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The Effects of Spray Volume on the Management of *Bemisia tabaci* (Hemiptera: Aleyrodidae) in the Greenhouse

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Abstract: The sweetpotato whitefly, *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae), is a major insect pest of poinsettias (*Euphorbia pulcherrima* Willd. ex Klotzsch; Family: Euphorbiaceae) in the greenhouse. Currently, neonicotinoids are widely used for *B. tabaci* management in the greenhouse, which is less favored by the consumers because of the potential nontarget effects of these insecticides on beneficial insects. Little is known on how the high spray volumes of spinetoram (20%) + sulfoxaflor (20%) (XXpire®) affect the *B. tabaci* population in the greenhouse. The objective of the study was to determine the efficacy of spinetoram + sulfoxaflor and dinotefuran (Zylam®) applied as foliar-spray volumes (high, referred to as spench, and low, referred to as foliar) and soil drench against *B. tabaci*. The high foliar-spray volume application (spench) of both insecticides reduced the *B. tabaci* immature densities, compared with low foliar-spray volume (foliar) and soil drench applications. The soil drench application did not provide adequate *B. tabaci* control regardless of insecticide type. Spinetoram + sulfoxaflor applied as a high-spray volume treatment was moderately effective in controlling *B. tabaci* nymphs relative to nontreated control.

Keywords: sweetpotato whitefly; XXpire; spinetoram; sulfoxaflor; Zylam; dinotefuran; efficacy; spench; drench

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1. Introduction

The sweetpotato whitefly, *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae), is a serious insect pest of many ornamental plants, including poinsettias (*Euphorbia pulcherrima* Willd. ex Klotzsch; Family: Euphorbiaceae)) in the greenhouse [1]. In 2019, the potted poinsettias were valued at USD 215.9 million, and 46.8 million potted plants were sold in the US [2], which includes both wholesale and retail markets. Among potted flower plants, poinsettias are the leading crop and represent 20.9% of potted flower plants sold. All immatures and adult stages of *B. tabaci* directly feed on the foliage of poinsettias, and the feeding causes injury symptoms, such as wilting, yellowing, and mottling [1]. In addition, *B. tabaci* excretes sugary honeydew on the leaf surface, which is often infected with black sooty mold fungus. Thus, the *B. tabaci* infestation is unacceptable, as it affects the aesthetic value and salability of the potted poinsettias.

The adult *B. tabaci* colonizes on the abaxial leaf surface of poinsettias [1]. They oviposit pear-shaped eggs, which hatches in 5 to 7 days. The first instars, which are often referred to as crawlers, are the only mobile nymphal stage of *B. tabaci*. Once the crawlers settle on the abaxial leaf surface, they molt through three more immobile stages and emerge as adults from the pseudopupae [3]. *B. tabaci* undergoes many generations in the greenhouse, with each generation completed at 16 to 31 days depending on the temperature [4]. *B. tabaci* feed on phloem sap of poinsettias from leaves and cause direct feeding damage [4].

Multiple tactics have been administered to control *B. tabaci* in the greenhouse. Augmentative release of biological control agents has been employed and provided a degree of control [5–7]. For example, the augmentative release of two natural enemies—*Eretmocerus eremicus* (Rose and Zolnerowich) and *Amblyseius swirskii* (Athias-Henriot)—have provided

partial control of *B. tabaci* [8,9]. Management of *B. tabaci* using biological control agents has been assisted with selective, compatible insecticides [1,7]. Nevertheless, insecticides continue to be the major tactic adopted by the growers in commercial poinsettias production in the US.

Insecticides are preventatively applied for the management of *B. tabaci* on poinsettias in greenhouses. Although contact and systemic insecticides are recommended for *B. tabaci* control on poinsettias [10], insecticides with systemic properties such as neonicotinoids are widely used [9,11]. However, the use of neonicotinoids, such as clothianidin, dinotefuran, imidacloprid, and thiamethoxam, have been under public scrutiny [12–15], as neonicotinoids can affect the activity of pollinators [16]. In addition, the repeated applications of active ingredients with similar modes of action [17] increase the risk of resistant *B. tabaci* populations [18–21]. Thus, alternative tactics for *B. tabaci* control are actively sought, including active ingredients [22,23] and improved insecticide delivery methods that enhance the insecticide coverage for *B. tabaci* control [24,25]. XXpire® (40%) (Corteva AgriScience, Indianapolis, Indiana, USA) contains spinetoram (20%, spinosyn) and sulfoxaflor (20%, sulfoximine) and is one of the novel insecticide products registered against *B. tabaci* control in the greenhouse. Sulfoxaflor, in particular, has shown evidence of effective activity against many piercing–sucking insect pests [26–29]. Thus, the objective of the study was to determine the utility of spinetoram + sulfoxaflor applied at two rates using two foliar spray volumes (low and high) and drench, and compare them to dinotefuran (Zylam® (10%), PBI-Gordon Corporation, Shawnee, Kansas, USA).

2. Materials and Methods

2.1. Plant

The experiment was carried out in 1.9 L (Catalogue #SP650, 16.5 cm diameter, 12.5 cm high, Shuttle Pot, East Jordan Plastics, East Jordan, Michigan, USA) potted poinsettia plants in a greenhouse on the University of Georgia, Griffin Campus, Griffin, Georgia, USA, in 2020. The 5-week old plants were purchased from a commercial greenhouse, Fayetteville, Georgia, USA. The plants were not treated with insecticides and were maintained in a greenhouse at the University of Georgia in Griffin Campus at 28 °C, ~55% relative humidity (RH), and 16:8 h (light: dark). The long light hours prevented the development of the reddening of leaves. The plants were growing in potting media containing peat (88.7%), perlite (5.9%), lawn lime (1.8%), fine lime (1.1%), fertilizer (0.7%) (Uni-Mix Granular fertilizer, ICC fertilizer, Dublin, Ohio, USA: 11:5:11 (NPK)), Gypsum (1.1%), and wetting agent (0.4%) (Aquagrow, Aquatrols®, Paulsboro, New Jersey, USA: Exothylated alkyl phenols (11%), fatty acid ester (1.5%), and the rest inert materials). The poinsettia plants were irrigated every other day using a watering can.

2.2. Insect

The *B. tabaci* colony was maintained at 28 °C on potted lantana plants (*Lantana camara* L.) in rearing cages (Bugdorm®, Cat#BugDorm-4M4590, 47.5 × 47.5 × 93.0 cm (WDH), MegaView Science Co., Ltd., Taiwan). The *B. tabaci* adults were "Biotype B", which was characterized by using random amplification of polymorphic DNA–PCR techniques by C. L. McKenzie, Horticultural Research Laboratory at USDA ARS in Fort Pierce, Florida, USA. The poinsettia plants used in the experiment were infested with *B. tabaci* adults. Six *B. tabaci*-infested potted lantana plants were placed around the experimental potted poinsettia plants in the greenhouse for a week. The *B. tabaci* adults migrated from lantana plants to poinsettia plants. The five poinsettia leaves were randomly sampled (one leaf per plant) and checked for *B. tabaci* eggs and 1st instar nymphs at every 2 d intervals. The study was initiated when at least 10 *B. tabaci* eggs or young nymphs were found per leaf.

2.3. Insecticide

Two insecticides products—XXpire® (sulfoxaflor (20%) + spinetoram (20%), Corteva AgriScience, Indianapolis, Indiana, USA) and Zylam® (dinotefuran (10%), PBI/Gordon

Corporation, Shawnee, Kansas, USA)—were used in the experiment. Two rates of XXpire, 140.1 g product (referred to as XXpire low) and 245.2 g product (referred to as XXpire high) per hectare, respectively, and one rate of Zylam, 584.6 mL product per hectare were used in the experiment. The insecticide rates were mixed with water at variable water volumes described in the experimental design section. An adjuvant, CapSil® (Aquatrols®, Paulsboro, NJ, USA) a 100% active blend of organosilicone and nonionic surfactants (100% Polyether–polymethylsiloxane copolymer) was added to all XXpire treatments.

2.4. Experimental Design

Two rates of XXpire (low and high, as described in the previous section) and one rate of Zylam were applied at three water volumes of 1870.8, 3741.6, and 7483.2 L/ha. The water volumes, 1870.8 and 3741.6 L/ ha, were sprayed on poinsettia foliage using a CO_2-powered single boom (one nozzle) handheld sprayer at 206.8 kPa and are referred to as the "foliar" and "spench" treatments, respectively. To deliver spray volumes, 1870.8 (foliar) and 3741.6 (spench) L/ha, two different nozzle tips, TeeJet 8002VS (yellow-colored tip) and TeeJet 8004EVS (red-colored tip, TeeJet Technologies, Glendale Heights, IL, USA), respectively, were used. These two nozzle tips delivered insecticide solutions at 11.6 (foliar) and 18.3 (spench) mL/s, and hereafter, these water volumes are referred to as the foliar and spench treatments, respectively. The third water volume, 7483.2 L/ha, was applied as a soil drench, where 19.6 mL of the insecticide solution was slowly poured into the potting media of each pot using a graduated plastic container.

The treatments included in the experiment were (1) XXpire low foliar, (2) XXpire low spench, (3) XXpire low drench, (4) XXpire high foliar, (5) XXpire high spench, (6) XXpire high drench, (7) Zylam foliar, (8) Zylam spench, (9) Zylam drench, and (10) nontreated check. The treatments were arranged in randomized complete block design, with eight plant replications. Poinsettia plants were placed 30.5 cm apart from each other on the greenhouse bench. The individual potted poinsettia plant was the experimental unit. The insecticide treatments were applied on 7 October 2020. CapSil (adjuvant) was added to all of the XXpire treatments, whereas Zylam treatments did not receive CapSil. Insecticide treatments were applied only once when the threshold of 10 *B. tabaci* eggs or nymphs was achieved.

2.5. Evaluation

To determine *B. tabaci* densities, a random, fully expanded leaf was sampled per plant and was individually placed in a plastic Ziploc bag. In the laboratory, the numbers of live young (1st and 2nd instars) and late instars (3rd and pupae) of *B. tabaci* were quantified per poinsettia leaf at 14, 22, and 28 days after application (DAA) using dissecting microscopes (Leica M125, Leica Microsystems, Wetzlar, Germany) at 10× magnification. At 7 DAA, the young and later instars were not specifically separated; instead, the total number of nymphs was quantified per leaf from all treatments.

2.6. Statistical Analyses

Statistical analyses for the experiment were conducted using the SAS software [30]. For analysis purposes, the experiment was treated as a factorial design, where insecticide and method were the factors. For the insecticide factor, there were three levels: XXpire low and high, and Zylam; in terms of method, the three levels were foliar, spench, and drench. The numbers of live young (1st and 2nd instars), late instars (3rd and pupae), and all instars (combined) of *B. tabaci* were subjected to a two-way analysis of variance (ANOVA) using the generalized linear model procedure (PROC GLIMMIX) in SAS. The models had a log-link function with Poisson distribution for each sampling date. The method used was Laplace. The treatments (insecticide and method) and their interaction were fixed effects, whereas replications were random effects. Furthermore, to determine the effects of insecticide or method, one-way ANOVA was conducted by method or insecticide using a generalized linear model procedure (PROC GLIMMIX) in SAS. The models had

a log-link function with Poisson distribution for each sampling date. The method used was Laplace. The least-squares means were separated by pairwise *t*-test ($p < 0.05$) after back-transforming the data using the PROC PLM procedure in SAS.

To determine the individual effects of treatments on the *B. tabaci* densities, Student's *t*-tests were performed for each insecticide–method combination, along with nontreated control, using PROC TTEST procedure in SAS ($p = 0.05$).

3. Results

The effects of insecticide, method, and their interaction were significantly different for young, late, and all instars combined at 7, 14, 21, and 28 DAA after application (Table 1).

Table 1. Analysis of variance of *B. tabaci* immatures observed on poinsettia leaves after application of insecticides at three foliar spray or drench volumes.

After Application	Treatment	Young Instars *			Late Instars †			All Immature Stages		
		F	df	*p*	*F*	df	*p*	*F*	df	*p*
7 DAA	Insecticide [a]	-	-	-	-	-	-	86.7	2.56	<0.001
	Method [b]	-	-	-	-	-	-	293.0	2.56	<0.001
	Insecticide × Method	-	-	-	-	-	-	35.4	4.56	<0.001
14 DAA	Insecticide	133.7	2.56	<0.001	95.1	2.56	<0.001	240.4	2.56	<0.001
	Method	107.2	2.56	<0.001	244.7	2.56	<0.001	343.9	2.56	<0.001
	Insecticide × Method	35.6	4.56	<0.001	8.6	4.56	<0.001	32.1	4.56	<0.001
21 DAA	Insecticide	92.7	2.55	<0.001	102.3	2.55	<0.001	173.8	2.55	<0.001
	Method	39.7	2.55	<0.001	157.5	2.55	<0.001	164.3	2.55	<0.001
	Insecticide × Method	26.1	4.55	<0.001	3.8	4.55	0.008	27.2	4.55	<0.001
28 DAA	Insecticide	172.6	2.55	<0.001	232.0	2.55	<0.001	416.4	2.55	<0.001
	Method	208.2	2.55	<0.001	170.9	2.55	<0.001	386.6	2.55	<0.001
	Insecticide × Method	39.4	4.55	<0.001	62.7	4.55	<0.001	62.3	4.55	<0.001

* 1st and 2nd instars; † 3rd and pupal stages; [a] two rates of spinetoram + sulfoxaflor (XXpire®) and a rate of dinotefuran (Zylam®); and [b] insecticides applied with water volumes, 1870.8, 3741.6, and 7483.2 L/ha. The first two water volume treatments were sprayed using TeeJet 8002VS (referred to as "foliar") and TeeJet 8004EVS (referred to as "spench"), and the third water volume was drenched to the soil media of the potted poinsettia plant.

3.1. Young Instars

At 14 DAA, the numbers of *B. tabaci* were significantly lower in the spench treatment than in the foliar, followed by the drench treatment for the low XXpire low ($F_{2,14} = 64.3$; $p < 0.001$) and Zylam treatments ($F_{2,14} = 38.3$; $p < 0.001$; Figure 1A). For the XXpire high treatment, the densities of *B. tabaci* were significantly lower in the spench treatment than in the drench, followed by foliar treatments ($F_{2,14} = 108.3$; $p < 0.001$). Among insecticide treatments applied as foliar, the numbers of *B. tabaci* were significantly lower in the Zylam treatment than in XXpire low, followed by XXpire high treatments ($F_{2,14} = 72.6$; $p < 0.001$; Figure 1A). For the spench treatment, the numbers of *B. tabaci* were significantly lower in the Zylam treatment than in XXpire high, followed by XXpire low treatments ($F_{2,14} = 42.6$; $p < 0.001$). However, there were no significant differences between XXpire high and Zylam treatments in *B. tabaci* densities for the drench treatment but were significantly lower than in the XXpire low treatment ($F_{2,14} = 101.6$; $p < 0.001$; Figure 1A).

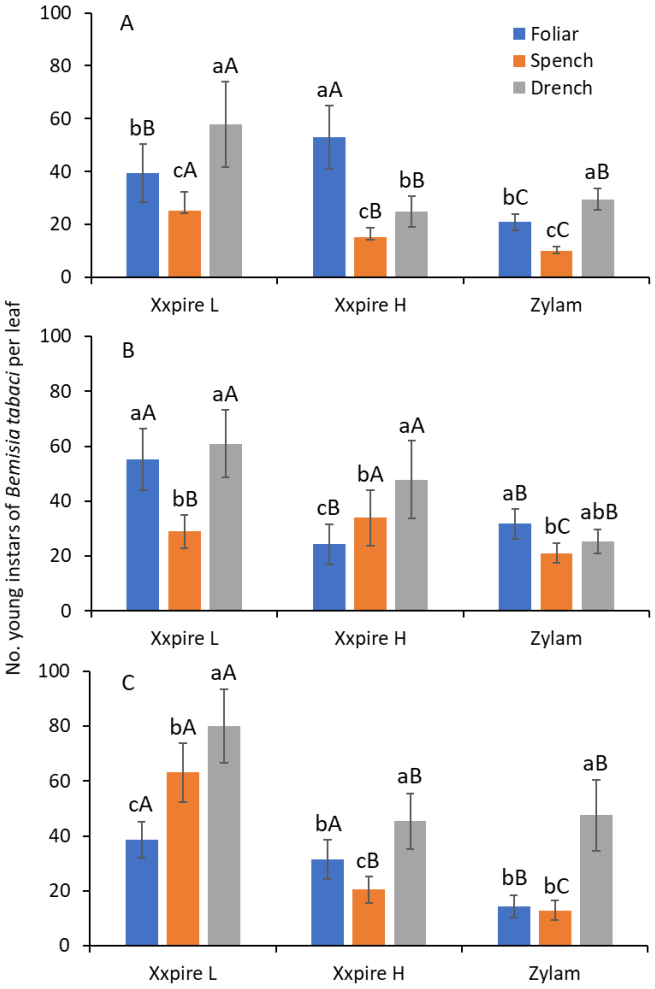

Figure 1. Young instars. Least-squares mean (±SE) number of young instars of *B. tabaci* observed on poinsettia leaves treated with various insecticides and application methods in the greenhouse at (**A**) 14, (**B**) 21, and (**C**) 28 days after application. Same lower-case letters among methods within insecticide treatment are not significantly different at $\alpha = 0.05$ (Tukey–Kramer test), and same upper-case letters among same-colored bars (application method) are not significantly different at $\alpha = 0.05$ (Tukey–Kramer test).

At 21 DAA, for the XXpire low treatment, the numbers of young instars of *B. tabaci* were significantly lower in the spench treatment than in foliar and drench treatments ($F_{2,13} = 52.6$; $p < 0.001$; Figure 1B). For the XXpire high treatment, the densities of *B. tabaci* were significantly lower in the foliar treatment than in spench, followed by drench treatments ($F_{2,14} = 39.3$; $p < 0.001$). For the Zylam treatment, a significantly lower number of *B. tabaci* was observed in the spench treatment, compared with that in foliar treatments ($F_{2,14} = 9.5$; $p = 0.003$; Figure 1B). Among insecticide treatments, for the foliar treatment, the densities of *B. tabaci* were significantly lower in XXpire high and Zylam treatments than in the XXpire low treatment ($F_{2,14} = 61.7$; $p < 0.001$). For the spench treatment, the numbers of *B. tabaci* were significantly lower in the Zylam treatment than in XXpire low, followed by XXpire high treatments ($F_{2,14} = 24.5$; $p < 0.001$). For the drench treatment, the numbers of *B. tabaci* were significantly lower in the Zylam treatment than in XXpire high and low treatments ($F_{2,13} = 70.9$; $p < 0.001$; Figure 1B).

At 28 DAA, for the XXpire low treatment, the numbers of *B. tabaci* were significantly lower in the foliar treatment than in spench, followed by drench treatments ($F_{2,13} = 58.3$; $p < 0.001$; Figure 1C). For XXpire high, *B. tabaci* densities were significantly lower in the spench treatment than in foliar, followed by drench treatments ($F_{2,14} = 44.4$; $p < 0.001$). For the Zylam treatment, the numbers of *B. tabaci* were significantly lower in spench and

foliar treatments than in the drench treatment ($F_{2,14}$ = 142.7; $p < 0.001$). Among insecticide treatments, for the foliar treatment, the densities of *B. tabaci* were significantly lower in the Zylam treatment than in XXpire treatments ($F_{2,14}$ = 36.2; $p < 0.001$; Figure 1C). For the spench treatment, the numbers of *B. tabaci* were significantly lower in the Zylam treatment than in XXpire high, followed by XXpire low treatments ($F_{2,14}$ = 153.7; $p < 0.001$). For the drench treatment, the numbers of *B. tabaci* were significantly lower in Zylam and XXpire high treatments than in the XXpire low treatment ($F_{2,13}$ = 27.4; $p < 0.001$; Figure 1C).

3.2. Late Instars

At 14 DAA, the numbers of late instars of *B. tabaci* were significantly lower in the spench treatment than in foliar, followed by drench treatments for the XXpire low treatment ($F_{2,14}$ = 174.7; $p < 0.001$; Figure 2A). The densities of *B. tabaci* were significantly lower in the spench treatment than in foliar and drench treatments for XXpire high ($F_{2,14}$ = 82.3; $p < 0.001$) and Zylam treatments ($F_{2,14}$ = 41.3; $p < 0.001$). Among the applied insecticides, the numbers of *B. tabaci* were significantly lower in the Zylam treatment than in XXpire low, followed by XXpire high treatments, for foliar ($F_{2,14}$ = 51.9; $p < 0.001$) and drench treatments ($F_{2,14}$ = 132.8; $p < 0.001$; Figure 2A). For the spench treatment, the numbers of *B. tabaci* were significantly lower in Zylam and XXpire high treatments than in the XXpire low treatment ($F_{2,14}$ = 5.7; p = 0.016).

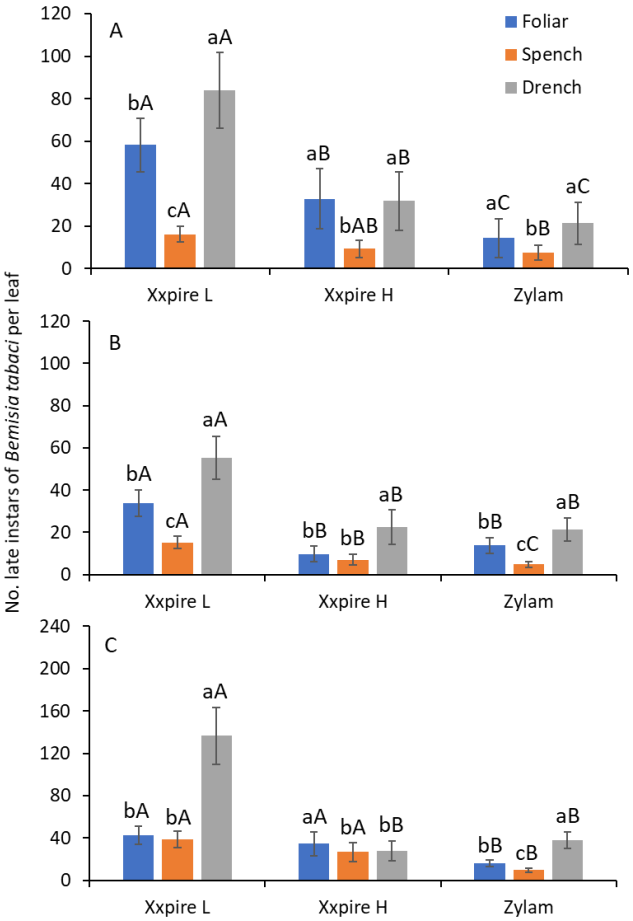

Figure 2. Late instars. Least-squares mean (±SE) numbers of late instars of *B. tabaci* observed on poinsettia leaves treated with various insecticides and application methods in the greenhouse at (**A**) 14, (**B**) 21, and (**C**) 28 days after application. Same lower-case letters among methods within insecticide treatment are not significantly different at $\alpha = 0.05$ (Tukey–Kramer test), and same upper-case letters among same-colored bars (application method) are not significantly different at $\alpha = 0.05$ (Tukey–Kramer test).

At 21 DAA, the numbers of *B. tabaci* were significantly lower in the spench treatment than in foliar and drench treatments, for XXpire low ($F_{2,13}$ = 82.4; $p < 0.001$) and Zylam treatments ($F_{2,14}$ = 43.0; $p < 0.001$; Figure 2B). For the XXpire high treatment, the densities of *B. tabaci* were significantly lower in foliar and spench treatments than in the drench treatment ($F_{2,14}$ = 56.3; $p < 0.001$). Among insecticide treatments, the densities of *B. tabaci* were significantly lower in XXpire high and Zylam treatments than in the XXpire low treatment for foliar ($F_{2,14}$ = 55.6; $p < 0.001$) and drench ($F_{2,13}$ = 54.1; $p < 0.001$) treatments. For the spench treatment, the numbers of *B. tabaci* were significantly lower in the Zylam treatment than in XXpire low, followed by the XXpire high treatments ($F_{2,14}$ = 21.3; $p < 0.001$; Figure 2B).

At 28 DAA, for the XXpire low treatment, the numbers of *B. tabaci* were significantly lower in foliar and spench treatments than in the drench treatment ($F_{2,13}$ = 283.7; $p < 0.001$; Figure 2C). For the XXpire high treatment, the *B. tabaci* densities were significantly lower in spench and drench treatments than in the foliar treatment ($F_{2,14}$ = 7.1; $p = 0.007$). For the Zylam treatment, the numbers of *B. tabaci* were significantly lower in the spench treatment than in the foliar, followed by the drench treatments ($F_{2,14}$ = 85.7; $p < 0.001$). Among insecticide treatments, the densities of *B. tabaci* were significantly lower in the Zylam treatment than in XXpire treatments for foliar ($F_{2,14}$ = 59.3; $p < 0.001$) and spench treatments ($F_{2,14}$ = 67.6; $p < 0.001$). For the drench treatment, the numbers of *B. tabaci* were significantly lower in Zylam and XXpire high treatments than in the XXpire low treatment ($F_{2,13}$ = 295.9; $p < 0.001$; Figure 1C).

3.3. All Instars Combined

At 7 DAA, for the XXpire low treatment, the numbers of all *B. tabaci* instars were significantly lower in the spench treatment than in drench, followed by foliar treatments ($F_{2,14}$ = 154.8; $p < 0.001$; Figure 3A). The *B. tabaci* densities were significantly lower in the spench treatment than in foliar, followed by drench treatments, for XXpire high ($F_{2,14}$ = 118.3; $p < 0.001$) and Zylam treatments ($F_{2,14}$ = 112.6; $p < 0.001$). Among insecticide treatments, for the foliar treatment, the densities of *B. tabaci* were significantly lower in the Zylam treatment than in XXpire high, followed by XXpire low treatments ($F_{2,14}$ = 133.8; $p < 0.001$). For the spench treatment, the numbers of *B. tabaci* were significantly lower in the Zylam treatment than in the XXpire low treatment but were not significantly different between Xxipire low and high treatments ($F_{2,14}$ = 25.6; $p < 0.001$). For the drench treatment, the numbers of *B. tabaci* were significantly lower in Zylam and XXpire low treatments than in the XXpire high treatment ($F_{2,14}$ = 12.3; $p < 0.001$; Figure 3A).

At 14 DAA, the numbers of *B. tabaci* instars were significantly lower in the spench treatment than in foliar, followed by drench treatments for XXpire low ($F_{2,14}$ = 236.3; $p < 0.001$; Figure 3B). For the XXpire high treatment, the densities of *B. tabaci* were significantly lower in the spench treatment than in drench, followed by foliar treatments ($F_{2,14}$ = 164.7; $p < 0.001$). For the Zylam treatment, the densities of *B. tabaci* were significantly lower in the spench treatment than in foliar and drench treatments, which had similar densities ($F_{2,14}$ = 77.6; $p < 0.001$). Among the applied insecticides, for the foliar treatment, the numbers of *B. tabaci* were significantly lower in the Zylam treatment than in XXpire treatments ($F_{2,14}$ = 107.3; $p < 0.001$; Figure 3B). The numbers of *B. tabaci* were significantly lower in the Zylam treatment than in XXpire high, followed by the XXpire low treatment, for spench ($F_{2,14}$ = 42.9; $p = 0.016$) and drench treatments ($F_{2,14}$ = 230.3; $p < 0.001$; Figure 3B).

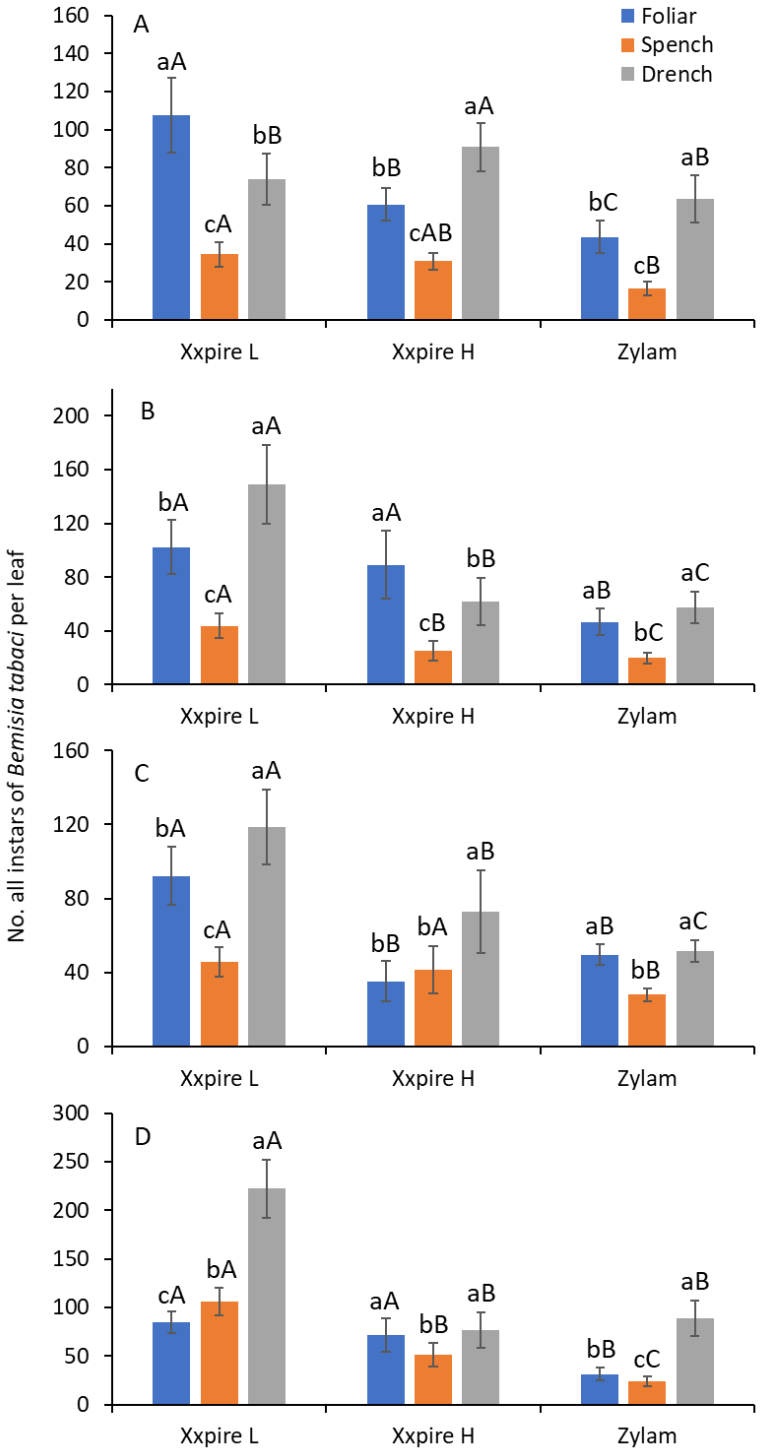

Figure 3. Combined instars. Least-squares mean (±SE) numbers of all instars of *B. tabaci* observed on poinsettia leaves treated with various insecticides and application methods in the greenhouse at (**A**) 7, (**B**) 14, (**C**) 21, and (**D**) 28 days after application. Same lower-case letters among methods within insecticide treatment are not significantly different at $\alpha = 0.05$ (Tukey–Kramer test), and same upper-case letters among same-colored bars (application method) are not significantly different at $\alpha = 0.05$ (Tukey–Kramer test).

At 21 DAA, the numbers of *B. tabaci* instars were significantly lower in the spench treatment than in foliar, followed by drench treatments, for the XXpire low treatment ($F_{2,13} = 125.3$; $p < 0.001$; Figure 3C). For the XXpire high treatment, the densities of *B. tabaci* were significantly lower in foliar and spench treatments than in the drench treatment

($F_{2,14}$ = 81.9; $p < 0.001$). For the Zylam treatment, the numbers of *B. tabaci* were significantly lower in the spench treatment than in foliar and drench treatments ($F_{2,14}$ = 32.5; $p < 0.001$). Among insecticide treatments, for the foliar treatment, the densities of *B. tabaci* were significantly lower in XXpire high and Zylam treatments than in the XXpire low treatment ($F_{2,14}$ = 115.7; $p < 0.001$; Figure 3C). For the spench treatment, the numbers of *B. tabaci* were significantly lower in the Zylam treatment than in XXpire treatments ($F_{2,14}$ = 32.7; $p < 0.001$). For the drench treatment, the numbers of *B. tabaci* were significantly lower in the Zylam treatment than in XXpire high, followed by XXpire low treatments ($F_{2,13}$ = 113.8; $p < 0.001$; Figure 3C).

At 28 DAA, for the XXpire low treatment, the numbers of *B. tabaci* instars were significantly lower in the foliar treatment than in spench, followed by drench treatments ($F_{2,13}$ = 284.9; $p < 0.001$; Figure 3D). For the XXpire high treatment, the densities of *B. tabaci* were significantly lower in the spench treatment than in foliar and drench treatments, which had similar densities ($F_{2,14}$ = 26.2; $p < 0.001$). For the Zylam treatment, the numbers of *B. tabaci* were significantly lower in the spench treatment than in foliar, followed by drench treatments ($F_{2,14}$ = 226.8; $p < 0.001$). Among insecticide treatments, for the foliar treatment, the densities of *B. tabaci* were significantly lower in the Zylam treatment than in XXpire treatments ($F_{2,14}$ = 93.4; $p < 0.001$; Figure 3D). For the spench treatment, the numbers of *B. tabaci* were significantly lower in the Zylam treatment than in XXpire high, followed by XXpire low treatments ($F_{2,14}$ = 189.2; $p < 0.001$). For the drench treatment, the numbers of *B. tabaci* were significantly lower in Zylam and XXpire high treatments than in the XXpire low treatment ($F_{2,13}$ = 262.7; $p < 0.001$; Figure 3D).

3.4. Treatment Comparisons and Efficacy Scores

On XXpire low treatments, none of the insecticide–method combination treatments significantly reduced *B. tabaci* densities, compared with the nontreated check treatment (Table 2; Figure 4). For XXpire high treatments, the numbers of *B. tabaci* were significantly lower in the spench treatment at 14 DAA (Figure 4B), and in the foliar treatment at 21 DAA (Figure 4C), than in the nontreated check treatment (Table 2). For Zylam treatments, the numbers of *B. tabaci* were significantly lower in spench treatments than in nontreated check treatments at 7 (Figure 4A), 14 (Figure 4B), 21 (Figure 4C), and 28 (Figure 4D) DAA. Foliar applications (foliar and spench) significantly reduced *B. tabaci* densities, compared with the nontreated check treatment in terms of Zylam treatment at 28 DAA (Table 2; Figure 4D). The drench treatment did not affect *B. tabaci* densities for any insecticide–method combination treatments, compared with the nontreated check treatment, at any days after application.

Table 2. All densities of *B. tabaci* observed on poinsettia leaves treated, with the specific insecticide–method combination compared with nontreated check treatment in the greenhouse, were analyzed using Student's *t*-test.

Treatment	Method	7 DAA [a]		14 DAA		21 DAA		28 DAA	
		t	*p*	*F*	*p*	*F*	*p*	*F*	*p*
XXpire low	Foliar	−1.1	0.279	−0.5	0.867	0.0	0.991	1.2	0.263
	Spench	1.1	0.274	1.7	0.122	2.0	0.064	0.6	0.547
	Drench	−0.5	0.595	−1.2	0.259	−0.9	0.382	−1.5 *	0.166
XXpire high	Foliar	0.1	0.942	−0.3	0.802	2.2	**0.042**	1.1	0.301
	Spench	1.3	0.223	2.4	**0.032**	1.7	0.117	1.6	0.130
	Drench	−0.8	0.453	0.8	0.444	0.2	0.848	1.1	0.308
Zylam	Foliar	0.7	0.503	1.7	0.112	1.9	0.077	2.4	**0.029**
	Spench	2.3	**0.038**	3.2	**0.007**	3.1	**0.009**	2.7	**0.018**
	Drench	−0.2	0.879	1.2	0.239	1.9	**0.073**	0.7	0.521

[a] day after application; * df = 13 and the rest df = 14. *p*-values in bold are significantly different at α = 0.05.

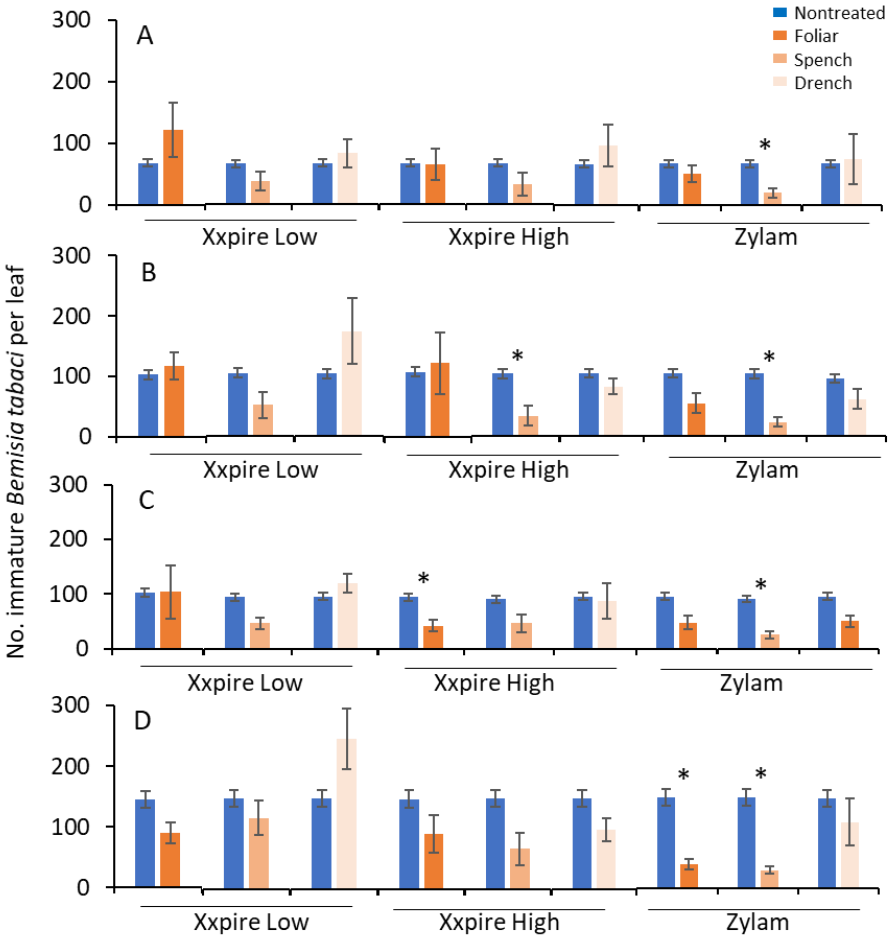

Figure 4. All instars of *B. tabaci* (mean (±SE)) observed on poinsettia leaves treated on insecticide–method combination treatments compared with nontreated check treatment in the greenhouse at (**A**) 7, (**B**) 14, (**C**) 21 and (**D**) 28 days after application. The asterisks (*) indicate the significant difference between specific insecticide–method combination treatment and nontreated check treatment (Student's *t*-test; $\alpha = 0.05$).

4. Discussion

The results showed that the foliar spray with increased water volume improved the *B. tabaci* control. Although the exact reason for this result is unclear, it is most likely due to improved spray coverage on the foliage or improved translaminar movement when using a nozzle tip that discharged more insecticide solution than the nozzle tip that discharged less insecticide solution. This is especially important for *B. tabaci* control, as they colonize the abaxial side of the leaves. Previously, many studies showed a similar result when systemic insecticides were tested against many piercing–sucking and some chewing insect pests. When a greater spray volume of acetamiprid was applied against citrus mealybug, *Planococcus citri* (Risso), it caused >70% mortality than at lower volumes [31]. Wang et al. [32] showed the improved efficacy of imidacloprid + lambda–cyhalothrin applied at a greater spray volume (>16.8 L/ha) using an unmanned aerial vehicle against wheat aphid, *Rhopalosiphum padi* (Linnaeus) than that applied at lower volumes. The efficacy of spirotetramat against Asian citrus psyllid, *Diaphorina citri* Kuwayama, and citrus leafminer, *Phyllocnistis citrella* Stainton, improved when the spray volume was increased regardless of application methods, such as airblast or Proptec rotary atomizer sprayers [33]. The densities of the Western tarnished plant bug, *Lygus hesperus* Knight, were significantly reduced when sulfoxaflor was applied at a greater spray volume using an electrostatic sprayer [29]. These studies showed that increasing the spray volume of systemic insecticides can improve pest control.

Previous studies reported that dinotefuran is more toxic to *B. tabaci* than other neonicotinoids, such as imidacloprid and thiamethoxam [34,35], and also when applied as a soil drench [11]. Additionally, the soil drench application of dinotefuran was effective in controlling other piercing–sucking insects, such as hemlock woolly adelgid, *Adelges tsugae* (Annand) [36], and *Bagrada hilaris* (Burmeister) [37]. In the current study, however, the soil drench application failed to deliver adequate *B. tabaci* control using dinotefuran. It is unclear why the drench application did not provide acceptable *B. tabaci* control. One reason could be the high water volume (7483.2 L/ha) used for drench application in the current study. The water volume used in the commercial container plants varies by the insecticide product (as specified in the label) and container volume. Perhaps, the water volume used for drench application in the current study excessively diluted the concentration of active ingredients in the solution. For example, the water volume used by Gill and Chong [11] for drench application of dinotefuran was 935.4 L/ha, which was eight times lower than what was used in the current study. Some growers use high water volume for insecticide spray for better coverage and efficacy (S.V.J., personal communications). In addition, the dinotefuran product used in Gill and Chong [11] contained 20% of dinotefuran (Safari® 20 SG, Valent USA, Walnut Creek, CA, USA), whereas the product (Zylam) used in the current study had only 10% of dinotefuran.

The spinetoram + sulfoxaflor (XXpire) provided reasonable *B. tabaci* control when applied as a high spray volume (spench) than foliar or drench applications. Spinetoram component of XXpire is active on insects mostly by contact or ingestion of residues [38], which is a less probable exposure route on nymphs of *B. tabaci* infested on poinsettia. Sulfoxaflor has activity against piercing–sucking insects [39]. The efficacy of spinetoram + sulfoxaflor was inconsistent in suppressing the nymphal stages of *B. tabaci* [11,40]. The maximum registered label rate for XXpire in the US is 192.6 g/ha [41], and XXpire high rate used in the current study was 245.2 g/ha, which is the off-label rate. Additionally, the spray volume typically used in the ornamentals is 935.4 L/ha. In the current study, higher spray volumes of 1870.8 and 3741.6 L/ha were used for low (foliar) and high (spench) foliar sprays, respectively. The results indicated that higher foliar spray volume (spench) effectively reduced nymphal densities of *B. tabaci* even at a low XXpire rate, 140.1 g/ha. These data suggest that spinetoram + sulfoxaflor can provide alternative options for *B. tabaci* control when the application method is modified to higher spray volume and installation of spray nozzle tip that delivers more insecticide solution than a typical nozzle tip would deliver. It is worth noting that sulfoxaflor is placed in group 4 as neonicotinoids [17]; thus, the use of XXpire, especially outdoors, should be consistent with the product label to reduce exposure to pollinators.

Improved insecticide coverage will refine the integrated pest management program for *B. tabaci* in the greenhouse. There are many reasons to support this statement. First, better coverage improves the insecticide efficacy by exposing most insects to the applied insecticide [42]. This can be especially true if the primary mode of exposure is by contact. In the current study, the spinetoram component of XXpire primarily works by contact exposure. The sulfoxaflor component of XXpire is typically translaminar and efficacious on piercing–sucking insect pests, such as whiteflies. Dinotefuran (Zylam) is known for its systemic activity within the plant, but it is also effective as a contact poison. Thus, improved coverage of both XXpire and Zylam should improve their efficacy against *B. tabaci*. Second, contact exposure is more efficacious if the behavior of the target insect involves active movement on the leaf surface. The adults and first instars of *B. tabaci* may wander on the foliage until they settle at a spot on the leaf surface. In addition, all stages of *B. tabaci* are mostly found on the abaxial leaf surface, suggesting that insecticide coverage on the abaxial leaf surface is essential. These two behaviors of *B. tabaci* likely helped improve XXpire and Zylam when applied with greater water volume. Third, greater insecticide coverage may have helped reduce the development of resistance to these insecticides through improved efficacy. Finally, the improved coverage and efficacy of insecticide likely reduced the population of *B. tabaci* below threshold levels, which provided opportunities for biological

control agents to suppress the residual *B. tabaci* population post-insecticide application. However, the effects of insecticide coverage on specific biological control agents present on the plants during insecticide application warrant more research.

5. Conclusions

A high water volume (spench) application of insecticides effectively reduced the nymphs of *B. tabaci*. The drench application of insecticides did not provide adequate *B. tabaci* control regardless of the type of active ingredient. When XXpire and Zylam were applied with high volumes of water, they were moderately effective in controlling *B. tabaci* nymphs. Although these results, especially the use of high spray volume and increased delivery rate of insecticide solution, could potentially improve the integrated pest management programs for *B. tabaci*, more research is warranted for determining how this tactic would affect the utility of biological control for various pests including *B. tabaci* in the greenhouse.

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