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Chemical Control of Powdery Mildew of Bigleaf Hydrangea

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***Abstract.* The efficacy of the fungicide pydiflumetofen + difenoconazole (Postiva) was evaluated at varying application rates and intervals for the control of powdery mildew (*Golovinomyces orontii,* formerly *Erysiphe polygoni*) in bigleaf hydrangea (*Hydrangea macrophylla* 'Nikko Blue'). Container-grown hydrangeas were arranged in a completely randomized design with six single-plant replications. Experiments were done in 2022 and 2023 under both greenhouse and shade house conditions (56% shade). Powdery mildew in hydrangea was developed naturally. Pydiflumetofen + difenoconazole at 1.1, 1.6, and 2.2 ml·L^{-1} and a standard fungicide azoxystrobin + benzovindiflupyr (Mural) at 0.5 g·L^{-1} were sprayed to runoff on 2-, 4-, and 6-week intervals. Plants that were not treated with fungicide served as the control. Plants were evaluated weekly for disease severity (0% to 100% foliage affected) and defoliation (0% to 100% defoliation). The season-long area under the disease progress curve (AUDPC) and defoliation progress curve (AUDFC) were calculated for the evaluation period. The initial and final plant height and width were recorded, and height and width increase were determined. Pydiflumetofen + difenoconazole and azoxystrobin + benzovindiflupyr significantly reduced final disease severity, AUDPC, and defoliation both in the greenhouse and shade house compared with control plants. In both greenhouse trials and the 2022 shade house trial, AUDFC was reduced in all treatments compared with the control plants. However, AUDFC was not reduced by all treatments in the 2023 shade house trial. Pooled over application intervals, the low rate of pydiflumetofen + difenoconazole was as effective as the medium and high rates of pydiflumetofen + difenoconazole and azoxystrobin + benzovindiflupyr in reducing final powdery mildew severity and AUDPC both in the greenhouse and shade house in both 2022 and 2023. No significant differences between application intervals were noted in final disease severity and progress. Control of powdery mildew with fungicides failed to increase plant dimensions (i.e., plant height and width) compared with the no fungicide control. Because all application rates and intervals of pydiflumetofen + difenoconazole provided comparable powdery mildew disease control, it is suggested that using a low rate of pydiflumetofen + difenoconazole with the longest application interval (6 weeks) is the most cost-effective approach for managing powdery mildew in bigleaf hydrangeas.**

The woody ornamental nursery industry is an important agricultural sector in the United States that generates more than $5.5 billion in annual wholesale values (National Agriculture Statistics Service 2020). Among woody ornamentals, hydrangeas are valued for their large, colorful inflorescences and are widely used in commercial and residential plantings, as well as in field nurseries and greenhouses. In 2019, hydrangeas contributed $155,547,000 in total sales in the United States (National Agriculture Statistics Service 2020). Plant health is an important consideration in maximizing profitability. However, the health, appearance, and ornamental values of these crops are often negatively impacted by diseases, rendering them unmarketable. Powdery mildew in bigleaf hydrangea (*Hydrangea macrophylla*) is a destructive foliar disease (Baysal-Gurel et al. 2016).

Powdery mildew is a widespread disease that has many species. Each species of powdery mildew has a limited host range (Burgess and Williamson 2021). *Golovinomyces orontii* (synonym *Erysiphe polygoni*) is the disease-causing agent in bigleaf hydrangea (Baysal-Gurel et al. 2016; Hagan et al. 2004; Halcomb and Sandra 2010; Li et al. 2009). Powdery mildew has both asexual and sexual life cycles. The asexual life cycle involves the dispersal of conidia to plant surfaces, where appressorium, or structures that penetrate the host cell wall, develop (Vielba-Fernández et al. 2020). Fungal hyphae overwinter in plant debris and plant parts (Baysal-Gurel et al. 2016; Burgess and Williamson 2021). Chasmothecia defines the sexual life cycle of powdery mildew, and these structures contain asci, sac-like structures that produce ascospores that develop when conditions are unfavorable (Boddy 2016). Chasmothecia serve as overwintering structures and produce ascospores for infection in the next growing season (Hacquard 2014). Spores and fungal hyphae are able to disperse via air and plant-to-plant contact (Baysal-Gurel et al. 2016; Burgess and Williamson 2021). Hydrangeas growing in greenhouses and shade houses are particularly susceptible to powdery mildew due to the favorable environmental conditions (Dirr 2004). Powdery mildews can occur in a wide range of environments, such as temperate, arid, subarctic, and tropical habitats (Ale-Agha et al. 2008). For *G. orontii* in the southeastern United States, annual epidemics occur during the summer until midfall. *G. orontii* produces small, fuzzy gray circles or patches on the adaxial leaf surface, which is favored by high humidity, a dry leaf surface, and warm days with cool nights (Baysal-Gurel et al. 2016; Dirr 2004). As the disease progresses, leaves on the plant are covered with whitish mildew growth, extensive chlorosis or yellowing, and premature defoliation (Sinclair and Lyon 2005). Severe powdery mildew disease has also been shown to retard plant growth and reduce flowering (Baysal-Gurel et al. 2016).

Management of fungal diseases require sanitation to prevent overwintering and spread of inoculum. Additionally, fungicide use is the most common and effective method to prevent fungal diseases in nursery crops. For powdery mildew management on ornamentals, azoxystrobin (Hagan et al. 2004), clarified hydrophobic extract of neem oil, copper actanoate, myclobutanil, potassium bicarbonate, propiconazole, tebuconazole, and triticonazole have been used (Hagan 2022). These fungicides were applied at 7- to 14-d intervals throughout the growing season. However, there are not many studies regarding the influence of rates and application intervals of fungicides in controlling diseases. Understanding how application rates and intervals differ or are similar can aid in making decisions regarding hydrangea disease management. This understanding can also aid in the effectiveness of fungicide applications and cost-saving strategies.

The objective of this study was to test the efficacy of application rates and intervals on the control of powdery mildew of hydrangea with the fungicide pydiflumetofen + difenoconazole on hydrangea and compare the efficacy of pydiflumetofen + difenoconazole within greenhouse and shade house conditions. Pydiflumetofen 6.9% + difenoconazole 11.5% (Postiva; Syngenta Crop Protection LLC, Greensboro, NC, USA) is a recently developed

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novel fungicide and is considered to provide broad-spectrum control of diseases such as Botrytis, *Fusarium*, leaf spots and powdery mildew in ornamentals.

Materials and Methods

Fungicides pydiflumetofen + difenoconazole (Postiva) and azoxystrobin + benzovindiflupyr (Mural; Syngenta Crop Protection LLC) were evaluated in a greenhouse or shade house using the bigleaf hydrangea (*Hydrangea macrophylla*) cultivar Nikko Blue. Plants in each trial were 1-year-old plants potted in 1-gal containers. All experiments were conducted in 2022 and 2023 at the Tennessee State University Otis L. Floyd Nursery Research Center in McMinnville, TN, USA. Nursery mix (processed pine bark (55% to 65%), Canadian sphagnum peat, and sand) (Morton's Horticultural Products, McMinnville, TN, USA) was used as the potting medium for plants. Plants were fertilized with 100.6 mL of liquid fertilizer (24–8–16 Miracle-Gro®; Scotts Miracle-Gro Company, Marysville, OH, USA) and 5.7 g of granular controlled release fertilizer (18–6–8 Nutricote®; Arysta LifeScience America, New York, NY, USA) before their respective trials. Fungicides tested were three rates of pydiflumetofen + difenoconazole (1.1, 1.6, and 2.2 $ml·L^{-1}$) and a single rate of azoxystrobin + benzovindiflupyr (0.5 $g·L^{-1}$), with each treatment containing 4% v/v of Capsil spray adjuvant (Aquatrols, Paulsboro, NJ, USA). Treatments were repeated at a 2-, 4-, or 6-week interval and applied as a foliar spray with a backpack CO_2 pressurized sprayer (Bellspray, Inc., Opelousas, LA, USA) equipped with a TeeJet XR8002VS nozzle at 30 psi to runoff. Powdery mildew occurred naturally in each trial. Disease severity and defoliation were evaluated every 7 d from the beginning of the trial period until 2 weeks after the last fungicide application and were expressed as a percentage of the foliage area affected. Plant height and width were taken at the beginning and end of each trial to determine height and width increase. Measurements were taken for height by measuring from the base (potting mix line) to the tip of the plant. The width was measured from the leaf tip to leaf tip, the widest horizontal spread, and the spread perpendicular to the widest spread. Plant height and width increase was calculated by subtracting the initial from the final measurements. If there were significant differences, percent increase was calculated by subtracting the smaller value from the larger value and dividing by the smaller value, then multiplying by 100.

Greenhouse trials. In 2022, hydrangea plants were irrigated using overhead irrigation (SpinNet nozzle; Hummert International, Earth City, MO, USA) for 2 min twice a day in May, Jun, Jul, and Aug 2022. Plants were arranged in a completely randomized design with six single-plant replications, inside a greenhouse with 15% shade. Initial and final height and width were taken on 3 May and 9 Aug, respectively. Fungicides were applied on 4 May, 18 May, 1 Jun, 15 Jun, 29 Jun, 13 Jul, and 27 Jul 2022 for the 2-week interval; 4 May, 1 Jun, 29 Jun, and 27 Jul 2022 for the 4-week interval; and 4 May, 15 Jun, and 27 Jul 2022 for the 6-week interval. No fungicide-treated plants were included as controls. Plants were evaluated for disease severity and percent defoliation on 3 May, 10 May, 17 May, 24 May, 31 May, 7 Jun, 14 Jun, 21 Jun, 28 Jun, 5 Jul, 12 Jul, 19 Jul, 26 Jul, 2 Aug, and 9 Aug 2022. Average maximum temperatures for May, Jun, Jul, and 1–9 Aug 2022 were 30.9, 33.9, 30.2, and 28.9 °C, respectively; average minimum temperatures were 19.2, 19.0, 20.3, and 19.8 °C, respectively; average humidity was 99.1%, 99.3%, 96.1%, and 96%, respectively.

For the second trial, plants were irrigated using overhead irrigation system for 2 min twice a day in Jan, Feb, Mar, Apr, and May 2023. Plants were arranged inside a greenhouse with 15% shade in a completely randomized design with six single-plant replications. Initial and final height and width were taken on 27 Jan and 8 May 2023, respectively. Fungicides were applied on 30 Jan, 13 Feb, 27 Feb, 13 Mar, 27 Mar, 10 Apr, and 24 Apr 2023 for the 2-week interval; 30 Jan, 27 Feb, 27 Mar, and 24 Apr 2023 for the 4-week interval; and 30 Jan, 13 Mar, and 24 Apr 2023 for the 6-week interval. Plants that were not treated with fungicides served as the control. Plants were evaluated for disease severity and defoliation on 30 Jan, 6 Feb, 13 Feb, 20 Feb, 27 Feb, 6 Mar, 13 Mar, 20 Mar, 27 Mar, 3 Apr, 10 Apr, 17 Apr, 24 Apr, 1 May, and 8 May 2023. Average maximum temperatures in the greenhouse for Jan, Feb, Mar, Apr, and May 2023 were 26.9, 27.1, 27.3, 27.3, and 30.9 °C; average minimum temperatures were 17.2, 17.8, 17.9, 18.3, and 18.4 °C; and average humidity was 90.4, 81.0, 89.0, 98.8, and 99.5%, respectively.

Shade house trials. In 2022, plants were irrigated with overhead irrigation system (Orbit 55032 1/2″ BRS Sprinkler Head; Orbit® Inc., North Salt Lake, UT, USA) for 15 min twice a day in June, July, August, September, and October under 56% shade. Plants were arranged in a completely randomized design with six single-plant replications. Initial and final plant height and width were recorded on 27 Jun 2022 and 6 Oct 2022, respectively. Fungicides were sprayed on 28 Jun, 12 Jul, 26 Jul, 9 Aug, 6 Sep, and 20 Sep 2022 for the 2-week interval; 28 Jun, 26 Jul, 23 Aug, and 20 Sep 2022 for the 4-week interval; and 28 Jun, 9 Aug, and 20 Sep 2022 for the 6-week interval. Plants were evaluated for disease severity and defoliation on 30 Jun, 7 Jul, 14 Jul, 21 Jul, 28 Jul, 4 Aug, 11 Aug, 18 Aug, 25 Aug, 1 Sep, 8 Sep, 15 Sep, 22 Sep, 29 Sep, and 6 Oct 2022. Average maximum temperatures for 28–30 Jun, Jul, Aug, Sep and 1–6 Oct 2022 were 31.1, 32.5, 30.4, 27.8, and 26.8 °C; average minimum temperatures were 17.8, 21.3, 19.6, 14.1, and 9.9 °C; and the total rainfall was 2.5, 154.9, 99.1, 111.8, and 0.0 mL, respectively.

For the second shade house trial, plants were irrigated with overhead irrigation system for 15 min twice a day in May, June, July, and August under 56% shade. Plants were arranged in a completely randomized design with six single-plant replications. Initial and final plant height and width were measured on 1 May 2023 and 11 Aug 2023, respectively. Fungicides were applied as treatments on 4 May, 18 May, 1 Jun, 15 Jun, 29 Jun, 13 Jul, and 27 Jul 2023 for the 2-week interval; 4 May, 1 Jun, 29 Jun, and 27 Jul 2023 for the 4-week interval; and 4 May, 15 Jun, and 27 Jul 2023 for the 6-week interval. Plants were evaluated for disease severity and defoliation on 4 May, 11 May, 18 May, 25 May, 1 Jun, 8 Jun, 15 Jun, 22 Jun, 29 Jun, 6 Jul, 13 Jul, 20 Jul, 27 Jul, 3 Aug, and 10 Aug 2023. Average maximum temperatures for 4–31 May, Jun, Jul and 1–10 Aug 2023 were 25.7, 28.7, 30.8, and 27.6 °C; average minimum temperatures were 13.8, 15.7, 19.7, and 16.8 °C; and total rainfall was 150.8, 83.8, 68.8, and 75.4 mL, respectively.

Statistical analysis. The season-long area under the disease progress curve (AUDPC) and area under the defoliation progress curve (AUDFC) (Bowen and Roark 2001) were calculated for the evaluation period using the formula: $\Sigma([(x_i + x_{i-1})/2](t_i - t_{i-1}))$ where x_i is the rating at each evaluation time and $(t_i - t_{i-1})$ is the number of days between evaluations. Treatment effects on plant height, width, AUDPC, and AUDFC were analyzed with a one-way analysis of variance (ANOVA) using PROC GLM in SAS 9.4 (SAS Institute, Cary, NC, USA). Means were separated by Tukey's test with significance at $P < 0.05$. Percent data on final disease severity and defoliation were analyzed using general linear mixed model with a logit link and beta distribution (PROC GLIMMIX) and means were separated using LS means. Factorial two-way ANOVA was performed to determine the main and interactive effects of fungicide application rate and interval. The control treatment was removed to facilitate the two-way factorial analysis. Means were separated by the Tukey test ($P < 0.05$).

Results

Greenhouse trials. In 2022, final defoliation, season-long defoliation (AUDFC), final disease severity, and AUDPC were the highest in nontreated control. No significant differences were noted among treatments on height or width increases (Table 1). All combinations of pydiflumetofen + difenoconazole and azoxystrobin + benzovindiflupyr significantly reduced defoliation, AUDFC, final disease severity, and AUDPC compared with the non-treated control plants. Hydrangea treated with azoxystrobin + benzovindiflupyr at the 2-week interval, along with all pydiflumetofen + difenoconazole applications rates at the 2-week interval and the medium and high rate of pydiflumetofen + difenoconazole at the 4-week interval had significantly lower final disease severity. All treatments at the 2- and 4-week interval had the lowest AUDPC compared with the 6-week interval of all respective treatments. All application rates at all intervals of pydiflumetofen + difenoconazole and at the 2- and 4-week interval of azoxystrobin + benzovindiflupyr had the lowest final defoliation percentage. The 2- and 4-week interval of the low and high application rate, as well as all application intervals at the

Table 1. Fungicide effects on plant growth, defoliation (0% to 100% defoliation), AUDFC, final powdery mildew (*Golovinomyces orontii*) severity (0% to 100% affected), and AUDPC of bigleaf hydrangea (*Hydrangea macrophylla*) grown in a greenhouse from May to Aug 2022.

Treatment	Application rate	Application interval (weeks)	Ht increase (cm)[i]	Width increase (cm)[ii]	Final defoliation (%)[iii]	AUDFC[iv]	Final severity (%)[iii]	AUDPC[iv]
Pydiflumetofen + difenoconazole	1.1 $mL \cdot L^{-1}$	2	18.5 ± 5.8 a[i]	22.8 ± 5.7 a	3.0 ± 0.0 bc	70.3 ± 31.3 bc	8.0 ± 4.0 def	326.7 ± 133.0 c–f
		4	26.3 ± 4.0 a	25.5 ± 4.0 a	3.0 ± 1.0 bc	85.8 ± 10.5 bc	8.0 ± 2 cde	521.2 ± 112.4 b–f
		6	22.8 ± 3.1 a	24.7 ± 2.3 a	4.0 ± 1.0 bc	95.4 ± 34.9 b	11.0 ± 2.0 bcd	644.0 ± 133.6 bcd
	1.6 $mL \cdot L^{-1}$	2	18.0 ± 1.8 a	20.5 ± 2.9 a	2.0 ± 1.0 c	83.7 ± 26.9 bc	6.0 ± 2.0 c–f	344.2 ± 120.9 c–f
		4	19.7 ± 4.2 a	18.3 ± 2.7 a	3.0 ± 0.0 bc	82.3 ± 8.5 bc	7.0 ± 1.0 c–f	437.8 ± 74.1 b–f
		6	17.8 ± 6.3 a	23.0 ± 4.6 a	3.0 ± 1.0 bc	70.0 ± 15.8 bc	16.0 ± 3.0 b	821.9 ± 122.1 bc
	2.2 $mL \cdot L^{-1}$	2	21.8 ± 4.0 a	28.2 ± 6.6 a	3.0 ± 1.0 bc	39.1 ± 12.9 bc	2.0 ± 0.0 f	72.9 ± 24.6 f
		4	21.2 ± 2.5 a	26.3 ± 4.5 a	1.0 ± 1.0 c	26.0 ± 12.7 c	4.0 ± 1.0 ef	181.7 ± 52.4 def
		6	23.2 ± 2.5 a	28.3 ± 6.0 a	3.0 ± 1.0 bc	96.8 ± 19.9 bc	16.0 ± 5.0 bc	912.0 ± 262.0 b
Azoxystrobin + benzovindiflupyr	0.5 $g \cdot L^{-1}$	2	20.5 ± 2.2 a	31.9 ± 2.4 a	2.0 ± 1.0 bc	53.4 ± 19.7 bc	6.0 ± 1.0 def	131.0 ± 35.7 ef
		4	27.7 ± 4.9 a	38.4 ± 5.3 a	3.0 ± 0.0 bc	98.9 ± 28.9 b	7.0 ± 2.0 cde	426.4 ± 157.1 b–f
		6	23.0 ± 3.6 a	32.7 ± 6.2 a	4.0 ± 1.0 b	104.1 ± 26.4 b	11.0 ± 3.0 b–e	622.4 ± 169.2 b–e
Nontreated control			26.8 ± 3.5 a	22.7 ± 6.7 a	13.0 ± 2.0 a	431.2 ± 39.5 a	87.0 ± 3.0 a	5659.8 ± 453.0 a
P			0.7451	0.2496	<0.0001	<0.0001	<0.0001	<0.0001
F			0.70	1.28	21.62	15.95	30.47	67.31

[i] Height increase = final height – initial height.

[ii] Width increase = [(final widest width – initial widest width) + (final perpendicular width – initial perpendicular width)] ÷ 2.

[iii] Final defoliation and powdery mildew severity evaluation was performed on 9 Aug.

[iv] AUDPC (or AUDFC) = $\Sigma\{[(x_i + x_{i-1})/2](t_i - t_{i-1})\}$, where x_i is the disease severity rating (or defoliation ratings) at each evaluation time and $(t_i - t_{i-1})$ is the number of days between evaluations.

[v] Means followed by a different lowercase letter within a column are significantly different ($P \leq 0.05$). One-way analysis of variance was used to evaluate treatment effects on height increase, width increase, AUDFC, and AUDPC. Means were compared using Fisher's least significant difference test with an $\alpha = 0.05$. Percent data (final defoliation and severity) were analyzed according to general linear mixed model with a logit link and beta distribution (PROC GLIMMIX).

AUDPC = area under the disease progress curve; AUDFC = area under the defoliation progress curve.

medium application rate of pydiflumetofen + difenocona and the 2-week interval of azoxystrobin + benzovindiflupyr had the lowest AUDFC. There were no significant differences among height and width increase among treatments and nontreated control (Table 1).

The factorial two-way ANOVA showed a significant effect of application interval but not application rate and no rate × interval interactions on final disease severity and AUDPC among treatments (Table 2). Application rate, interval, and rate × interval interaction did not have a significant impact on height, final defoliation, and AUDFC. Rate had a significant effect on width.

In 2023, control plants had the highest final defoliation, AUDFC, final disease severity, and AUDPC. All rates and intervals of pydiflumetofen + difenoconazole and azoxystrobin + benzovindiflupyr significantly reduced final disease severity, defoliation, AUDFC, and AUDPC compared with the nontreated control (Table 3). Significantly lower final disease severity was obtained with all application intervals of the low, medium, and high rate of pydiflumetofen + difenoconazole and the 2- and 4-week application interval of azoxystrobin + benzovindiflupyr. All application intervals of pydiflumetofen + difenoconazole and the 2- and 4-week application of interval azoxystrobin + benzovindiflupyr had the lowest AUDPC. All low- and high-application rates at all application intervals, and 2-week interval of the medium application rate of pydiflumetofen + difenoconazole had the lowest final defoliation percentage, which was lower than all azoxystrobin + benzovindiflupyr treatments at each application interval. All treatment rates at all application intervals were similar in AUDFC. There were no significant differences in height increase among the treatments and nontreated control. There was a significant difference of width increase difference between the medium pydiflumetofen + difenoconazole treatment at the 4-week interval and azoxystrobin + benzovindiflupyr at the 6-week interval. The percent width increase for this difference was 137% (Table 3).

The two-way ANOVA showed no significant effect on application rate, interval or the rate × interval interaction for final disease severity or AUDPC (Table 2). Height was unaffected by application rate, interval or rate × interval. Application rate and interval had a significant effect on final defoliation and width. Application rate, interval, and rate × interval interaction had no significant effects on AUDFC (Table 2).

Shade house trials. In 2022, the final powdery mildew disease severity was 45% on nontreated control plants. The nontreated control had the highest level of final powdery mildew severity, AUDPC, final defoliation, and AUDFC, which was significantly higher than treated plants (Table 4). While most treatments were statistically similar, the 2-week interval at the high rate of pydiflumetofen + difenoconazole provided the best control for final disease severity and AUDPC. Treatments of the medium rate of pydiflumetofen + difenoconazole at the 2-week interval and azoxystrobin + benzovindiflupyr at the 4-week interval had the lowest height increase. Treatments of the high rate of pydiflumetofen +

Table 2. *P* value from two-way analysis of variance testing effects of application rate, application interval, and their interaction on final disease severity, AUDPC, final defoliation, AUDFC, and plant growth (height and width) in greenhouse and shade house conditions in 2022 and 2023.

	2022						2023					
	Greenhouse			Shade house			Greenhouse			Shade house		
	Rate	Interval	Rate × interval	Rate	Interval	Rate × interval	Rate	Interval	Rate × interval	Rate	Interval	Rate × interval
Final disease severity	0.7236	<0.0001	0.3547	0.5463	0.6359	0.7692	0.0209	0.1695	0.5169	<0.0001	0.1575	0.5879
AUDPC	0.4306	<0.0001	0.2966	0.6800	0.4234	0.6654	0.0145	0.1440	0.2203	<0.0001	0.1443	0.2880
Final defoliation	0.2993	0.1446	0.6386	0.8016	0.6379	0.8810	0.0007	0.0026	0.2416	0.6850	0.1719	0.2949
AUDFC	0.2884	0.1700	0.4327	0.9426	0.4756	0.6301	0.3129	0.0686	0.1818	0.5404	0.1985	0.6178
Height	0.4191	0.3711	0.9301	0.0449	0.0497	0.1015	0.7408	0.7360	0.5335	0.1085	0.1941	0.9352
Width	0.0054	0.9020	0.9373	0.3023	0.1581	0.0074	0.0412	0.0002	0.4286	0.2718	0.1409	0.8907

AUDPC = area under the disease progress curve; AUDFC = area under the defoliation progress curve.

Table 3. Fungicide effects on plant growth, defoliation (0% to 100% defoliation), AUDFC, final powdery mildew (*Golovinomyces orontii*) severity (0% to 100% affected), and AUDPC of bigleaf hydrangea (*Hydrangea macrophylla*) grown in a greenhouse from Jan to May 2023.

Treatment	Application rate	Application interval (weeks)	Ht increase (cm)[i]	Width increase (cm)[ii]	Final defoliation (%)[iii]	AUDFC[iv]	Final severity (%)[iii]	AUDPC[iv]
Pydiflumetofen + difenoconazole	1.1 ml·L^{-1}	2	7.7 ± 3.1 a[v]	18.9 ± 4.6 ab	3.8 ± 1.4 e	202.7 ± 91.5 b	5.0 ± 3.5 d	379.2 ± 281.9 c
		4	6.3 ± 3.3 a	17.4 ± 6.4 ab	5.0 ± 0.0 c–e	271.8 ± 26.2 b	9.6 ± 5.1 cd	624.2 ± 334.9 bc
		6	6.5 ± 2.6 a	20.0 ± 3.6 ab	5.0 ± 0.0 c–e	208.3 ± 60.8 b	7.5 ± 2.7 cd	509.0 ± 272.4 bc
	1.6 ml·L^{-1}	2	4.8 ± 2.2 a	9.2 ± 4.3 b	4.2 ± 1.3 de	218.8 ± 45.0 b	9.6 ± 4.6 b–d	632.9 ± 246.5 bc
		4	7.8 ± 5.0 a	12.7 ± 2.0 ab	5.8 ± 2.6 cd	237.4 ± 66.6 b	10.0 ± 4.2 b–d	647.5 ± 270.6 bc
		6	8.5 ± 5.1 a	19.7 ± 5.4 ab	5.4 ± 1.0 cd	258.2 ± 81.3 b	10.8 ± 3.8 bc	720.4 ± 231.6 bc
	2.2 ml·L^{-1}	2	6.8 ± 4.6 a	11.8 ± 7.2 ab	4.6 ± 1.0 c–e	207.4 ± 46.6 b	6.3 ± 3.8 cd	437.5 ± 267.3 c
		4	6.0 ± 2.6 a	12.8 ± 5.1 ab	5.0 ± 0.0 c–e	282.3 ± 29.8 b	11.3 ± 4.4 bc	758.3 ± 279.8 bc
		6	5.7 ± 4.1 a	17.7 ± 4.3 ab	5.0 ± 0.0 c–e	223.4 ± 65.0 b	8.8 ± 2.1 cd	507.5 ± 211.0 bc
Azoxystrobin + benzovindiflupyr	0.5 g·L^{-1}	2	6.3 ± 4.0 a	14.1 ± 9.4 ab	5.4 ± 1.0 cd	235.4 ± 89.0 b	11.7 ± 8.3 b–d	714.6 ± 507.3 bc
		4	4.0 ± 2.7 a	11.9 ± 6.3 ab	5.8 ± 2.0 c	245.6 ± 42.3 b	10.4 ± 5.6 b–d	673.8 ± 366.8 bc
		6	7.0 ± 4.7 a	21.8 ± 5.6 a	7.9 ± 1.9 b	325.8 ± 119.3 b	14.2 ± 3.8 b	1073.3 ± 197.9 b
Nontreated control			3.3 ± 2.2 a	18.6 ± 6.4 ab	17.5 ± 5.2 a	690.1 ± 122.8 a	45.8 ± 5.8 a	2242.9 ± 141.5 a
P			0.5206	0.0029	<0.0001	<0.0001	<0.0001	<0.0001
F			0.93	2.9	27.73	17.94	22.31	16.16

[i] Height increase = final height – initial height.
[ii] Width increase = [(final widest width – initial widest width) + (final perpendicular width – initial perpendicular width)] ÷ 2.
[iii] Final defoliation and powdery mildew severity evaluation was performed on 8 May.
[iv] AUDPC (or AUDFC) = $\Sigma\{[(x_i + x_{i-1})/2](t_i - t_{i-1})\}$, where x_i is the disease severity rating (or defoliation ratings) at each evaluation time and $(t_i - t_{i-1})$ is the number of days between evaluations.
[v] Means followed by a different lowercase letter within a column are significantly different ($P \leq 0.05$). One-way analysis of variance was used to evaluate treatment effects on height increase, width increase, AUDFC, and AUDPC. Means were compared using Fisher's least significant difference test with an $\alpha = 0.05$. Percent data (final defoliation and severity) were analyzed according to general linear mixed model with a logit link and beta distribution (PROC GLIMMIX).
AUDPC = area under the disease progress curve; AUDFC = area under the defoliation progress curve.

difenoconazole at the 6-week interval had the highest height increase. The percent increase between the means was 425.0%. Treatments of the medium rate of pydiflumetofen + difenoconazole at the 4-week interval had the lowest width increase and the high rate of pydiflumetofen + difenoconazole at the 6-week interval had the largest width increase. The percent increase between these means was 388.2% (Table 4).

The two-way ANOVA showed that there was no effect of application rate, application interval, and application rate × interval interaction on final disease severity and AUDPC (Table 2). Application rate and application interval had a significant effect on plant height, whereas application rate × interval interaction had a significant effect on plant width. In addition, no significant effects on defoliation or AUDFC by application rate, interval, or rate × interval interaction were recorded. Final defoliation and AUDFC were similar among treatments (Table 2).

In 2023, the nontreated control had significantly greater a final disease severity of 60.8%. All fungicide treatments significantly reduced final disease severity, AUDPC, defoliation and AUDFC compared with the nontreated control

Table 4. Fungicide effects on plant growth, defoliation (0% to 100% defoliation), AUDFC, final powdery mildew (*Golovinomyces orionti*) severity (0% to 100% affected) and AUDPC of bigleaf hydrangea (*Hydrangea macrophylla*) grown in a shade house from Jun to Oct 2022.

Treatment	Application rate	Application interval (weeks)	Ht increase (cm)[i]	Width increase (cm)[ii]	Final defoliation (%)[iii]	AUDFC[iv]	Final severity (%)[iii]	AUDPC[iv]
Pydiflumetofen + difenoconazole	1.1 ml·L^{-1}	2	5.3 ± 0.7 ab[v]	6.1 ± 1.3 a–c	3.8 ± 0.9 b	139.5 ± 17.2 b	14.2 ± 3.7 bc	708.6 ± 134.9 bc
		4	2.7 ± 0.8 b–d	8.1 ± 1.1 ab	5.8 ± 1.1 b	242.3 ± 27.9 b	14.2 ± 3.6 bc	634.8 ± 96.2 bc
		6	2.2 ± 0.8 cd	3.9 ± 1.0 cd	5.2 ± 1.6 b	182.5 ± 39.6 b	9.6 ± 1.4 bc	519.8 ± 77.5 bc
	1.6 ml·L^{-1}	2	1.2 ± 0.8 d	7.4 ± 2.1 a–c	4.6 ± 0.4 b	207.3 ± 23.0 b	9.6 ± 1.4 bc	519.6 ± 75.2 bc
		4	2.3 ± 0.8 cd	1.7 ± 0.4 d	4.2 ± 1.4 b	168.7 ± 44.6 b	16.7 ± 5.4 b	826.2 ± 211.3 b
	2.2 ml·L^{-1}	6	3.0 ± 1.2 b–d	4.1 ± 1.2 b–d	5.8 ± 1.4 b	187.3 ± 30.0 b	14.2 ± 4.8 bc	581.9 ± 151.5 bc
		2	4.8 ± 1.2 a–c	8.1 ± 2.2 ab	3.8 ± 0.6 b	147.0 ± 9.9 b	8.8 ± 2.1 c	429.9 ± 104.4 c
		4	2.7 ± 0.6 b–d	3.6 ± 1.2 cd	4.3 ± 1.3 b	188.3 ± 38.7 b	10.0 ± 0.0 bc	558.5 ± 27.7 bc
		6	6.3 ± 1.8 a	8.3 ± 1.6 a	5.4 ± 1.2 b	200.2 ± 33.6 b	10.8 ± 1.9 bc	591.7 ± 38.5 bc
Azoxystrobin + benzovindiflupyr	0.5 g·L^{-1}	2	3.5 ± 1.0 a–d	4.7 ± 1.5 a–d	5.8 ± 1.7 b	189.9 ± 53.6 b	11.7 ± 3.3 bc	610.1 ± 165.4 bc
		4	1.2 ± 0.8 d	3.6 ± 1.3 cd	5.8 ± 1.4 b	211.0 ± 45.3 b	11.7 ± 3.1 bc	641.0 ± 137.5 bc
		6	4.2 ± 1.5 a–c	5.7 ± 1.4 a–d	5.0 ± 2.0 b	190.5 ± 50.1 b	12.1 ± 3.1 bc	563.8 ± 124.6 bc
Nontreated control			4.2 ± 0.7 a–c	3.5 ± 1.5 cd	17.5 ± 2.5 a	523.5 ± 61.1 a	45.0 ± 8.6 a	2006.6 ± 234.5 a
P			0.0157	0.0178	<0.0001	<0.0001	<0.0001	<0.0001
F			2.31	2.27	7.46	6.11	7.00	8.88

[i] Height increase = final height – initial height.
[ii] Width increase = [(final widest width – initial widest width) + (final perpendicular width – initial perpendicular width)] ÷ 2.
[iii] Final defoliation and powdery mildew severity evaluation was performed on 6 Oct.
[iv] AUDPC (or AUDFC) = $\Sigma\{[(x_i + x_{i-1})/2](t_i - t_{i-1})\}$, where x_i is the disease severity rating (or defoliation ratings) at each evaluation time and $(t_i - t_{i-1})$ is the number of days between evaluations.
[v] Means followed by a different lowercase letter within a column are significantly different ($P \leq 0.05$). One-way analysis of variance was used to evaluate treatment effects on height increase, width increase, AUDFC, and AUDPC. Means were compared using Fisher's least significant difference test with an $\alpha = 0.05$. Percent data (final defoliation and severity) were analyzed according to General Linear Mixed Model with a logit link and beta distribution (PROC GLIMMIX).
AUDPC = area under the disease progress curve; AUDFC = area under the defoliation progress curve.

(Table 5). Although many of the treatments were similar, treatments of pydiflumetofen + difenoconazole at the 2- and 6-week interval at the medium rate provide the best control for the AUDPC. Treatments of pydiflumetofen + difenoconazole at the 2-week interval at the medium rate and the 4-week interval of the high rate provided the best control of final disease severity. The lowest rate of pydiflumetofen + difenoconazole at the 2-week interval had the lowest amount of final defoliation. Many of the treatments were similar in AUDFC. Height and width increase among treatments and nontreated control were not significantly different. (Table 5).

The two-way ANOVA showed a significant effect of application rate but not for application interval and application rate × interval interaction on final disease severity and AUDPC (Table 2). Application rate, interval, or rate × interval interaction also did not significantly differ for on defoliation, AUDFC, plant height, and width (Table 2).

Discussion

Powdery mildew is a major threat to the production of hydrangea. The fungicide azoxystrobin + benzovindiflupyr (Mural) is commonly recommended for the management of this disease, while pydiflumetofen (6.9%) + difenoconazole (11.5%) (Postiva) is a recently released fungicide, with components belonging to Fungicide Resistance Action Committee (FRAC) mode of action (MOA) Groups 7 and 3, respectively (FRAC 2022). Pydiflumetofen is classified as a succinate-dehydrogenase inhibitor (SDHI), which prevents the growth of fungi by blocking the enzyme involved in fungal cell respiration. Difenoconazole, the demethylation inhibitor fungicide, hinders fungal growth through the inhibition of ergosterol biosynthesis, which is an essential component of the plasma membrane of certain fungi. Once applied, pydiflumetofen + difenoconazole moves into the wax layer of the leaf to create a layer of protection. Pydiflumetofen + difenoconazole slowly penetrates and spreads throughout plant tissue within 24 h of application. Initial spore germination, penetration, and mycelial growth are also prevented by pydiflumetofen + difenoconazole (Syngenta 2022). The combination of these MOAs allows for a defense against multiple pathogens as well as aiding to prevent resistance development (Syngenta 2022). Mural is composed of azoxystrobin (30%), a strobilurin fungicide in MOA Group 11, and benzovindiflupyr (15%) (also known as solatenol), a succinyl dehydrogenase inhibitor in MOA Group 7. Azoxystrobin is a systemic that moves throughout the plant and can even provide extended protection for new plant growth. Azoxystrobin also provides plant health benefits by affecting physiological processes. Some benefits are lower transpiration rates, ethylene production reduction and increased efficiency for photosynthesis. Benzovindiflupyr is also an SDHI that is attracted to the binding site in the mitochondria of fungal cells. Azoxystrobin + benzovindiflupyr blocks this site, which stops the mitochondria processes, and fungi cannot survive (Syngenta 2021). Both fungicides are recommended to control fungal diseases on ornamental crops.

In the current study, the effectiveness of pydiflumetofen + difenoconazole was compared with the fungicide azoxystrobin + benzovindiflupyr over a range of application rates and intervals, as well as with a negative control. All application rates and intervals of pydiflumetofen + difenocozazole (Postiva) were effective in controlling both powdery mildew disease severity and progress in bigleaf hydrangea (both in the greenhouse and shade house) compared with the nontreated control. Furthermore, in the current study, pydiflumetofen + difenoconazole was as effective as the standard fungicide azoxystrobin + benzovindiflupyr for controlling powdery mildew. In an earlier study, pydiflumetofen + difenoconazole at 0.8 to 2.2 mL·L^{-1} significantly reduced powdery mildew and spot anthracnose of dogwood (*Cornus florida* 'Cherokee Princess') under shade house conditions (56% shade) (Baysal-Gurel 2021). As such, pydiflumetofen + difenoconazole is an effective alternative fungicide to azoxystrobin + benzovindiflupyr or can be included in the rotation program for controlling powdery mildew on bigleaf hydrangea.

In the current study, pydiflumetofen + difenoconazole was tested in three rates (low, medium, and high rates) and intervals (2, 4, and 6 weeks) for controlling powdery mildew of bigleaf hydrangea. Fungicides can pose a risk to the environment by residues persisting in soils and waterways (Wightwick et al. 2010). There is also the risk of fungicide resistance if fungicides are not properly used and rotated (Corkley et al. 2021). Providing fungicides that have multiple MOAs is more ideal than using single-site MOA fungicides (van den Bosch et al. 2014). Reducing the amount of active ingredient applications should be the major objective of current fungicide efficacy studies because such practices can reduce the environmental impact and could also reduce the cost to growers. The amount of fungicide applied can be reduced

Table 5. Fungicide effects on plant growth, defoliation (0% to 100% defoliation), AUDFC, final powdery mildew (*Golovinomyces orontii*) severity (0% to 100% affected) and AUDPC of bigleaf hydrangea (*Hydrangea macrophylla*) grown in a shade house from May to Aug 2023.

Treatment	Application rate	Application interval (weeks)	Ht increase (cm)[i]	Width increase (cm)[ii]	Final defoliation (%)[iii]	AUDFC[iv]	Final severity (%)[iii]	AUDPC[iv]
Pydiflumetofen + difenoconazole	1.1 mL·L^{-1}	2	1.5 ± 1.4 a[v]	2.2 ± 1.8 a	1.8 ± 1.8 d	62.7 ± 52.7 b	6.7 ± 3.0 de	268.9 ± 140.3 bc
		4	1.7 ± 1.5 a	3.3 ± 2.1 a	3.9 ± 3.2 b–d	140.9 ± 102.8 b	8.3 ± 4.4 de	294.6 ± 187.1 bc
		6	2.7 ± 1.4 a	3.8 ± 1.0 a	2.8 ± 1.8 b–d	128.3 ± 81.7 b	9.2 ± 3.4 cde	331.3 ± 146.8 bc
	1.6 mL·L^{-1}	2	1.7 ± 1.6 a	1.8 ± 0.98 a	2.7 ± 2.0 b–d	118.4 ± 97.8 b	5.6 ± 3.4 e	224.9 ± 142.5 c
		4	2.8 ± 4.3 a	3.3 ± 1.6 a	3.5 ± 2.3 b–d	145.8 ± 95.2 b	8.1 ± 4.8 de	313.0 ± 184.0 bc
		6	3.2 ± 1.5 a	2.5 ± 1.1 a	4.6 ± 2.5 bc	191.3 ± 134.4 ab	7.9 ± 4.0 de	246.5 ± 112.0 c
	2.2 mL·L^{-1}	2	0.67 ± 0.52 a	3.6 ± 4.4 a	2.8 ± 1.8 b–d	118.4 ± 57.5 b	9.2 ± 4.7 de	317.3 ± 140.8 bc
		4	1.0 ± 0.89 a	4.3 ± 2.2 a	4.8 ± 2.6 b–d	185.8 ± 114.0 ab	6.8 ± 3.8 e	318.0 ± 163.2 bc
		6	1.7 ± 1.0 a	3.2 ± 2.0 a	3.1 ± 2.7 b–d	125.1 ± 99.9 b	8.3 ± 3.8 de	310.3 ± 118.0 bc
Azoxystrobin + benzovindiflupyr	0.5 g·L^{-1}	2	1.8 ± 1.2 a	2.2 ± 1.1 a	3.5 ± 2.3 b–d	143.5 ± 95.6 b	11.7 ± 5.8 cd	413.0 ± 118.3 bc
		4	2.0 ± 1.1 a	3.4 ± 1.2 a	2.4 ± 1.5 cd	115.8 ± 75.6 b	14.6 ± 5.1 bc	499.6 ± 132.2 bc
		6	1.8 ± 1.5 a	2.2 ± 1.0 a	5.0 ± 2.2 b	200.1 ± 123.5 ab	17.5 ± 5.2 b	678.4 ± 178.3 b
Nontreated control			1.8 ± 1.2 a	2.9 ± 1.7 a	14.2 ± 5.6 a	385.6 ± 157.7 a	60.8 ± 9.7 a	2548.9 ± 571.6 a
P			0.4596	0.5738	<0.0001	0.0012	<0.0001	<0.0001
F			1	0.88	8.2	3.2	34.08	50.8

[i] Height increase = final height – initial height.

[ii] Width increase = [(final widest width – initial widest width) + (final perpendicular width – initial perpendicular width)] ÷ 2.

[iii] Final defoliation and powdery mildew severity evaluation was performed on 10 Aug.

[iv] AUDPC (or AUDFC) = $\Sigma\{[(x_i + x_{i-1})/2](t_i - t_{i-1})\}$, where x_i is the disease severity rating (or defoliation ratings) at each evaluation time and $(t_i - t_{i-1})$ is the number of days between evaluations.

[v] Means followed by a different lowercase letter within a column are significantly different ($P \leq 0.05$). One-way analysis of variance was used to evaluate treatment effects on height increase, width increase, AUDFC, and AUDPC. Means were compared using Fisher's least significant difference test with an $\alpha = 0.05$. Percent data (final defoliation and severity) were analyzed according to general linear mixed model with a logit link and beta distribution (PROC GLIMMIX).

AUDPC = area under the disease progress curve; AUDFC = area under the defoliation progress curve.

either by reducing the application rate or by reducing the number of applications per crop growing season. In the current study, the low rate of pydiflumetofen + difenoconazole was as effective as the medium and high rate of pydiflumetofen + difenoconazole in both greenhouse and shade house in 2022 and 2023. Interestingly, the low rate of pydiflumetofen + difenoconazole was more effective than high rate of pydiflumetofen + difenoconazole in reducing powdery mildew in one greenhouse trial. No significant differences were noted between the different application intervals of pydiflumetofen + difenoconazole and azoxystrobin + benzovindiflupyr in final disease severity and progress. Hydrangea growth was minimally affected during these trials, which may be due to the short trial duration or reduced disease pressure. Differing growth among these trials can be attributed to conditions and time of year that the trial was conducted. Prolonged powdery mildew symptoms can negatively impact photosynthesis, shoot growth, defoliation, and stunt plant growth (Amiri n.d.; Hagan 2022). Plants remain in nurseries for a longer period than herein, and negative impacts on the growth of a plant by disease are often reported.

Improper use of a fungicide via excessive application is a problem in many production systems. In the current study, the low rate of pydiflumetofen + difenoconazole provided similar or better protection of hydrangea from powdery mildew compared with the medium and high rates of pydiflumetofen + difenoconazole and azoxystrobin + benzovindiflupyr. Likewise, the 6-week application interval provided a similar powdery mildew disease control compared with the 2- and 4-week application intervals. It can be recommended that growers and landscapers use the lowest application rate at the longest interval tested in this study.

Shade houses and greenhouses are a primary way that hydrangeas are produced in Tennessee. Conducting trials in both conditions allowed better insight on powdery mildew infection of hydrangea and ways to combat powdery mildew fungicide resistance using multisite MOA fungicides. Disease in both conditions was similar, which indicates that both were able to provide ideal conditions for powdery mildew development. These results show that being able to treat and control powdery mildew in greenhouses and shade houses is important. This research can aid in developing or supplementing a fungicide rotation program for powdery mildew of hydrangea.

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