato whitefly management programs in poinsettia crops at many operations continue to rely on highly intensive insecticide application programs (Hoddle and Van Driesche, 1996; Stevens et al., 2000; Vafaie et al., 2021).

Drench and/or foliar applications of neonicotinoids and other systemic or translaminar insecticides form the basis of conventional chemical management programs against sweetpotato whitefly on poinsettia (Stevens et al., 2000; Vafaie et al., 2021). Translaminar pesticides, sometimes called locally systemic pesticides, are those that move into and across a leaf but remain restricted to the leaf that has received the treatment (McGrath, 2004). Systemic pesticides, in addition to having translaminar activity, can be translocated throughout the plants via the xylem or phloem. Reliance on neonicotinoid insecticides for pest management has certain benefits

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¹Clemson University, Pee Dee Research and Education Center, 2200 Pocket Road, Florence, SC 29506

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Current address for G.S.G.: Iron Ox, Inc., 955 Terminal Way, San Carlos, CA 94070

J.H.C. is the corresponding author. E-mail: juanghc@clemson.edu.

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
29.5735	fl oz	mL	0.0338
0.0781	fl oz/100 gal	mL·L ⁻¹	12.8000
0.3048	ft	m	3.2808
0.0929	ft ²	m ²	10.7639
3.7854	gal	L	0.2642
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
6.4516	inch ²	cm ²	0.1550
28.3495	oz	g	0.0353
0.0749	oz/100 gal	g·L ⁻¹	13.3526
1	ppm	mg·L ⁻¹	1
6.8948	psi	kPa	0.1450
(°F - 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

and risks (Bethke and Cloyd, 2009). Neonicotinoids provide a major benefit of effective and persistent suppression of sweetpotato whitefly populations. However, the negative impacts of neonicotinoids on pollinator health have been prominently noted (Goulson et al., 2015). Despite their generally poor understanding of the risks and benefits of neonicotinoids to pollinators and floriculture, many consumers demand pollinator-friendly, pollinator-safe, or neonicotinoid-free plants (Blacquière et al., 2012; Getter et al., 2016; Rihn and Khachatryan, 2016; Wei et al., 2020; Wollaeger et al., 2015). In response to changing consumer preference, many operations have eliminated or planned to eliminate neonicotinoids from their pest management programs. Growers interested in producing neonicotinoid-free poinsettias (and other ornamental plants) are looking for alternatives to neonicotinoids.

We conducted a study to document the efficacies of selected systemic and translaminar insecticides, which have been identified or are being used as alternatives to neonicotinoids by growers, in managing a sweetpotato whitefly population when the insecticides were applied as foliar sprays or substrate drench to a poinsettia crop. The efficacies of these alternatives were compared with dinotefuran and imidacloprid, two neonicotinoids commonly used for sweetpotato whitefly management in poinsettia production. The selected alternatives represent six modes of action, with chemical and practical application properties that are different from the neonicotinoids (Chong et al., 2015). Although reports of the efficacy and comparisons among small groups of the selected alternatives are available (e.g., Arthurs et al., 2017), there is no published study in which all of these alternatives are compared simultaneously. The efficacy of the selected alternatives relative to commonly used neonicotinoids could be interpreted more accurately in a simultaneous comparative study. Our study goal was to provide growers and pest management practitioners the information needed to select the most efficacious alternative(s) to neonicotinoids.

Materials and methods

PLANT MAINTENANCE AND SWEETPOTATO WHITEFLY INFESTATION. Rooted 'Enduring Red' poinsettia

cuttings, which were available from the propagator (Raker-Roberta's Young Plants, Litchfield, MI) at the time of the experiment, were planted in standard 6-inch plastic pots [≈ 1 L (Landmark Plastic Corp., Akron, OH)] filled with moist substrate (Fafard 3M; Sun Gro Horticulture, Agawam, MA). The propagator reported that the stock plants were treated with azadirachtin and *Beauveria bassiana* (trade name, application rate, and application frequency of the insecticides were not reported) before the cuttings were taken. Residue of these insecticides broke down quickly; thus, we believe they did not influence the outcomes of our intended treatments 8 weeks after transplant.

Each pot was fertilized at transplant with 1 teaspoon (≈ 10 g) 14N-6.1P-11.6K slow-release fertilizer (Osmocote 14-14-14; ICL Specialty Fertilizers, Summerville, SC). Plants were grown in a greenhouse (8×8 m) maintained at $28 \pm 5^\circ\text{C}$ and $75\% \pm 15\%$ relative humidity at the research greenhouse complex at Clemson University Pee Dee Research and Education Center, Florence, SC. The plants were irrigated daily and fertilized at 150 ppm nitrogen weekly. No insecticide or fungicide, other than those evaluated, was applied between transplant and the end of this study.

The experiment began 8 weeks after transplant when the plants reached 6 to 8 inches. The plants were infested naturally during the 8-week period by sweetpotato whitefly adults (MEAM1 or "B" biotype) dispersing from a colony maintained on collards (*Brassica oleracea* Acephala group) in another greenhouse unit of the same greenhouse complex. Plants were assigned to the treatments based on pre-treatment sweetpotato whitefly nymph densities to achieve similar densities among treatments.

INSECTICIDE APPLICATIONS. We compared the efficacy of 10 systemic or translaminar insecticides with those of two neonicotinoid insecticides registered for sweetpotato whitefly management on ornamental crops (Table 1). Imidacloprid (Marathon II; OHP, Bluffton, SC) and dinotefuran (Safari 20SG; Valent USA, Walnut Creek, CA) are neonicotinoids [Insecticide Resistance Action Committee (IRAC) Group 4A], flupyradifurone (Altus; Bayer Environmental Science, Cary,

NC) is a butenolide (IRAC Group 4D), spirotetramat (Kontos, Bayer Environmental Science) is a tetramic acid derivative (IRAC Group 23), and chlorantraniliprole (Acelepryn; Syngenta Crop Protection, Greensboro, NC) and cyantraniliprole (Mainspring GNL, Syngenta Crop Protection) are diamides (IRAC Group 28); these insecticides are systemic and are registered for both spray and drench applications. Cyclaniliprole (Sarisa, OHP) is another diamide, but is registered only for foliar application. XXpire (Corteva AgriSciences, Johnston, IA) contains two active ingredients (sulfoxaflor and spinetoram); sulfoxaflor (IRAC Group 4C) is a systemic insecticide but XXpire is registered for foliar application only. Afidopyropen (Ventigra; BASF Corp., Research Triangle Park, NC), pymetrozine (Endeavor, Syngenta Crop Protection), pyrifluquinazon (Rycar; SePRO Corp., Carmel, IN) and flonicamid (Aria; FMC Corp., Philadelphia, PA) target different sites on the chordotonal organs; only pymetrozine is registered for both foliar and drench applications. To achieve complete 2×12 factorial design, all selected insecticides were applied as foliar sprays (twice at 14-d interval) or substrate drench (once) at their respective label rates (Table 1). It is important to recognize that afidopyropen, cyclaniliprole, flonicamid, pyrifluquinazon, and spinetoram + sulfoxaflor are not registered for drench application in greenhouses in the United States.

A nonionic surfactant (Capsil; Aquatrols, Paulsboro, NJ) was mixed with all insecticide solutions used for foliar spray at the label rate of 6 fl oz/100 gal, and surfactant-alone solution was used as the untreated control for foliar spray. Surfactant was not mixed in solutions used for substrate drench; instead, water was used as the untreated control for drench treatment.

Foliar applications were made on 10 and 24 Sept. 2019. Plants assigned to a treatment were arranged randomly within a premarked 5×5 -ft (25 ft^2) area on the greenhouse floor, and the premeasured insecticide solution was applied to the plants at an application volume of 100 gal/acre with a compressed carbon dioxide sprayer (30 psi) fitted with a single flat fan nozzle (XR-8002VS; TeeJet Technologies, Springfield, IL). Drench application was applied on 10 Sept. 2019. Insecticide solutions were prepared and poured

Table 1. List of insecticides, and their application methods and rates evaluated against sweetpotato whiteflies on poinsettia plants grown in greenhouse.

Treatment ^z	Product trade name ^y	Application method ^x	Product application rate ^w
Afidopyropen	Ventigra	Spray	7 fl oz/100 gal
		Drench	7 fl oz/100 gal
Chlorantraniliprole	Acelepryn	Spray	8 fl oz/100 gal
		Drench	12 fl oz/100 gal
Cyantraniliprole	Mainspring GNL	Spray	8 fl oz/100 gal
		Drench	12 fl oz/100 gal
Cyclaniliprole	Sarisa	Spray	27 fl oz/100 gal
		Drench	27 fl oz/100 gal
Dinotefuran	Safari 20 SG	Spray	8 oz/100 gal
		Drench	12 oz/100 gal
Flonicamid	Aria	Spray	4.3 oz/100 gal
		Drench	4.3 oz/100 gal
Flupyradifurone	Altus	Spray	14 fl oz/100 gal
		Drench	3.7 fl oz/100 gal
Imidacloprid	Marathon II	Spray	1.7 fl oz/100 gal
		Drench	1.7 fl oz per 1000 6-inch pots
Nonionic surfactant	Capsil	Spray	6 fl oz/100 gal
Pymetrozine	Endeavor	Spray	5 oz/100 gal
		Drench	5 oz/100 gal
Pyrifluquinazon	Rycar	Spray	3.2 fl oz/100 gal
		Drench	3.2 fl oz/100 gal
Spinetoram + sulfoxaflor	XXpire	Spray	2.75 oz/100 gal
		Drench	2.75 oz/100 gal
Spirotetramat	Kontos	Spray	3.4 fl oz/100 gal
		Drench	3.4 fl oz/1000 6-inch pots
Water	–	Drench	N/A

^zNonionic surfactant (polyether-polymethylsiloxane-copolymer) was added to all insecticide solutions for foliar spray application. Surfactant-alone solution was used as the untreated control for foliar spray application, whereas water was used as untreated control for substrate drench application.

^yAcelepryn (18.4% chlorantraniliprole; Syngenta Crop Protection, Greensboro, NC), Altus (17.09% flupyradifurone; Bayer Environmental Science, Cary NC), Aria (50% flonicamid; FMC Corp., Philadelphia, PA), Capsil (100% polyether-polymethylsiloxane-copolymer; Aquatrols, Paulsboro, NJ), Endeavor (50% pymetrozine, Syngenta Crop Protection), Kontos (22.4% spirotetramat, Bayer Environmental Science), Mainspring GNL (18.66% cyantraniliprole, Syngenta Crop Protection), Marathon II (21.4% imidacloprid; OHP, Bluffton, SC), Rycar (20.2% pyrifluquinazon; SePRO Corp., Carmel, IN), Safari 20 SG (20% dinotefuran; Valent USA, Walnut Creek, CA), Sarisa (4.55% cyclaniliprole, OHP), Ventigra (9.78% afidopyropen; BASF Corp., Research Triangle Park, NC), and XXpire (20% spinetoram + 20% sulfoxaflor; Corteva Agriscience, Johnston, IA).

^zFoliar sprays were applied twice in 14 d, whereas substrate drench was applied once. Afidopyropen, cyclaniliprole, flonicamid, pyrifluquinazon, and spinetoram + sulfoxaflor are not registered for drench application in greenhouses in the United States.

^w1 fl oz/100 gal = 0.0781 mL·L⁻¹, 1 oz/100 gal = 0.0749 g·L⁻¹, 1 fl oz = 29.5735 mL, 1 inch = 2.54 cm.

evenly over substrate surface at an application volume of 4 fl oz/pot (recommended application volume for 6-inch pots) with a glass beaker. The plants were irrigated 4 h before the treatment, but we did not measure the substrate moisture content before drench treatment.

Plants were returned to the benches when the insecticide solutions on foliage had dried or stopped leaching from the pots. Sprayed and drenched plants were arranged in the same block, with treatments randomized within each block. Plants were

not caged, so sweetpotato whitefly adults were able to disperse among the plants. Each treatment was replicated four times, with each plant representing a replicate.

SWEETPOTATO WHITEFLY DENSITY ASSESSMENT. Sweetpotato whitefly densities were assessed 2 weeks before the first application (pretreatment), and weekly after the application for 8 weeks. Three leaves, one from each of high, medium, and low sections of each plant were randomly selected, and the number of sweetpotato whitefly adults on each leaf was counted in

situ so that adults were not disturbed by leaf collection and flew away. The selected leaves were then detached from the plants, brought back into the laboratory in petri dishes, and the number of nymphs (all instars combined) on a randomly selected 1-inch² area on each leaf was counted under stereomicroscopes.

We did not observe any phytotoxicity (leaf area showing chlorosis or necrosis) and residue (leaf area covered with residue) on poinsettia leaves at 7 and 14 d after each application of any insecticide.

DATA ANALYSIS. Densities of adults and nymphs on the three leaves of a single plant were averaged for each sampling date, and the average densities were log₁₀(x + 0.1)-transformed before been subjected to two-way analysis of variance (ANOVA), with product and application method as the main factors [PROC GLM (SAS version 9.2; SAS Institute, Cary, NC)]. When ANOVA detected significant difference at $\alpha = 0.05$, back-transformed means were separated with Fisher's least significant difference test. Densities of whitefly adults and nymphs on water- or surfactant-treated plants were used to calculate percent reduction in whitefly population for drench and spray treatments, respectively.

Results

INSECTICIDAL EFFICACY AGAINST SWEETPOTATO WHITEFLY NYMPHS. Pretreatment nymph and adult densities did not differ significantly among insecticides and application methods (Tables 2 and 3), suggesting that assigning plants to treatments based on pretreatment nymph densities successfully created similar initial sweetpotato whitefly densities among treatments. Mean densities of nymphs on treated plants were not significantly lower than those on the water- or surfactant-treated plants (control) at 7 and 14 d after treatment (DAT) (Table 2).

Mean nymph densities were significantly different among insecticides at 28 to 56 DAT and between application methods at 28 to 42 DAT (Table 2). At 28 DAT, plants sprayed with spirotetramat, cyantraniliprole, and cyclaniliprole harbored 90%, 84%, and 82%, respectively, fewer nymphs than plants sprayed with surfactant solution. At 35 DAT, all insecticide-

Table 2. Efficacy of foliar spray and substrate drench application of selected insecticides in reducing the densities of sweetpotato whitefly nymphs on poinsettia plants grown in a greenhouse.

Application method	Product	Time after treatment (d)								
		-14	7	14	21	28	35	42	49	56
Spray	Nonionic surfactant (control for spray)	4.1 ± 1.7	4.4 ± 1.9	1.8 ± 1.0	1.6 ± 0.8	4.9 ± 2.0 a ^y	9.2 ± 3.4 a	8.5 ± 2.8 a	18.2 ± 5.0 a	12.3 ± 4.0 a
	Imidacloprid	7.2 ± 1.6	3.9 ± 2.2	2.6 ± 1.8	0.5 ± 0.3	2.8 ± 1.9 ab	2.5 ± 1.1 b	3.7 ± 1.2 bcde	2.2 ± 1.2 bc	4.2 ± 1.4 bc
	Dinotefuran	7.1 ± 1.8	6.9 ± 2.7	3.0 ± 1.4	0.3 ± 0.3	3.0 ± 2.1 ab	1.0 ± 0.5 b	0.2 ± 0.2 c	0.8 ± 0.5 c	0.8 ± 0.5 bc
	Spinetoram + sulfoxaflo ^r	7.4 ± 2.7	4.5 ± 1.7	3.8 ± 1.8	0.4 ± 0.3	1.7 ± 1.0 ab	0.7 ± 0.5 b	1.9 ± 0.7 cde	6.8 ± 2.4 b	6.4 ± 3.0 b
	Flupyradifurone	7.2 ± 1.3	7.5 ± 2.4	2.5 ± 1.2	0.8 ± 0.4	1.8 ± 1.1 ab	3.9 ± 0.9 b	3.8 ± 1.4 bcd	2.7 ± 0.8 bc	3.5 ± 1.1 bc
	Pyrethrin	7.6 ± 2.9	3.6 ± 1.8	3.5 ± 1.5	1.6 ± 0.4	3.4 ± 1.5 ab	2.6 ± 0.6 b A	6.7 ± 1.5 ab	13.5 ± 2.9 a	13.5 ± 3.4 a
	Pyridinylquinazolinone	7.1 ± 1.7	1.7 ± 0.8	1.1 ± 0.9	0.5 ± 0.3	1.7 ± 0.9 ab	1.6 ± 0.9 b	1.0 ± 0.8 de	0.1 ± 0.1 c	0.3 ± 0.3 c
	Afidopyropen	7.1 ± 2.4	8.0 ± 3.1	1.8 ± 1.3	0.7 ± 0.4	1.2 ± 0.5 ab	2.5 ± 1.1 b	2.3 ± 0.6 cde	5.5 ± 2.1 bc	5.9 ± 2.8 bc
	Spirotetramat	6.9 ± 2.4	5.8 ± 2.6	2.8 ± 1.8	0.7 ± 0.4	0.5 ± 0.2 b	1.3 ± 0.7 b	0.9 ± 0.9 de B	4.5 ± 2.0 bc	2.4 ± 1.0 bc
	Chlorantraniliprole	7.2 ± 1.7	3.6 ± 1.5	2.1 ± 1.4	1.3 ± 0.4	2.3 ± 1.1 ab	1.8 ± 1.0 b	1.8 ± 0.6 cde	3.0 ± 1.2 bc	3.3 ± 1.2 bc
	Cyantraniliprole	7.2 ± 1.7	2.3 ± 1.5	2.7 ± 1.4	1.5 ± 0.6	0.8 ± 0.6 b	1.6 ± 1.0 b	0.6 ± 0.3 de	1.5 ± 0.6 bc	0.7 ± 0.4 bc
	Cyflumetofen	7.1 ± 2.0	1.8 ± 0.9	1.4 ± 1.0	0.1 ± 0.1	0.9 ± 0.8 b A	1.3 ± 0.9 b	2.3 ± 1.1 cde	1.9 ± 1.1 bc	3.8 ± 1.6 bc
	Fenprophamid	7.1 ± 1.3	4.3 ± 1.9	5.8 ± 2.3	1.1 ± 0.5	3.7 ± 2.1 ab	4.3 ± 2.1 b	4.8 ± 1.7 bc	4.3 ± 1.1 bc	5.8 ± 1.8 bc
	Water (control for drench)	9.7 ± 2.5	3.8 ± 1.5	2.4 ± 0.9	2.3 ± 1.3	3.6 ± 1.0 abc	6.4 ± 1.4 ab	9.7 ± 1.7 a	7.7 ± 1.9 ab	11.5 ± 2.9 a
Drench	Imidacloprid	5.0 ± 1.9	3.1 ± 1.5	0.9 ± 0.5	0.4 ± 0.3	1.6 ± 0.9 bc	2.0 ± 1.4 cd	2.2 ± 1.2 cd	0.6 ± 0.3 de	1.1 ± 0.5 de
	Dinotefuran	7.4 ± 2.7	6.5 ± 2.6	2.2 ± 1.6	0.3 ± 0.2	2.0 ± 1.3 bc	1.1 ± 1.0 d	2.6 ± 0.9 cd	0.6 ± 0.4 de	1.4 ± 1.0 de
	Spinetoram + sulfoxaflo ^r	7.1 ± 2.6	6.7 ± 2.5	2.9 ± 1.7	0.3 ± 0.3	0.6 ± 0.5 c	0.8 ± 0.3 d	2.0 ± 0.9 d	4.7 ± 1.8 bcde	3.5 ± 1.4 cde
	Flupyradifurone	7.2 ± 1.3	4.5 ± 2.0	2.3 ± 1.0	0.8 ± 0.6	2.6 ± 1.4 abc	4.2 ± 1.3 abcd	2.9 ± 0.9 bcd	2.3 ± 0.7 cde	4.2 ± 1.7 bcde
	Pyrethrin	7.1 ± 1.8	5.4 ± 1.7	1.9 ± 0.9	0.9 ± 0.4	5.9 ± 1.4 a	5.8 ± 1.8 abc B	8.3 ± 2.0 abc	10.0 ± 3.1 a	9.7 ± 3.2 ab
	Pyridinylquinazolinone	6.9 ± 2.2	5.5 ± 2.3	2.2 ± 1.3	2.4 ± 1.1	4.0 ± 1.7 abc	6.1 ± 2.6 abc	6.8 ± 3.4 abcd	8.7 ± 2.4 ab	10.3 ± 2.2 a
	Afidopyropen	7.0 ± 1.5	4.4 ± 2.2	1.8 ± 0.9	2.6 ± 1.3	4.9 ± 1.5 ab	8.3 ± 2.3 a	9.8 ± 3.1 a	6.5 ± 1.9 abc	9.4 ± 3.3 ab
	Spirotetramat	7.5 ± 3.0	4.3 ± 1.7	1.4 ± 0.9	0.7 ± 0.4	3.0 ± 2.2 abc	3.2 ± 1.5 bcd	4.5 ± 1.2 abcd A	2.4 ± 0.9 cde	4.0 ± 1.0 bcde
	Chlorantraniliprole	7.2 ± 1.7	5.3 ± 2.2	3.7 ± 1.9	0.9 ± 0.4	2.1 ± 0.9 abc	2.8 ± 1.1 bcd	3.5 ± 1.4 bcd	6.5 ± 2.2 abc	6.5 ± 2.2 abcd
	Cyantraniliprole	7.0 ± 2.0	7.1 ± 2.5	0.9 ± 0.5	2.0 ± 1.1	1.7 ± 1.2 bc	1.2 ± 0.9 d	1.2 ± 0.6 d	0.2 ± 0.2 e	0.8 ± 0.4 e
	Cyflumetofen	6.9 ± 2.2	2.5 ± 1.2	3.8 ± 1.7	0.6 ± 0.3	3.4 ± 1.1 abc B	3.8 ± 1.2 bcd	8.9 ± 5.1 ab	7.8 ± 1.7 ab	8.0 ± 2.4 abc
	Fenprophamid	7.1 ± 1.7	6.7 ± 2.9	5.1 ± 2.9	0.5 ± 0.4	3.2 ± 1.8 abc	3.8 ± 1.2 bcd	3.3 ± 0.9 bcd	5.1 ± 1.0 bcd	7.3 ± 1.4 abc
	Fenprophamid ^x	0.9090	0.7094	0.7166	0.9549	0.0298	0.0301	0.0043	0.1771	0.0559
	P > F (Product)	0.9993	0.9686	0.8874	0.0953	0.0045	<0.0001	<0.0001	<0.0001	<0.0001
	P > F (Product × Method)	0.9172	0.9920	0.9619	0.6663	0.6699	0.4937	0.1007	0.0002	0.0031

^a1 nymph/inch² = 0.1550 nymph/cm².^bMeans within an application method followed by the same small letters are not significantly different among products according to Fisher's least significant difference (LSD) at $\alpha = 0.05$. Means within a product followed by capital letters are not significantly different between application methods according to Fisher's LSD.^cData were $\log_{10}(x + 0.1)$ transformed before analysis by two-way ANOVA at $\alpha = 0.05$.

Table 3. Efficacy of foliar spray and substrate drench application of selected insecticides in reducing the densities of sweetpotato whitefly adults on poinsettia plants grown in a greenhouse.

Application method	Product	Time after treatment (d)									
		-14	7	14	21	28	35	42	49	56	
Spray	Nonionic surfactant (control for spray)	2.7 ± 1.9	0.1 ± 0.1	0.2 ± 0.1	2.2 ± 0.6 ab ^z	12.8 ± 4.3 abc	3.8 ± 0.9 cde	4.8 ± 2.4 bc	2.3 ± 0.9 c	3.3 ± 2.2 abc	
	Imidacloprid	0.3 ± 0.3	0	0.1 ± 0.1	1.7 ± 0.1 ab	2.4 ± 0.3 c	1.8 ± 0.7 e	2.6 ± 1.2 c	0.9 ± 0.4 c	0.6 ± 0.5 bc	
	Dinotefuran	2.4 ± 1.3	0.2 ± 0.2	0	0.4 ± 0.2 b	9.8 ± 6.0 c	2.5 ± 0.7 de	2.3 ± 0.7 c	1.3 ± 0.9 c	0.3 ± 0.3 c	
	Spinetoram + sulfoxaflor	1.4 ± 0.4	0.3 ± 0.3	0	2.7 ± 0.4 ab	6.8 ± 0.5 c	10.8 ± 2.7 ab	5.7 ± 1.1 abc	7.3 ± 3.6 ab	2.4 ± 0.7 abc	
	Flupyradifurone	0.8 ± 0.3	0.2 ± 0.2	0.1 ± 0.1	5.4 ± 3.2 a	9.3 ± 2.7 c	7.8 ± 1.3 abcd	8.1 ± 3.2 abc	4.3 ± 2.1 abc	1.3 ± 1.0 abc	
	Pymetrozine	0.6 ± 0.4	0	0.1 ± 0.1	3.9 ± 1.4 ab	21.8 ± 6.5 ab	6.3 ± 1.5 bcde	12.4 ± 5.6 ab	3.3 ± 1.0 bc	4.4 ± 1.9 a	
	Pyrifluquinazon	1.8 ± 1.0	0	0	1.1 ± 1.0 ab	4.7 ± 2.4 c	2.3 ± 0.2 de	1.7 ± 0.1 c	0.6 ± 0.4 c	0.7 ± 0.2 bc	
	Afidopyropen	2.7 ± 1.4	0.2 ± 0.1	0.2 ± 0.1	2.8 ± 1.0 ab	8.4 ± 1.8 c	9.3 ± 3.5 abc	13.6 ± 6.3 a	4.6 ± 2.2 abc	3.8 ± 2.5 ab	
	Spirotetramat	0.8 ± 0.2	0.1 ± 0.1	0.2 ± 0.1	4.9 ± 3.8 a	23.1 ± 7.0 a	12.1 ± 3.1 a	8.8 ± 2.8 abc	8.1 ± 1.1 a	1.4 ± 1.1 abc	
	Chlorantraniliprole	1.4 ± 0.3	0.2 ± 0.2	0.2 ± 0.1	2.1 ± 0.1 ab	7.3 ± 1.5 c	6.3 ± 1.2 bcde	3.6 ± 1.8 c	1.7 ± 0.9 c	1.0 ± 0.2 abc	
	Cyantraniliprole	1.4 ± 0.5	0.2 ± 0.2	0.3 ± 0.2	2.0 ± 0.9 ab	4.3 ± 0.9 c	4.1 ± 1.2 cde	1.8 ± 0.3 c	0.7 ± 0.5 c	0.2 ± 0.1 c	
	Cyclaniliprole	0.9 ± 0.5	0.1 ± 0.1	0	1.5 ± 0.5 ab	4.1 ± 2.4 c	4.8 ± 2.1 cde	2.6 ± 0.5 c	2.0 ± 1.1 c	2.1 ± 1.1 abc	
	Flonicamid	1.3 ± 0.7	0.1 ± 0.1	0.3 ± 0.3	4.3 ± 1.2 ab	11.5 ± 4.4 bc	8.6 ± 2.8 abc	3.8 ± 1.0 c	2.8 ± 1.4 c	0.6 ± 0.2 bc	
	Drench	Water (control for drench)	0.5 ± 0.2	0	0.3 ± 0.3	3.8 ± 1.1 a	9.1 ± 4.0 ab	6.4 ± 1.7 abc	5.0 ± 1.2 ab	1.7 ± 1.0 b	1.2 ± 0.4 bc
		Imidacloprid	0.8 ± 0.3	0.1 ± 0.1	0.1 ± 0.1	0.9 ± 0.5 b	4.1 ± 1.8 b	3.3 ± 1.7 abc	2.0 ± 0.9 b	1.8 ± 0.5 b	0.3 ± 0.2 bc
Dinotefuran		3.3 ± 2.3	0	0.4 ± 0.3	1.9 ± 0.9 ab	3.8 ± 1.1 b	2.7 ± 1.7 c	1.7 ± 0.3 b	0.5 ± 0.3 ab	0.3 ± 0.2 c	
Spinetoram + sulfoxaflor		1.5 ± 0.7	0.1 ± 0.1	0	1.7 ± 0.6 ab	5.8 ± 1.07 ab	3.2 ± 1.0 bc	5.2 ± 3.2 ab	2.6 ± 1.7 ab	0.4 ± 0.3 bc	
Flupyradifurone		0.8 ± 0.3	0	0.1 ± 0.1	2.8 ± 0.6 ab	6.0 ± 1.7 ab	3.6 ± 1.6 abc	5.1 ± 2.0 ab	3.3 ± 1.3 a	2.2 ± 1.4 abc	
Pymetrozine		0.7 ± 0.4	0.2 ± 0.2	0.4 ± 0.3	4.3 ± 0.8 ab	7.8 ± 2.8 ab	8.5 ± 1.2 abc	3.3 ± 1.7 b	5.8 ± 2.9 ab	1.2 ± 0.5 bc	
Pyrifluquinazon		1.8 ± 0.7	0.1 ± 0.1	0.5 ± 0.3	6.3 ± 3.7 a	9.5 ± 3.3 ab	10.3 ± 6.6 abc	3.7 ± 0.9 b	3.5 ± 1.5 ab	2.3 ± 0.8 ab	
Afidopyropen		0.8 ± 0.4	0	0.9 ± 0.5	4.8 ± 2.1 ab	6.5 ± 2.4 ab	12.7 ± 7.3 ab	14.1 ± 10.5 a	3.0 ± 1.7 b	3.8 ± 1.4 a	
Spirotetramat		1.2 ± 0.4	0	0.3 ± 0.2	2.6 ± 1.2 ab	7.8 ± 2.2 ab	3.8 ± 1.0 abc	3.8 ± 1.0 b	1.4 ± 0.5 ab	0.3 ± 0.2 bc	
Chlorantraniliprole		1.6 ± 0.6	0.2 ± 0.2	0.2 ± 0.1	4.5 ± 1.6 ab	10.3 ± 1.4 ab	2.1 ± 0.4 c	5.5 ± 1.5 ab	3.6 ± 1.3 b	1.3 ± 0.6 bc	
Cyantraniliprole		0.8 ± 0.5	0	0	0.8 ± 0.3 b	2.3 ± 0.5 b	1.7 ± 0.5 c	3.0 ± 1.3 b	0.8 ± 0.2 b	0.4 ± 0.3 bc	
Cyclaniliprole		1.9 ± 0.9	0	0.1 ± 0.1	6.3 ± 3.3 a	14.0 ± 8.6 a	12.9 ± 5.9 a	3.2 ± 1.5 b	1.4 ± 0.4 b	0.6 ± 0.4 bc	
Flonicamid		2.5 ± 1.2	0.1 ± 0.1	0.2 ± 0.1	3.3 ± 1.9 ab	6.6 ± 1.0 ab	3.8 ± 1.5 abc	3.6 ± 1.2 b	2.1 ± 0.6 b	0.9 ± 0.4 bc	
<i>P</i> > <i>F</i> (Method) ^y		0.8953	0.1905	0.1072	0.2092	0.2461	0.1131	0.4368	0.9261	0.5560	
<i>P</i> > <i>F</i> (Product)		0.5741	0.9973	0.4432	0.0236	0.0155	0.0584	0.0368	0.0311	0.0073	
<i>P</i> > <i>F</i> (Product × Method)		0.7022	0.8008	0.5539	0.0164	0.2992	0.1531	0.5890	0.1929	0.3730	

^aMeans within an application method followed by the same small letters are not significantly different among products according to Fisher's least significant difference (LSD) test at $\alpha = 0.05$. Means within a product followed by capital letters are not significantly different between application methods according to Fisher's LSD.

^yData were $\log_{10}(x + 0.1)$ transformed before analysis by two-way ANOVA at $\alpha = 0.05$.

sprayed plants and plants drenched with imidacloprid, dinotefuran, spinetoram + sulfoxaflor, and cyantraniliprole had significantly lower densities of nymphs than their respective untreated control. At 42 to 56 DAT, plants sprayed with all insecticides, except for pymetrozine, harbored significantly lower densities of nymphs. Plants drenched with imidacloprid, dinotefuran, flupyradifurone, and cyantraniliprole had significantly fewer nymphs than the water-treated plants at 42 to 56 DAT (Table 2). Plants drenched with spinetoram + sulfoxaflor, spirotetramat, chlorantraniliprole, and flonicamid, on the other hand, produced inconsistent results and had significantly fewer nymph densities compared with water-treated plants at either one or two of three intervals [i.e., 42, 49, and 56 DAT (Table 2)]. Plants sprayed with dinotefuran, pyri-fluquinazon, and cyantraniliprole, and those drenched with imidacloprid, dinotefuran, and cyantraniliprole consistently had the lowest nymph densities at 35 to 56 DAT.

We observed a general pattern for plants sprayed with an insecticide to harbor fewer nymphs than plants drenched with the same insecticides (Table 2). However, we did not observe significantly different nymph densities on plants treated with different application methods of the same insecticides at 28 to 56 DAT, except for cyclaniliprole at 28 DAT, pymetrozine at 35 DAT, and spirotetramat at 42 DAT (Table 2). Spray application of cyclaniliprole at 28 DAT, pymetrozine at 35 DAT, and spirotetramat at 42 DAT was significantly more effective in reducing nymph densities than drench application.

ANOVA detected a significant interaction between insecticides and application methods at 49 and 56 DAT (Table 2). The interaction appeared to be driven, at least in part, by a greater reduction in nymph densities by spray application than by drench application of pyri-fluquinazon at 49 DAT (90%) and 56 DAT (97%).

INSECTICIDAL EFFICACY AGAINST SWEETPOTATO WHITEFLY ADULTS. Sweetpotato whitefly adult densities fluctuated greatly among treatments in this study. Adult densities differed among insecticides at 21 to 56 DAT, but were similar between the application methods throughout this study (Table 3).

At 21 DAT, plants drenched with imidacloprid and cyantraniliprole had significantly lower adult densities than those drenched with water. However, for other sampling dates, insecticides and application methods that had resulted in the lowest adult densities did not result in adult densities that were significantly different from the untreated control.

A significant interaction between insecticides and application methods was detected at 21 DAT (Table 3). The significant interaction was partially driven by a greater reduction in adult densities due to spray application of pyri-fluquinazon and cyclaniliprole compared with when the same insecticides were applied by drench.

Discussion

Efficacies of the tested insecticides against nymphs were consistent over the course of this study, whereas their efficacies against adults varied greatly among sampling intervals. The observed differences in efficacies against nymphs and adults may result from an inherent difference in susceptibility between nymphs and adults (Chen et al., 2018). For instance, spiromesifen, flonicamid, acetamiprid, thiamethoxam, and spirotetramat were more toxic to sweetpotato whitefly nymphs than adults (Brück et al., 2009; Chen et al., 2018; Kontsedalov et al., 2009). Also, untreated and treated plants were not caged, thus allowing adult sweetpotato whiteflies to disperse freely among plants in our study. Because adults typically have a greater tolerance for insecticide residue, individuals dispersing from an untreated plant to a treated plant might not be killed immediately by the insecticide residue, and thus, might have been counted during a snapshot sampling of adult abundance. Even if the residue eventually killed the adults, the data taken before they died had inflated the adult abundance on the treated plants and led us to a wrong conclusion about the toxicity of the insecticide treatment. Therefore, we question the value of a snapshot sampling approach for a highly mobile adult stage, such as that of sweetpotato whitefly, and caution against using adult counts as the sole indication of treatment effect. Our caution should be further evaluated. Our subsequent discussion in this report will focus mainly on insecticide efficacy

against nymphs, which was found to generate a more consistent pattern.

We found that foliar spray application of all insecticides provided better control of sweetpotato whitefly nymphs than drench application. In our study, neonicotinoid insecticides (dinotefuran and imidacloprid) remained the most effective insecticides in suppressing nymph densities in a poinsettia crop regardless of whether the insecticides were applied as a drench or foliar spray. Among the alternatives to neonicotinoids, cyantraniliprole was the only insecticide that was consistently as effective as the neonicotinoids when applied with both application methods. However, the value of other insecticides as alternatives to neonicotinoids depended on the application method.

Foliar spray appeared to be the quicker and more effective application method compared with substrate drench in reducing the abundance of sweetpotato whitefly nymphs. Eleven of the 12 insecticides tested, when sprayed, consistently resulted in significantly lower nymph densities compared with the untreated plants from 35 to 56 DAT. Foliar sprays of cyantraniliprole, spirotetramat, and cyclaniliprole reduced nymph densities within the shortest time (28 DAT). Among these insecticides, cyantraniliprole provided the greatest suppression of nymph densities throughout the study. Our results are in line with Gill et al., (2019), where a cyantraniliprole spray application (8 fl oz/100 gal) harbored significantly lower sweetpotato whitefly nymphs on poinsettia compared with flonicamid, spirotetramat, flupyradifurone, afidopyropen, pymetrozine, and dinotefuran. Similarly, a previous study on zinnia (*Zinnia elegans*) reported that a single spray application (4 fl oz/100 gal) of cyantraniliprole resulted in the lowest sweetpotato whitefly nymphal densities compared with cyclaniliprole and flonicamid insecticides (Arthurs et al., 2017). We also observed that spray applications of pyri-fluquinazon and dinotefuran were as effective as cyantraniliprole in controlling sweetpotato whitefly nymphs, but the reduction in nymph densities by pyri-fluquinazon and dinotefuran only became evident at 35 DAT. Spray application of imidacloprid, spinetoram + sulfoxaflor, flupyradifurone, afidopyropen, chlorantraniliprole, and flonicamid also resulted in significantly lower

nymph densities than those on the surfactant-sprayed plants at 35 DAT, although these insecticides were not as effective as cyantraniliprole, pyrifluquinazon, and dinotefuran.

When plants were drenched with insecticides, significant reductions of nymph densities were observed on plants treated with cyantraniliprole, imidacloprid, dinotefuran, and spinetoram + sulfoxaflor at 35 DAT. However, cyantraniliprole was the only alternative that had provided consistent suppression of nymph populations most comparable to those achieved by neonicotinoids throughout this study. Drench application of flupyradifurone and spirotetramat also suppressed populations of sweetpotato whitefly nymphs; however, suppression by these insecticides was not observed until 42 and 49 DAT, respectively. Although plants drenched with spinetoram + sulfoxaflor, flonicamid, and chlorantraniliprole harbored significantly lower sweetpotato whitefly nymphal densities, their effect was not consistent throughout the study. Pymetrozine, pyrifluquinazon, afidopyropen, and cyclaniliprole were the least effective insecticides, with plants drenched with these insecticides harboring as many nymphs as the control plants (drenched with water). It is important to remember that, except for pymetrozine, these insecticides were not registered for drench application, and our data demonstrated that they should not be used as such.

The choice of an appropriate neonicotinoid alternative for the control of sweetpotato whiteflies depends on the preferred application method. Based on our study, cyantraniliprole was the most effective alternative to neonicotinoids by both spray and drench application. This insecticide reduced sweetpotato whitefly nymph densities significantly as soon as 28 DAT by foliar spray and 35 DAT by drench, and its efficacy lasted consistently throughout our study (56 DAT). Other insecticides, namely afidopyropen, chlorantraniliprole, cyclaniliprole, flonicamid, flupyradifurone, pyrifluquinazon, spirotetramat, and spinetoram + sulfoxaflor are valuable partners in an insecticide rotation program when applied as foliar sprays. Some of these insecticides can also serve important roles in developing a spray program that is compatible with biological control programs against

sweetpotato whiteflies and other major arthropod pests.

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