Effect of Silicon-based Fertilizer Applications on Nymphal Development and Adult Emergence of the Greenhouse Whitefly (Hemiptera: Aleyrodidae) Feeding on Poinsettia[1]

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Abstract This study assessed the effect of silicon-based fertilizer treatments on development of the greenhouse whitefly, *Trialeurodes vaporariorum* (Westwood), while feeding on poinsettia, *Euphorbia pulcherrima* (Willd. ex Klotzsch). A potassium silicate fertilizer was applied at treatment rates of 0, 50, 100, 400, and 800 ppm silicon as a growing medium drench. The mean development time, proportion (%) of pupae and proportion of *T. vaporariorum* adult emergence were determined for each assessment period. Total silicon concentration in the aboveground tissues (leaves and stems) of poinsettia plants were measured at 4 time intervals throughout the study, using a plant alkaline fusion technique (PAFT) silicon determination procedure. Total moisture content (g), height (cm), and number of fully-expanded mature leaves of the poinsettia plants also were measured. Our results showed significant differences in silicon concentration with poinsettia plants receiving the 100, 400, and 800 ppm silicon treatments having the highest silicon concentrations (1240, 1193, and 1121 mg kg^{-1} silicon, respectively) in the aboveground tissues. However, there were no significant differences in development time or emergence rates of *T. vaporariorum* adults when feeding on poinsettia plants treated with potassium silicate in the nutrient solutions. There also were no significant differences in moisture content (g), height (cm), and number of fully-expanded mature leaves of poinsettia plants associated with the silicon-based fertilizer treatments. Incorporating potassium silicate into nutrient solutions did not confer resistance to *T. vaporariorum* populations developing on poinsettia leaves, and applications of the silicon-based fertilizer failed to enhance the plant growth parameters measured, height (cm), number of fully-expanded mature leaves, and moisture content (g).

Key Words silicon, resistance, greenhouse, pest management, floriculture

Whiteflies (Hemiptera: Aleyrodidae) are among the most injurious insect pests of greenhouse and agricultural crops (Harris 1974, Mound and Halsey 1978, Puritch et al. 1982). Globally, the annual losses due to whitefly infestations is difficult to estimate due to the extent of regions affected, multitude of plant hosts, increased management costs, and reduced product marketability (Oliveira et al. 2001). For example, infestations of the sweetpotato whitefly B-biotype *Bemisia tabaci* (Gennadius) results in an annual economic loss of over $200 million (Faust 1992).

Whiteflies ingest plant sap by inserting their piercing-sucking mouthparts into the phloem tissue of host plants resulting in stunting, wilting, fruit drop, and reduced vigor

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and aesthetic quality (Flint 1995, Harris 1974, Johnson et al. 1992, Smith et al. 1970). Whitefly feeding leads to the excretion of honeydew that is an excellent growing medium for certain black sooty mold fungi (*Cladosporium* sp.), which inhibits photosynthesis and decreases plant vigor (Johnson et al. 1992, Malais and Ravensberg 1992, Parr et al. 1976, Yee et al. 1998). Additionally, whiteflies are major vectors of viral diseases such as tomato yellow mottle virus and cassava mosaic geminivirus, which are both vectored by sweetpotato whitefly B-biotype. Many closteroviruses such as beet pseudo-yellow virus, lettuce infectious yellow virus, bean golden mosaic virus, and yellowing diseases of cucumber are vectored by the greenhouse whitefly, *Trialeurodes vaporariorum* (Westwood) (Coffin and Coutts 1995, Duffus 1965, Hilje and Stansly 2008, Legg et al. 2006, Mallowa et al. 2006, Wisler et al. 1998). The greenhouse whitefly infests over 200 plant species, including many economically important horticultural and food crops such as cucumber, *Cucumis sativus* (L.), eggplant, *Solanum melongena* (L.), poinsettia, *Euphorbia pulcherrima* (Willd. ex Klotzsch), and tomato, *Lycopersicon spp.* (Bilderback and Mattson 1977, Helgesen and Tauber 1974, Russell 1963, Van Lenteren and Noldus 1990, Žanić et al. 2008).

Greenhouse whitefly populations, in greenhouses, are typically managed using the parasitoid *Encarsia formosa* (Gahan) (Berndt and Meyhöfer 2008, Helgesen and Tauber 1974) or insecticides (Helgesen and Tauber 1974). Contact or systemic insecticides are primarily used to manage greenhouse whitefly, and in most cases, results in a rapid reduction in greenhouse whitefly populations (Žanić et al. 2008). However, whitefly populations have been shown to exhibit resistance to many insecticide classes such as the neonicotinoids (imidacloprid and thiamethoxam), selective feeding blockers (pymetrozine), organophosphates (malathion and parathion), pyrethroids (resmethrin), and insect growth regulators (buprofezin and pyriproxyfen) (Cahill et al. 1996, French et al. 1973, Georghiou and Lagunes-Tejeda 1991, Gorman et al. 2001, Horowitz et al. 2003, Parr et al. 1974, Wardlow et al. 1972, Žanić et al. 2008). Insecticide resistance is a constant concern among greenhouse producers and, additionally, insecticide applications may not be compatible with certain biological control agents or natural enemies (Cloyd and Dickinson 2006, Osborne 1981, Parr et al. 1976, Van Lenteren and Noldus 1990).

Therefore, greenhouse producers need to implement multiple management strategies to alleviate whitefly outbreaks such as promoting induced plant defenses, utilizing sanitation and cultural practices, and limiting the use of insecticides (Ellsworth and Martinez-Carrillo 2001, Van Lenteren and Noldus 1990). Nutrient solution management may avoid outbreaks of insect pest populations, thus reducing insecticide use in greenhouse production systems (Hogendorp et al. 2006). A method that may be effective in promoting resistance to insects is the application of supplemental silicon-based fertilizers (Rojanaridpiched et al. 1984). It has been reported that high levels of silicon in plants increases plant vigor and leaf epidermal toughness (Wadham and Parry 1981). Applications of silicon-based fertilizers to certain plant species including impatiens, *Impatiens wallerana* (Hook.); rose, *Rosa spp.*; sunflower, *Helianthus annuus* (L.); verbena, *Verbena hybrida* (Voss); and zinnia, *Zinnia elegans* (L.) have resulted in elevated silicon concentrations in plant tissues (Frantz et al. 2008, Gillmann et al. 2003, Voogt and Sonneveld 2001, Whittenberger 1945). The benefits associated with supplemental silicon-based fertilizer applications include protection from extreme environmental conditions such as increased heat tolerance, drought tolerance, and cold hardiness; and enhanced resistance to diseases and insect pests (Bélanger et al. 1995, Bi et al. 2006, Chérif et al. 1992a,b, 1994, Datnoff et al. 2001, Jones and

Handreck 1969, Ma and Yamaji 2006, Sangster and Hodson 1986). It has been suggested that silicon polymers in phloem elements such as the intracellular and intercellular tissues may disrupt insect feeding recognition behaviors. The presence of silicon polymers in plant tissues results in increased resistance to stylet penetration and elicits a nonpreference feeding response (Hayward and Parry 1973, Sōgawa 1982).

However, there is relatively minimal documentation or quantitative data to substantiate silicon's role in increasing resistance to insect pests, although there are a number of hypotheses (Datnoff 2005, Epstein 1994, Gomes et al. 2005, Hayasaka et al. 2008, Moore 1984, Sétamou et al. 1993, Tanaka and Park 1966, Wadham and Parry 1981) and that the use of silicon-based fertilizers may reduce insect pest outbreaks on horticultural crops when used in conjunction with other pest management strategies. Although the use of silicon-based fertilizer applications has been evaluated with green peach aphid, *Myzus persicae* (Ranger et al. 2009); no studies have assessed the effects of silicon-based fertilizer applications on whiteflies. Therefore, the purpose of this study was to investigate the effects of applying silicon-based fertilizers on development time and adult emergence of the greenhouse whitefly, *T. vaporariorum* when feeding on poinsettia, *E. pulcherrima*, grown under greenhouse conditions.

Materials and Methods

Plant parameters. Eighty-five *Euphorbia pulcherrima* 'Freedom red' plants were grown from rooted plugs (originally obtained from Buckley's Prairie Landscaping; Springfield, IL). On 1 September, 2006, the poinsettia plants were transplanted into 15.4-cm standard containers (Dillen Products; Middlefield, OH) filled with Sunshine® LC1 growing medium (Sun Gro Horticulture© Canada Ltd.; Bellevue, WA), which was composed of 70 - 80% Canadian sphagnum peat moss, perlite, dolomitic limestone, gypsum and a wetting agent. All plants were grown in a 10.7 × 9.1 m greenhouse on raised wire-mesh benches located in the Plant Sciences Laboratory Greenhouse Facility at the University of Illinois (Urbana-Champaign, IL). The temperature inside the greenhouse was 28 ± 2°C (day) and 20 ± 2°C (night). Poinsettia plants were grown under natural day-light conditions with no supplemental lighting.

Plant height (cm) was measured and recorded 6 times throughout the study by placing a metric ruler at the growing medium level and measuring from the base of the plant to the tip of the apical bud. The number of mature leaves was recorded 5 times during the study by counting the number of fully-expanded mature leaves from the base of the plant to the apical bud.

Moisture content (g) was determined after each of the 4 harvest periods and was calculated by subtracting the dry weight (g) of the poinsettia plants, which was determined by weighing the plant tissue after the drying process in a gravimetric oven set at 62 ± 2°C, from the wet weight (g) of the poinsettia plants. The wet weight (g) of the poinsettia plants was assessed by weighing the plant tissue on a balance (Model FX-2000 A and D Company, Limited; Tokyo, Japan) 2 h after harvest. The harvest and drying procedures are described later.

Greenhouse whitefly parameters. A greenhouse whitefly colony was established using an original population on lantana, *Lantana camara* (L.), stock plants grown in the Plant Sciences Laboratory Greenhouse Facility at the University of Illinois (Urbana-Champaign, IL). Adult greenhouse whiteflies were collected using an aspirator constructed from a 7-mm plastic vial (Thornton Plastic Co.; Salt Lake City, UT), surgical tubing, a metal nozzle, and a rubber stopper. The vials, containing

approx. 250 adult greenhouse whiteflies, were transferred to a 3.9 × 1.2 × 0.9 m insect rearing cage covered with antivirus insect screening (GreenTek; Edgerton, WI). We allowed the greenhouse whitefly adults to oviposit; subsequent generations then developed on the lantana and poinsettia plants located inside the rearing cage.

The lantana plants were started from cuttings and then transferred to 200-mm plastic azalea pots (Kord Products; Toronto, Canada) containing Sunshine® SB300 Universal growing medium (Sun Gro Horticulture© Canada Ltd.; Bellevue, WA). The components of the growing medium were 45 - 55% composted pine bark mixed with Canadian sphagnum peat moss, vermiculite, perlite, dolomitic limestone, gypsum, and a wetting agent. The poinsettia plants were started as cuttings obtained from stock plants grown in a greenhouse located in the Plant Sciences Laboratory Greenhouse Facility. The plants were grown in 15.4-cm standard containers filled with Sunshine® LC1 growing medium. Both the lantana and poinsettia plants received Peter's® 20 - 8.8 - 16.6 (N-P-K) fertilizer (Scotts-Sierra Horticultural Products; Marysville, OH) applied in a constant liquid feed program at 200 ppm N. Plants were located in a greenhouse (10.7 × 9.1 m) partitioned with antivirus insect screening suspended from the rafters.

The poinsettia 'Freedom Red' plants used for the study were inoculated with greenhouse whitefly adults on 9 October, 2006, to allow the females to lay eggs so we would have a similar cohort of individuals. Plants were approx. 13.4 cm tall 39 d after transplant. All 85 poinsettia plants were placed into a 3.9 × 1.2 × 0.9 m infestation cage, similar to the resident greenhouse whitefly rearing cage. Approximately 700 - 900 adult greenhouse whiteflies were introduced into the infestation cage as described previously. The poinsettia plants remained in the infestation cage for 6 h. All adult greenhouse whiteflies were then removed from the newly-infested poinsettia plants, via aspiration, and transferred back to the initial resident greenhouse whitefly rearing cage. The underside of poinsettia leaves were inspected for the presence of greenhouse whitefly eggs. Munger cells (described below) were placed over clusters of newly-oviposited greenhouse whitefly eggs and secured using 16-mm wire "twist ties." There were 3 Munger cells per poinsettia plant, with each attached to a single leaf. The Munger cells were positioned over the greenhouse whitefly egg clusters on the lowest 3 fully-expanded mature leaves, closest to the growing medium and approx. 7 - 12 cm above the growing medium. The total number of whitefly eggs within each Munger cell was recorded using a Nikon SMZ1000 stereoscope (Nikon Instruments Inc.; Melville, NY). To monitor development time, the Munger cells were inspected daily for the presence of greenhouse whitefly nymphs and pupae, and eventually adult emergence. The number of pupae was recorded for each assessment period (day) associated with each Munger cell. Additionally, the number of emerged adult greenhouse whiteflies was recorded throughout the study. These parameters were used to assess overall greenhouse whitefly development time.

Two-hundred ten Munger cells were constructed of Plexiglas (Illini Plastics; Champaign, IL). Four holes (4.0 mm diam) were drilled into 2 (64 × 39 mm) base plates of Plexiglas; one hole in each corner. A large hole (20 mm internal diameter) was drilled through the center of both base plates. A "miniature insect chamber" was created by attaching a cylindrical tube (20 mm internal diam and 13 mm in height) to the central hole of one of the base plates. The open end of the cylinder, most distant from the base plate, was covered with a circular (25 mm in diameter) piece of antivirus insect screening, which was then attached using a "hot glue gun", thus covering the top of the cylinder. The bottom of the base plate (with the cylinder attached) was affixed with a flat circular grommet-shaped foam pad (20 mm internal diameter). The foam pad

was in constant contact with the leaf surface, which prevented whiteflies from escaping from the Munger cells.

The poinsettia plants, with the attached Munger cells containing greenhouse whitefly eggs, were monitored for egg hatch, nymphal development, pupation, and adult emergence. Adult whiteflies were removed twice from the Munger cells to avoid honeydew production and any density-dependent factors within each Munger cell. The Munger cells were reattached to the exact location on the leaf after removing the adults. At the conclusion of the study, after adult greenhouse whitefly adults were first observed, the Munger cells were removed from the poinsettia leaves and the plants were harvested to assess total silicon concentration (described below).

Silicon application parameters. Treatments consisted of different rates of a soluble silicon-based fertilizer in the form of potassium silicate (ProTek® The Silicon Solution 0 - 0 - 3; Dyna-Gro Nutrient Solutions; Richmond, CA), which was mixed with the nutrient solution. ProTek® is composed of 3.7% potassium (as K_2O) and 7.8% silicate (as SiO_2) with a weight ratio of 2:1. The experimental design was a completely randomized design with 5 silicon rate treatments of 0, 50, 100, 400, and 800 ppm silicon. There were a total of 70 plants with 14 replicate plants per treatment. The nutrient solution was comprised of Peter's® 20 - 8.8 - 16.6 (N-P-K) fertilizer (Scotts-Sierra Horticultural Products; Marysville, OH), mixed at 200 ppm nitrogen and applied as a constant liquid feed. The silicon-based fertilizer nutrient treatment solutions were prepared and maintained in 68-L (61 × 40 × 42 cm) storage tote reservoirs (Rubbermaid® Home Products; Wooster, OH). The process of provisioning the silicon-based fertilizer nutrient treatments began by preparing the Peter's® fertilizer solution, followed by adding the soluble potassium silicate fertilizer (ProTek®) to the reservoir. For all the treatments, except the 800 ppm silicon treatment, potassium sulfate was added to compensate for the additional input of potassium from the silicon-based fertilizer. Finally, the pH was adjusted and maintained between 5.8 and 6.0 by adding sulfuric acid (Mallinckrodt Baker, Inc.; Paris, KY). The pH was measured using a pHTestr2 Double Junction pH meter (Oakton® Instruments; Vernon Hills, IL). All the reservoirs were emptied and new silicon-based fertilizer treatments prepared every 7 d so as to avoid the formation of precipitates, especially in the 800 ppm silicon treatment. All the poinsettia plants were fertilized as needed with the treatment nutrient solution applied as a constant liquid feed with each watering until leachate was observed exiting the drainage holes.

There were 4 harvest dates to determine total silicon concentration in the poinsettia plants throughout the study. The first harvest consisted of 15 poinsettia plants and was performed on 13 October 2006 43 d after transplant, to establish a baseline of total plant silicon concentration (mg kg^{-1} silicon) before plants received the first silicon-based fertilizer rate treatment, which was applied on 13 October 2006. The second harvest occurred on 27 October 2006 and consisted of 4 plants per silicon-based fertilizer rate treatment 57 d after transplant. The third harvest involved 5 plants and occurred on 10 November 2006 71 d after transplant. The final harvest on 4 December 2006 consisted of the 5 remaining plants 95 d after transplant and 52 d after plants had been inoculated with whiteflies. Each poinsettia plant was harvested by removing the aboveground plant portions (leaves and stems) via cutting the main stem at the surface of the growing medium and placing the plant tissue in a #20 brown paper bag (Commercial Bag and Supply; Des Moines, IA). Plant tissue was dried in a gravimetric oven (Precision Scientific Group; Chicago, IL) set at 62 ± 2°C until a constant weight was obtained. A constant weight (g) was determined by weighing and reweighing the plant tissue after approx. 3 d of exposure in the gravimetric oven. The

dried plant tissue was ground into a fine powder using a cyclone sample mill (Model 3,010 - 030 UDY Corp.; Fort Collins, CO) and stored at room temperature (approx. 22°C). All plant tissue was then processed using the plant alkaline fusion technique for total silicon determination (procedure described below) in a laboratory at the University of Illinois (Urbana, IL).

Plant alkaline fusion technique for total silicon determination. Fifty milligrams of ground plant tissue sample was dry-ashed in a 20-mL nickel crucible in a muffle furnace set at 550°C for 4 h. Two grams of anhydrous granular sodium hydroxide was added to each crucible and fused over a natural gas Bunsen burner for 15 min. After cooling, approx. 20 mL of deionized distilled water was added to each crucible and left for 6 - 8 h (overnight) to dissolve the fusion cake.

The next day, after full dissolution of the fusion cake, the silicate sample solution was transferred to a 150 mL polypropylene beaker and acidified using concentrated H_2SO_4 (added drop-wise) until a pH of 1.5 was obtained. The sample solution was brought to 250 mL in a volumetric flask.

A 25-mL aliquot of the silicon sample solution was used for colorimetric determination to obtain total silicon. The aliquot was acidified with 10 mL of 1N H_2SO_4, followed by 10 mL of ammonium paramolybdate tetrahydrate solution. The paramolybdate tetrahydrate solution was prepared by dissolving 54 g of ammonium paramolybdate $(NH_4)_6Mo_7O_{24}{\cdot}4H_2O$ in 800 mL of deionized distilled water. The pH was adjusted to 7 using 5N NaOH, and deionized distilled water was added for a final volume of 1-L. After 3 min, 5 mL of 20% tartaric acid was added to the sample solution, followed by 1 mL of a 1-amino-2-napthol-4-sulfonic acid (ANSA) reducing solution (Hallmark et al. 1982). The sample was agitated for 15 min, and left idle for 15 min to allow for full blue color development. Intensity of the blue-reduced silico-molybdate was measured using a spectrophotometer (Model UV-160 Shimadzu Corporation; Kyoto, Japan) at 820 nm.

Statistical analysis. Each Munger cell contained a different number of greenhouse whitefly cohorts. At each greenhouse whitefly assessment period, the number of greenhouse whitefly pupae was included in the adult numbers within each Munger cell, and subsequently was divided by the total number of individuals in the cohort. This value represented the mean proportion of greenhouse whitefly pupae for each assessment period or the cumulative proportion of the greenhouse whiteflies, which entered the pupal stage by the designated time interval (day). Greenhouse whitefly pupal development was compared temporally with the silicon-based fertilizer rate treatments.

Greenhouse whitefly adult emergence was assessed by determining the proportion of the number of emerged adults divided by the cohort in each Munger cell. The data were recorded over 6 time (day) intervals. The proportions of greenhouse whitefly adult emergence (%) were compared by different silicon-based fertilizer rate treatments over different greenhouse whitefly assessment periods.

Greenhouse whitefly development (pupae and adult emergence) was analyzed using a generalized linear model with a binomial distribution. A one-step autoregressive within-cluster correlation model was used to specify the autocorrelation of error involved in temporal development of the whitefly cohorts within plant subjects. The model predicted proportion of greenhouse whitefly pupae and adults based on time (day), silicon-based fertilizer rate treatment, and the interaction term (time*silicon-based fertilizer rate treatment). The SAS procedure GLIMMIX was used to build the model (SAS Institute 2002). A chi-square test was used to determine if there was a significant effect of time (day), silicon-based fertilizer treatment, or the interaction

parameter of time*silicon-based fertilizer treatment on whitefly development. Treatment means with significant differences were identified using Tukey studentized test for multiple comparisons.

The poinsettia data associated with total silicon concentration (mg kg^{-1} silicon) and moisture content (g) were analyzed using an analysis of variance (ANOVA) with the silicon-based fertilizer treatment rates as the main effect. Significant treatment means were separated using a Fisher's Protected Least Significant Difference (LSD) mean separation test.

A general mixed model with repeated measurements was used to test the effect of silicon-based fertilizer on poinsettia height (cm) and fully-expanded mature leaf count. A one-step autoregressive within-cluster correlation model was used to specify the autocorrelation of error involved in temporal development of the plants. The SAS procedure MIXED was used to build the model (SAS Institute 2002).

Results

The means and standard errors associated with the mean proportion (%) of greenhouse whitefly pupae are presented in Table 1. For all of the assessment periods, there were no significant differences among the silicon-based fertilizer rate treatments associated with the mean proportion of greenhouse whitefly pupae at an α level of 0.05 ($\chi^2 = 1.73$; df = 1; $P = 0.188$). The results pertaining to the time (day) parameter variable in the model were significant ($\chi^2 = 99.62$; df = 1; $P < 0.0001$); however the silicon-based fertilizer rate treatment*time interaction was not significant at α level of 0.05 ($\chi^2 = 2.81$; df = 1; $P = 0.094$).

The means and standard errors of the greenhouse whitefly emergence data are presented in Table 2. For all of the assessment periods, there were no significant differences among the silicon-based fertilizer rate treatments associated with the mean proportion of greenhouse whitefly adult emergence ($\chi^2 = 0.25$; df = 1; $P = 0.617$). The results pertaining to the time (day) parameter variable in the model were significant ($\chi^2 = 158.86$; df = 1; $P < 0.0001$); however, the silicon-based fertilizer treatment*time interaction was not significant ($\chi^2 = 0.46$; df = 1; $P = 0.4994$).

Total silicon concentration in the poinsettia tissues, as determined by the plant alkaline fusion technique, were significantly influenced by the silicon-based fertilizer rate treatments ($F = 13.96$; df = 5, 74; $P < 0.0001$). Plants receiving 0 and 50 ppm silicon were consistently lower in silicon concentration than the other silicon-based fertilizer treatments (100, 400, and 800 ppm silicon) over the final 2 harvests (Table 3). For the final harvest, poinsettia plants that received 100, 400, and 800 ppm silicon had over 1100 mg kg^{-1} silicon in the tissues, whereas plants that received 0 and 50 ppm silicon had <850 mg kg^{-1} silicon present in the tissues (Table 3).

Height (cm) of the poinsettia plants was not significantly influenced by the silicon-based fertilizer rate treatments ($F = 0.50$; df = 4, 305; $P = 0.735$). Poinsettia plants that received the 400 and 800 ppm silicon-based fertilizer treatment were shorter (25.8 and 25.6 cm, respectively), but this was not statistically different from the other silicon rate treatments (Table 4). The number of fully-expanded mature leaves recorded on the poinsettia plants were not significantly affected by the silicon-based fertilizer treatments ($F = 0.84$; df = 4, 235; $P = 0.499$). For the final assessment period (day) there was a difference of 2 fully-expanded mature leaves (14.2 - 16.2) across all the silicon rate treatments (Table 5). The silicon-based fertilizer rate treatments had no significant effect on moisture content of the poinsettia plants ($F = 0.06$; df = 4, 65; $P = 0.993$).

Table 1. Mean (± SEM) proportion (%) of greenhouse whitefly (GWF), *Trialeurodes vaporariorum* (Westwood) pupae for each assessment period (day), as a function of silicon-based fertilizer rate treatments (ppm) applied to poinsettia, *Euphorbia pulcherrima* (Willd. ex Klotzsch) plants; n = number of replicate plants per silicon rate treatment.

Silicon Rate Treatment (ppm)	GWF pupae 6-Nov (mean ± SEM) $n = 10$	GWF pupae 10-Nov (mean ± SEM) $n = 10$	GWF pupae 13-Nov (mean ± SEM) $n = 5$	GWF pupae 17-Nov (mean ± SEM) $n = 5$	GWF pupae 21-Nov (mean ± SEM) $n = 5$	GWF pupae 27-Nov (mean ± SEM) $n = 5$
0	29.0 ± 4.84a*	48.8 ± 6.42a	58.0 ± 9.56a	60.4 ± 9.86a	66.9 ± 6.89a	80.9 ± 6.72a
50	18.6 ± 2.63a	42.4 ± 4.57a	74.8 ± 3.40a	58.1 ± 11.46a	70.2 ± 7.61a	86.8 ± 13.19a
100	23.4 ± 2.69a	49.1 ± 5.09a	76.5 ± 9.65a	63.2 ± 5.14a	70.3 ± 4.88a	92.1 ± 3.84a
400	21.7 ± 2.95a	46.0 ± 7.55a	71.2 ± 1.19a	55.9 ± 4.36a	74.3 ± 5.26a	91.5 ± 7.54a
800	23.7 ± 2.77a	49.0 ± 4.82a	81.9 ± 4.58a	67.3 ± 13.09a	77.2 ± 7.27a	84.1 ± 8.04a

* Means followed by a common letter within a column are not significantly different ($P = 0.05$) as determined by Tukey's studentized mean separation test

Table 2. Mean (± SEM) proportion (%) associated with greenhouse whitefly (GWF), *Trialeurodes vaporariorum* (Westwood) adult emergence for each assessment period (day), as a function of silicon-based fertilizer rate treatments applied to poinsettia, *Euphorbia pulcherrima* (Willd. ex Klotzsch) plants; n = number of replicate plants per silicon rate treatment.

Silicon Rate Treatment (ppm)	GWF adult emergence 6-Nov (mean ± SEM) $n = 10$	GWF adult emergence 10-Nov (mean ± SEM) $n = 10$	GWF adult emergence 13-Nov (mean ± SEM) $n = 5$	GWF adult emergence 17-Nov (mean ± SEM) $n = 5$	GWF adult emergence 21-Nov (mean ± SEM) $n = 5$	GWF adult emergence 27-Nov (mean ± SEM) $n = 5$
0	1.8 ± 1.20a*	20.6 ± 5.02a	29.1 ± 10.92a	46.8 ± 8.07a	56.2 ± 9.90a	76.7 ± 6.16a
50	0.4 ± 3.30a	24.9 ± 4.67a	36.2 ± 1.85a	47.1 ± 12.26a	51.5 ± 8.90a	75.8 ± 12.07a
100	0.0 ± 0.12a	25.5 ± 3.08a	46.7 ± 8.33a	51.9 ± 5.99a	49.5 ± 3.18a	80.7 ± 3.34a
400	0.0 ± 0.00a	23.5 ± 6.84a	34.5 ± 9.14a	44.0 ± 3.45a	53.4 ± 6.99a	79.6 ± 5.71a
800	0.0 ± 0.71a	23.7 ± 4.20a	38.4 ± 8.82a	52.8 ± 12.69a	56.1 ± 6.81a	74.2 ± 8.48a

* Means followed by a common letter within a column are not significantly different ($P = 0.05$) as determined by Tukey's studentized mean separation test.

Table 3. Mean (± SEM) silicon concentration (mg kg^{-1} silicon) of poinsettia, *Euphorbia pulcherrima* (Willd. ex Klotzsch) plants associated with each assessment period (day) for the different silicon-based fertilizer rate treatments (ppm); n = number of plant replications per silicon-based fertilizer rate treatment.

Silicon Treatment Rate (ppm)	First Harvest (Oct 13) (mean ± SEM) n = 15	Second Harvest (Oct 27) (mean ± SEM) n = 4	Third Harvest (Nov 10) (mean ± SEM) n = 5	Fourth Harvest (Dec 4) (mean ± SEM) n = 5
Pre-treatment	803.80 ± 38.27	-	-	-
0	-	825.78 ± 69.66ab*	666.39 ± 18.90a	791.14 ± 61.07a
50	-	712.03 ± 40.98a	786.59 ± 73.65a	808.39 ± 26.24a
100	-	920.97 ± 18.19b	1105.29 ± 65.47b	1240.12 ± 75.21b
400	-	875.33 ± 44.40b	1140.00 ± 64.94b	1192.73 ± 111.43b
800	-	834.62 ± 29.48ab	1265.05 ± 30.11b	1121.58 ± 57.14b

* Means followed by a common letter within a column are not significantly different ($P = 0.05$) as determined by Fisher's protected least significant difference (LSD) mean separation test.

Table 4. Mean (± SEM) height (cm) for poinsettia, *Euphorbia pulcherrima* (Willd. ex Klotzsch) plants associated with each assessment period (day) for the different silicon-based fertilizer rate treatments (ppm); n = number of plant replications per silicon-based fertilizer rate treatment.

Silicon Treatment Rate (ppm)	13-Oct (mean ± SEM) n = 15	20-Oct (mean ± SEM) n = 14	6-Nov (mean ± SEM) n = 10	16-Nov (mean ± SEM) n = 5	27-Nov (mean ± SEM) n = 5	3-Dec (mean ± SEM) n = 5
Pre-treatment	14.10 ± 0.55a*	-	-	-	-	-
0	13.79 ± 0.35a	16.07 ± 0.35a	22.57 ± 0.54a	24.40 ± 0.62a	25.60 ± 0.93a	26.40 ± 1.21a
50	13.29 ± 0.34a	15.50 ± 0.37a	22.43 ± 0.48ab	23.90 ± 0.60a	26.20 ± 0.86a	26.80 ± 0.97a
100	13.21 ± 0.43a	15.86 ± 0.51a	21.86 ± 0.53ab	23.80 ± 0.84a	26.60 ± 1.12a	27.80 ± 0.86a
400	13.07 ± 0.38a	15.43 ± 0.49a	21.00 ± 0.56b	22.70 ± 0.83a	25.40 ± 1.86a	25.80 ± 2.03a
800	12.86 ± 0.36a	15.14 ± 0.42a	21.50 ± 0.56ab	23.10 ± 0.53a	24.60 ± 1.17a	25.60 ± 1.43a

* Means followed by a common letter within a column are not significantly different ($P = 0.05$) as determined by Fisher's protected least significant difference (LSD) mean separation test.

Table 5. Mean (± SEM) number of poinsettia, *Euphorbia pulcherrima* (Willd. ex Klotzsch), leaves per plant associated with each assessment period (day) for the different silicon-based fertilizer rate treatments (ppm); n = number of plant replications per silicon-based fertilizer rate treatment.

Silicon Treatment Rate (ppm)	20-Oct (mean ± SEM) n = 14	6-Nov (mean ± SEM) n = 10	16-Nov (mean ± SEM) n = 5	27-Nov (mean ± SEM) n = 5	3-Dec (mean ± SEM) n = 5
0	5.5 ± 0.45a*	9.9 ± 0.58a	11.1 ± 0.94a	14.2 ± 2.42a	16.2 ± 2.27a
50	6.8 ± 0.45b	11.2 ± 0.56a	12.2 ± 0.53ab	13.8 ± 0.49a	15.2 ± 0.73a
100	6.4 ± 0.37ab	10.8 ± 0.37a	12.9 ± 0.43b	14.6 ± 0.40a	16.6 ± 1.25a
400	7.2 ± 0.39b	11.1 ± 0.47a	12.5 ± 0.40ab	12.6 ± 0.40a	14.8 ± 0.97a
800	6.3 ± 0.49ab	10.0 ± 0.53a	11.6 ± 0.50ab	13.0 ± 0.83a	14.2 ± 0.97a

* Means followed by a common letter within a column are not significantly different ($P = 0.05$) as determined by Fisher's protected least significant difference (LSD) mean separation test.

The moisture content (g) differences of all the poinsettia plants across all treatments were <4.0 g on the final harvest date (Table 6).

Discussion

Applications of the potassium silicate fertilizer, at the various rates, did not negatively affect the mean proportion of greenhouse whitefly pupae or mean proportion of greenhouse whitefly adult emergence associated with whiteflies feeding on poinsettia plants receiving supplemental silicon-based fertilizer treatments. This suggests that silicon neither promoted nor stimulated any type of plant resistance. This response may be due to the range of silicon that accumulated in the poinsettias tissues (791.1 - 1240.1 mg kg^{-1} silicon), which may not be sufficient to inhibit greenhouse whitefly nymphal feeding. These results are in direct contrast to Correa et al. (2005), in which they found that silicon applications contributed to higher nymphal mortality and lengthened the development time of sweetpotato whitefly B-biotype feeding on cucumber. However, it should be noted that cucumber plants tend to absorb more silicon in aboveground tissues (13,000 - 19,000 mg kg^{-1} silicon) (Miyake and Takahashi 1983) than poinsettia plants (791.1 - 1240.1 mg kg^{-1}) used in our study. The high silicon concentrations detected in cucumber plants suggest the possibility of a silicon physical barrier, as opposed to the presence of induced systemic defense compounds such as peroxidases, polyphenoloxidases, and phenylalanine ammonia-lyases (Correa et al. 2005). In our study, the levels of peroxidases, polyphenoloxidases, phenylalanine ammonia-lyases, and chitinase enzymes were not quantified. We did not determine, in our study, where silicon had accumulated in specific tissues of the poinsettia plants, only the total silicon concentrations in the aboveground portions. It is reasonable to assume that any accumulated silicon was not deposited in the phloem and sieve tube elements, where both greenhouse whitefly nymphs and adults feed

Table 6. Mean (± SEM) moisture content (g) of poinsettia, *Euphorbia pulcherrima* (Willd. ex Klotzsch) plants associated with each assessment period (day) for the different silicon-based fertilizer rate treatments (ppm); n = number of plant replications per silicon-based fertilizer rate treatment.

Silicon Treatment Rate (ppm)	First Harvest (Oct 13) (mean ± SEM) n = 10	Second Harvest (Oct 27) (mean ± SEM) n = 4	Third Harvest (Nov 10) (mean ± SEM) n = 5	Fourth Harvest (Dec 4) (mean ± SEM) n = 5
Pre-treatment	25.57 ± 1.46	-	-	-
0	-	47.51 ± 2.98a*	59.84 ± 3.68a	77.00 ± 2.00a
50	-	51.41 ± 3.05a	55.51 ± 4.76a	76.20 ± 3.95a
100	-	50.41 ± 4.13a	59.36 ± 4.43a	76.06 ± 3.78a
400	-	54.42 ± 4.87a	61.59 ± 2.53a	74.78 ± 7.80a
800	-	53.32 ± 3.95a	60.24 ± 5.56a	73.09 ± 8.61a

* Means followed by a common letter within a column are not significantly different ($P = 0.05$) as determined by Fisher's protected least significant difference (LSD) mean separation test.

because there was no effect on the mean proportion of greenhouse whitefly pupae and adult emergence; however, in all likelihood, it may simply be due to a lack of silicon uptake. Whiteflies may avoid areas in plants where silicon is deposited and accumulates, or they can detect the presence of barriers. Whiteflies have modified mouthparts that allow them to establish feeding sites in the phloem sieve tubes by searching through the cuticle, epidermis, and mesophyll (Walling 2008) making it possible to detect the presence of secondary metabolites or any cellular barriers (Müller and Riederer 2005). This evasive feeding strategy may allow whiteflies to either avoid or deter any plant defenses. Moreover, this type of feeding behavior negates activating any defense-response genes (Thompson and Goggin 2006). Phloem-feeders such as whiteflies tend to avoid damaging cells, which fails to initiate the release of defense-response genes (Mewis et al. 2006, Kim and Jander 2007).

If greenhouse whiteflies (both nymphs and adults) were unable to obtain access (due to inhibition by silicon) to sufficient plant nutrients, then a decrease in the life history parameters would be expected. Silicon deposits in poinsettia are typically located on the leaf surface, around stomates and trichomes, indicating that silicon polymerizes as the dehydrating action of transpiration condenses and precipitates silicon polymers (Frantz et al. 2008, Raven 1983). Furthermore, silicon deposits occur less frequently in the phloem elements compared with xylem elements, due to soluble silicon being transported within the transpiration stream and polymerizing as a result of evapotranspiration. If silicon is not present in the cells associated with the phloem tissues or the vascular bundles, it may not inhibit greenhouse whitefly stylet penetration and thus feeding. Additionally, stylet entry through the stomates may follow an intercellular path through the parenchyma cells (Van Lenteren and Noldus 1990). There is a possibility that this entry pathway may be disrupted by the presence of polymerized silicon; however, results of our study suggest that this was not a major factor. Additionally, once greenhouse whiteflies insert their piercing-sucking mouthparts into phloem sieve elements a continual food supply is available, and so a single feeding site may be exploited for weeks (Hodkinson and Hughes 1982, Walling 2000).

In a study with wheat aphid, *Schizaphis graminum* (Rondani), feeding on sorghum, *Sorghum bicolor* (L.), plants treated with sodium silicate, it was determined that silicon reduced feeding preference and increased mortality. In addition, there were shorter prereproductive and reproductive periods compared with untreated plants (Carvalho et al. 1999). However, the greenhouse whitefly parameters measured in our study were associated with development rates, and not mortality, feeding preference, or reproduction as in Carvalho et al. (1999). In another study, wheat aphid, *S. graminum,* adults experienced higher mortality and decreased fecundity after feeding on wheat treated with sodium silicate (at 0.4% silicon) (Basagli et al. 2003, Gomes et al. 2005). We found that none of the silicon applications negatively influenced the greenhouse whitefly development parameters, which is contradictory to the effects of silicon applications on aphid life history parameters when feeding on wheat (Carvalho et al. 1999, Basagli et al. 2003, Gomes et al. 2005).

It should be noted that sorghum accumulates more silicon (ranging from 4,000 - 7,000 mg kg^{-1} silicon) in the aboveground tissues (Carvalho et al. 1999) than poinsettia (791.1 - 1240.1 mg kg^{-1} silicon). Wheat plants also accumulate more silicon in the aboveground tissues than poinsettia, even though total silicon concentrations in wheat were not reported in either study (Basagli et al. 2003, Gomes et al. 2005). However, Cotterill et al. (2007) indicated that silicon concentration ranges from 25,000 - 70,000 mg kg^{-1} silicon may be present in wheat plants with and without having received

silicon applications, which is over 10X the silicon concentrations detected in poinsettia (299.9 - 3,360 mg kg^{-1} silicon) (Frantz et al. 2008, Voogt et al. 2005). Apparently, poinsettia is more similar to coleus, *Solenstemon scutellarioides* (L.) Codd, than wheat or sorghum plants in terms of silicon absorption characteristics (Hogendorp 2008). Both poinsettia and coleus plants are considered silicon 'rejectors', with <0.5% silicon in plant tissues, whereas sorghum would be categorized as silicon 'neutral', and wheat would be considered a silicon 'accumulator' (Ma et al. 2001). However, unlike coleus, poinsettia absorbs more silicon from the nutrient solutions as the silicon application rate increases (Hogendorp 2008).

Applications of the silicon-based fertilizer to poinsettia plants, at the rates tested, more than likely did not result in increased epidermal thickness, increased intracellular and intercellular silica deposits, and silica polymer deposits accumulating at stomatal openings and conducting vessels as proposed by Ma (2004). Although, higher silicon concentrations were detected in poinsettia plants that received 100, 400, and 800 ppm silicon, whiteflies may not have been exposed to areas where silicon accumulated or they were able to avoid feeding in areas of the leaf that contained elevated silicon concentrations.

It is not well-understood where in poinsettia tissues silicon is being deposited, but it may be associated with the presence of trichomes on the leaf surface. For example, Frantz et al. (2008) detected silicon deposits at the base of trichomes, along the leaf margins, and at the ends of xylem elements such as stomatal structures on the surface of poinsettia leaves, after plants had been treated with a 2.0 mM potassium silicate solution. The presence of glandular hairs and trichomes may affect greenhouse whitefly performance on poinsettia plants; however, the qualitative characteristics of trichomes such as density, length, and type are also important characteristics that influence greenhouse whitefly preference (Bilderback and Mattson 1977, Neal and Bentz 1999, Van Lenteren and Noldus 1990). However, if silicon was present in areas where greenhouse whitefly nymphs and adults fed, there apparently was not a sufficient quantity of silicon to provide a mechanical barrier and thus inhibit feeding. It is difficult to assess how silicon may affect the quality of trichomes on poinsettia plants and how this may impact insect pests such as the greenhouse whitefly.

The silicon-based fertilizer treatments did not affect any of the plant growth parameters including final moisture content (g), height (cm), or the number of fully-expanded mature leaves. The impact of silicon on plant growth, yield, and development appears to be species specific, and not all horticultural crops may benefit from supplemental applications of silicon including poinsettia and coleus (Hogendorp 2008).

The potassium silicate fertilizer rate treatments resulted in significantly different concentrations of silicon accumulating in poinsettia tissues. Plants treated with 0 and 50 ppm silicon treatments had the lowest silicon concentration values (791.1 and 808.4 mg kg^{-1} silicon). However, it should be noted that 50 ppm silicon is the manufacturer's label rate, although there are no quantitative data available supporting the premise that this rate actually reduces plant stress caused by insects (as stated on the label), and the current study suggests there is no silicon-mediated insect resistance provided by supplemental silicon-based fertilizer applications to poinsettia plants. Furthermore, there is no quantitative data associated with the silicon requirements that may benefit poinsettia. A wide range of silicon concentration values in poinsettia tissues has been reported in the scientific literature ranging from 299.9 - 3,360 mg kg^{-1} silicon. However, silicon concentration is dependent on whether poinsettia plants are grown in "silicon-free" laboratory grade purified 18-ohm water (Frantz

et al. 2008), or grown in calcium-silicate-carbonate fertilizer mixed with the growing medium and further treated with 1 mmol silicon L^{-1} (Voogt et al. 2005). In the current study, 100 ppm silicon, as potassium silicate, increased poinsettia tissue silicon concentrations to approx. 1200 mg kg^{-1} silicon, whereas additional inputs of the silicon-based fertilizer did not increase overall silicon concentration in the plant tissues beyond this value.

Our study was not designed to assess if any differences in silicon concentrations detected in poinsettia tissue confered additional benefits associated with elevated silicon levels in plant tissue such as increased fungal resistance, reduced heat stress, mitigation of salt and metal toxicity, increased cold hardiness, or improved water relations. The poinsettia plants, as with most greenhouse-grown crops, were never "stressed," and so many of the associated benefits of silicon that are conferred in agronomic crops were not demonstrated (Marschner 1995). However, the elevated silicon concentrations in poinsettia tissues did not confer resistance to greenhouse whitefly based on no apparent effects on the mean proportion of pupae or development time and mean proportion of adult emergence. Moreover, the impact of applying silicon based fertilizers, at 100 ppm silicon, on trichomes; presence of defensive chemical compounds such as peroxidases, polyphenoloxidases, and phenylalanine ammonia-lyases associated with resistance to fungal pathogens merits further investigation. In conclusion, silicon applications to poinsettia had no negative effect on any of the greenhouse whitefly parameters measured and, therefore, may not protect poinsettia plants from whitefly outbreaks.

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