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Growth Control of Five Floriculture Species Using Paclobutrazol Liner Root Soaks

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Abstract
Applying plant growth regulators (PGRs) as pre-transplant liner root soaks offers floriculture growers an effective method of growth control in their crops. Five bedding plant species received a liner root soak with different paclobutrazol concentrations depending on their sensitivity to this PGR. Fuchsia and New Guinea impatiens were considered highly sensitive species while alternanthera, lantana, and coleus were considered moderately sensitive species. Rooting cubes of these liners were soaked, transplanted, and measured biweekly to determine optimal concentrations over time. After 6 weeks, concentrations of 0.5–4 $mg \cdot L^{-1}$ paclobutrazol were sufficient to minimize growth in most cultivars. Alternanthera growth was minimized with slightly higher concentrations of 6.5 $mg \cdot L^{-1}$ paclobutrazol, while coleus required >32 $mg \cdot L^{-1}$ paclobutrazol to minimize growth. This study provides paclobutrazol liner root soak recommendations for five cultivars of different floriculture crops, and highlights some of the differences among crop sensitivities to paclobutrazol liner root soaks.
Keywords**: Alternanthera, Coleus, Fuchsia, Impatiens, Lantana, PGR.**

1. Introduction

Chemical plant growth regulators (PGRs) are commonly used to manage excessive stem elongation in floriculture crop production (Whipker, 2021). Pre-transplant PGR liner root soaks are an alternative method growers can use to control growth in vigorous floriculture crops (Blanchard and Runkle, 2007). Previous studies investigating PGR liner root soaks reported effective growth control in several species using paclobutrazol (Schnelle and Barrett, 2010), uniconazole (Blanchard and Runkle, 2007), and flurprimidol (Whipker et al., 2003). Growers can yield numerous benefits from PGR liner root soaks, such as increased efficacy and reduced chemical waste (Cerveny and Barrett, 2005).

Factors impacting the efficacy and growth response to liner root soaks include the depth of the PGR solution, concentration, substrate moisture, and time between treatment and transplant (Cerveny and Barrett, 2005; Schnelle and Barrett, 2010; Schnelle et al., 2005). For instance, greater PGR solution depth increased liner soak efficacy (Cerveny and Barrett, 2005). Other factors such as soak duration were previously found to have little effect on plant growth (Schnelle and Barrett, 2010). For these reasons, it is imperative that liner soak recommendations be made with the specific treatment and timing related factors under which they were conducted, to better standardize treatment protocol. Other work also suggests that optimal liner soak concentrations must be determined for a greater range of crops and cultivars (Schnelle and Barrett, 2010).

Several studies have reported PGR liner root soaks as an effective method of growth control (Blanchard and Runkle, 2007; Schnelle and Barrett, 2010; Whipker et al., 2003); however, few studies have reported the effect of liner soaks at different stages of production. Comparing liner soak efficacy at earlier growth stages may yield useful information that can be used in commercial production practices. For instance, annual combination baskets use several species of bedding plants within a single container. Highly vigorous plants can quickly outcompete other species growing in the same container, leading to non-uniform growth and ultimately reducing appeal to consumers (Cerveny and Barrett, 2005; Schnelle et al., 2005). With the increasing popularity of combination baskets, it is important to determine methods of growth control that can accommodate plants with varying levels of vigor. This study investigated the effects of paclobutrazol liner root soaks over time and to determine optimal paclobutrazol liner root soak concentrations for several common floriculture species.

2. Materials and Methods

2.1 Plant Materials

Alternanthera (*Alternanthera brasiliana* 'Brazilian Red Hots'), coleus (*Plectranthus scutellarioides* 'Stained Glassworks Molten Lava'), fuchsia (*Fuchsia* 'Arêtes Upright Arroyo Grande'), lantana, (*Lantana* x *hybrida* 'New Gold'), and New Guinea impatiens (*Impatiens hawkeri* 'Sunstanding Fire Red') cuttings (Dümmen Orange, Columbus, OH) were stuck in 128-cell plug flats with cell dimensions of 2.5 × 2.5 × 3.8 cm (length × width × depth) on 5 April. The plug flats were filled with Sunshine® Mix #1 (Sun Gro Horticulture, Agawam, MA), and placed under mist in a glass glazed greenhouse at North Carolina State University (Raleigh, NC). Greenhouse day/night temperature set points were 24/18°C, and plants were grown under natural photoperiod.

2.2 Treatments

Rooted liners were treated with a paclobutrazol (Piccolo 10XC; Fine Americas, Walnut Creek, CA) soak on 4 May depending on their relative sensitivity to paclobutrazol. Fuchsia and New Guinea impatiens were considered highly sensitive species and were soaked in paclobutrazol concentrations of 0, 0.5, 1, 2, 4, and 8 $mg·L^{-1}$. Alternanthera, lantana, and coleus were considered moderately sensitive and soaked in paclobutrazol concentrations of 0, 2, 4, 8, 16, and 32 $mg·L^{-1}$. The root systems of liners were soaked in the paclobutrazol solution for 2 min with 75% of the root system submerged, and were then placed on a bench.

2.3 Experimental Design

Soaked liners were transplanted 24 h after treatment into 12.7-cm diameter pots (Poppelmann Plastics USA LLC, Claremont, NC) filled with Sunshine® Mix #1. There were six single-plant replicates of each treatment. Each pot was thoroughly irrigated with clear water, and plants were then randomized and placed on a greenhouse bench. Plants were placed on automatic irrigation and fertilized with a 13N–0.86P–10.8K fertilizer mixed at 150 $mg·L^{-1}$ N. Biweekly measurements were taken for plant height by measuring from the substrate to the highest point on the plant. Diameter was averaged by measuring the widest point of the plant and its perpendicular axis. The study was terminated 6 weeks after transplant.

2.4 Statistical Analysis

Data were analyzed with SAS (version 9.4) and visualized with GraphPad Prism (version 7.02; GraphPad Software, Inc., La Jolla, CA). PROC MIXED was used to conduct an analysis of variance. Data were then subjected to PROC REG and PROC NLIN to determine the best-fit linear, quadratic, or quadratic plateau regression model based on adjusted-r^2 and the corrected Akaike Information Criterion (AICc) (Spiess and Neumeyer, 2010). Regression models were then used to find the vertex for quadratic models or X_0 value where the model plateaus for quadratic plateau models. These values indicate the paclobutrazol concentration at which each growth parameter was minimized, past which point no greater growth control was attained.

3. Results and Discussion

Regression models were determined for each cultivar at 2, 4, and 6 weeks after treatment (WAT) to better understand the PGR effect over time. Growth trends were then graphically compared at each biweekly measurement (Fig. 1). The *y*-intercept indicated the maximum growth achieved by non-treated control plants. The plateau or minimum value associated with each model indicated where the effect of paclobutrazol was maximized, and growth was minimized. These minimum and maximum growth values were used to determine the percent growth control at each biweekly measurement. Additionally, paclobutrazol liner soak recommendations were made for each cultivar by determining the point on each regression model where total height control reached 50% of the maximum height control potential. This paclobutrazol concentration would result in plants that were roughly average the minimum and maximum height by the end of the study.

3.1 Alternanthera

Regression models for ‘Brazilian Red Hots’ alternanthera height indicated that the effect of paclobutrazol was limited 2 WAT, but became more prominent 4 and 6 WAT (Fig. 1A). Alternanthera height was minimized with 20.6, 2.8, and 6.5 $mg·L^{-1}$ paclobutrazol at 2, 4, and 6 WAT, respectively (Table 1). The high paclobutrazol concentration required to minimize growth 2 WAT was likely because there was little difference in height among treatments and the selected model provided a poor fit. The paclobutrazol concentrations required to minimize height controlled height by 63, 69, and 67% at 2, 4, and 6 WAT, respectively (Table 1). Alternanthera diameter (Fig. 1B) was minimized with 2.4, 2.9, and 6.5 $mg·L^{-1}$ paclobutrazol at 2, 4, and 6 WAT, respectively (Table 2). These paclobutrazol concentrations controlled diameter by 26, 48, and 51% at 2, 4, and 6 WAT, respectively (Table 2).

This demonstrates that paclobutrazol liner soaks had a greater effect on height than on diameter of 'Brazilian Red Hots' alternanthera. Additionally, the PGR effect wore off over time as the liner soak concentrations required to minimize height and diameter increased between 4 and 6 WAT. Growers should use liner soaks of ≤2 mg·L^{-1} paclobutrazol to prevent excessive stunting.

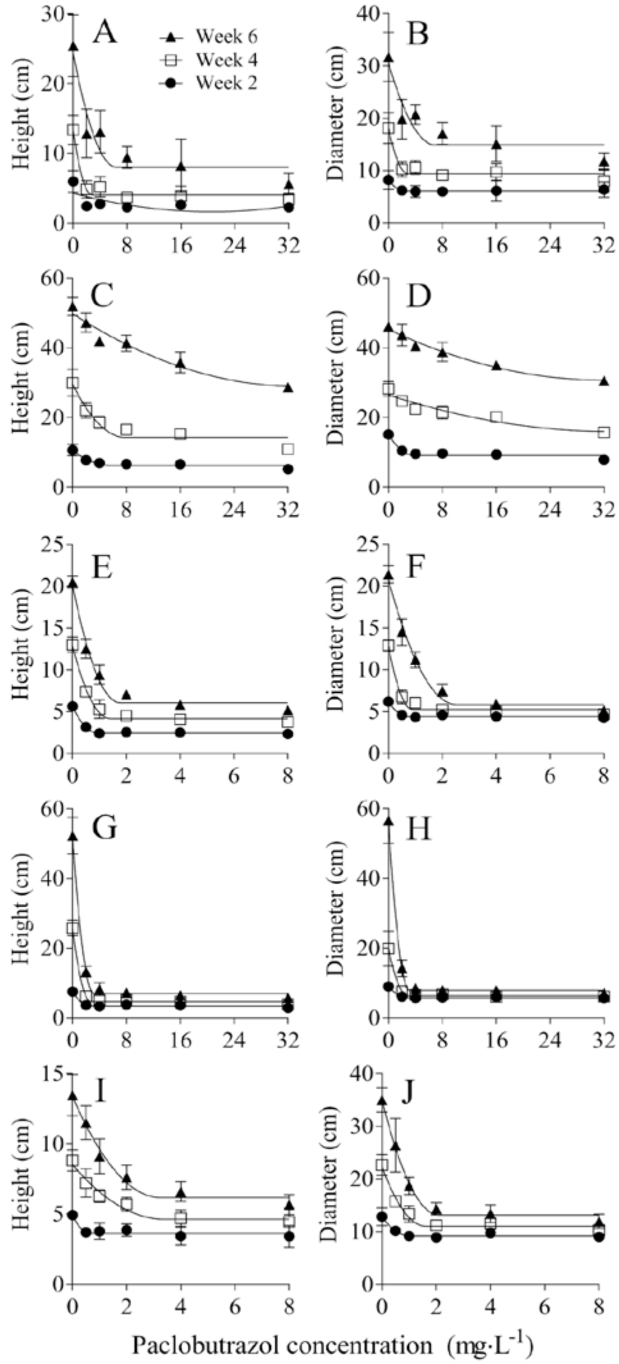

Figure 1. Regression models representing biweekly measurements of height and diameter, respectively, for 'Brazilian Red Hots' alternanthera (A and B), 'Stained Glassworks Molten Lava' coleus (C and D), 'Arêtes Upright Arroyo Grande' fuchsia (E and F), 'New Gold' lantana (G and H), and 'Sunstanding Fire Red' New Guinea impatiens (I and J).

Table 1. Best fit (Adj-r^2 and AICc[1]) quadratic (Q) or quadratic plateau (QP) regression models for alternanthera, coleus, fuchsia, lantana, and New Guinea impatiens height. Paclobutrazol concentrations required to reach the model minimum are indicated by X_0 or vertex values with the associated plateau or minimum of the selected regression equation.

Week	Model	Regression equation[2]	X_0 / Vertex	Plateau / Minimum	Adj–r^2	AICc
Alternanthera						
2	Q	$4.3 - 0.258x + 0.00625x^2$	20.6	1.6	0.30	22.2
4	QP	$13.4 - 6.61x + 1.175x^2$	2.8	4.1	0.85	31.6
6	QP	$24.4 - 5.07x + 0.3921x^2$	6.5	8.0	0.72	100.5
Coleus						
2	QP	$10.6 - 1.47x + 0.1229x^2$	6.0	6.2	0.73	8.1
4	QP	$29.7 - 3.90x + 0.2472x^2$	7.9	14.3	0.82	77.4
6	Q	$49.8 - 1.25x + 0.01873x^2$	33.4	28.9	0.87	80.4
Fuchsia						
2	QP	$5.7 - 6.81x + 3.627x^2$	0.9	2.5	0.93	-77.1
4	QP	$12.9 - 12.53x + 4.506x^2$	1.4	4.2	0.95	-12.3
6	QP	$20.2 – 16.0x + 4.522x^2$	1.8	6.1	0.96	11.2
Lantana						
2	QP	$7.6 - 3.08x + 0.5751x^2$	2.7	3.4	0.78	-8.7
4	QP	$25.9 - 15.43x + 2.819x^2$	2.7	4.7	0.98	19.0
6	QP	$52.3 - 28.35x + 4.436x^2$	3.2	7.0	0.98	70.1
New Guinea impatiens						
2	QP	$4.9 - 3.98x + 3.027x^2$	0.7	3.6	0.43	-37.5
4	QP	$8.5 - 2.28x + 0.3331x^2$	3.4	4.6	0.79	-13.5
6	QP	$13.4 - 4.45x + 0.6855x^2$	3.2	6.2	0.86	12.8

[1] Best fit statistics: Adj-r^2, adjusted coefficient of determination; AICc, corrected Akaike information criterion
[2] Models significant at $P \leq 0.0001$

3.2 Coleus

Regression models for 'Stained Glassworks Molten Lava' coleus height indicated that the effect of paclobutrazol was similar at weeks 2 and 4, but was drastically reduced 6 WAT (Fig. 1C). Coleus height was minimized with 6.0, 7.9, and >32 mg·L^{-1} paclobutrazol at 2, 4, and 6 WAT, respectively (Table 1). These paclobutrazol concentrations controlled height by 42, 52, and 42% at 2, 4, and 6 WAT, respectively (Table 1). Coleus diameter (Fig. 1D) was minimized with 3.8, >32, and 32 mg·L^{-1} paclobutrazol at 2, 4, and 6 WAT, respectively (Table 2). These paclobutrazol concentrations controlled diameter by 39, 40, and 32% at 2, 4, and 6 WAT, respectively (Table 2). Quadratic plateau models were not selected for height at 6 WAT or diameter at 4 or 6 WAT because the paclobutrazol concentration required to minimize growth was beyond the range of concentrations used in this study. This demonstrates that the PGR effect lessened over time for 'Stained Glassworks Molten Lava' coleus. The trend in percent growth control also alludes to the reduced PGR effect over time. Depending on the level of growth control desired, growers could use liner soaks of ≤8 mg·L^{-1} paclobutrazol to control growth without excessive stunting.

3.3 Fuchsia

Regression models for 'Arêtes Upright Arroyo Grande' fuchsia indicated that low paclobutrazol concentrations were required to control height (Fig. 1E). Fuchsia height was minimized with 0.9, 1.4, and 1.8 mg·L^{-1} paclobutrazol at 2, 4, and 6 WAT, respectively (Table 1). These paclobutrazol concentrations controlled height by 56, 67, and 79% at 2, 4, and 6 WAT, respectively (Table 1). Fuchsia diameter (Fig. 1F) was minimized with 0.7, 0.9, and 2.5 mg·L^{-1} paclobutrazol at 2, 4, and 6 WAT, respectively (Table 2). These paclobutrazol concentrations controlled diameter by 29, 66, and 70% at 2, 4, and 6 WAT, respectively (Table 2). Growth in terms of height and diameter was controlled with very low paclobutrazol concentrations. Growers should use a liner soak concentration of 0.5 mg·L^{-1} paclobutrazol to provide adequate growth control and prevent stunting.

Table 2. Best fit (Adj-r^2 and AICc[1]) quadratic (Q) or quadratic plateau (QP) regression models for alternanthera, coleus, fuchsia, lantana, and New Guinea impatiens diameter. Paclobutrazol concentrations required to reach the model minimum are indicated by X_0 or vertex values with the associated plateau or minimum of the selected regression equation.

Week	Model	Regression equation[2]	X_0 / Vertex	Plateau / Minimum	Adj–r^2	AICc
Alternanthera						
2	QP	$8.2 - 1.71x + 0.3512x^2$	2.4	6.1	0.23	26.4
4	QP	$18.2 - 6.03x + 1.036x^2$	2.9	9.4	0.74	53.0
6	QP	$30.6 - 4.46x + 0.3149x^2$	6.5	14.9	0.69	103.6
Coleus						
2	QP	$15.2 - 3.14x + 0.4099x^2$	3.8	9.2	0.84	4.9
4	Q	$26.5 - 0.63x + 0.0094x^2$	33.5	15.9	0.80	51.0
6	Q	$45.3 - 0.91x + 0.0142x^2$	32.0	30.7	0.87	56.0
Fuchsia						
2	QP	$6.2 - 4.89x + 3.314x^2$	0.7	4.4	0.80	-72.4
4	QP	$13.0 - 13.33x + 4.124x^2$	0.9	4.4	0.93	-5.5
6	QP	$19.7 - 13.18x + 3.069x^2$	2.5	5.9	0.95	21.9
Lantana						
2	QP	$9.0 - 2.18x + 0.3713x^2$	2.9	5.8	0.79	-29.5
4	QP	$20.0 - 9.36x + 1.617x^2$	2.9	6.4	0.86	56.6
6	QP	$56.7 - 31.15x + 4.977x^2$	3.1	7.9	0.98	81.7
New Guinea impatiens						
2	QP	$12.9 - 7.06x + 3.424x^2$	1.0	9.3	0.66	3.0
4	QP	$22.4 - 14.02x + 4.338x^2$	1.6	11.1	0.90	28.9
6	QP	$35.1 - 20.80x + 4.924x^2$	2.1	13.2	0.91	74.6

[1] Best fit statistics: Adj-r^2, adjusted coefficient of determination; AICc, corrected Akaike information criterion
[2] Models significant at $P \leq 0.0001$

3.4 Lantana

Regression models for 'New Gold' lantana height indicated that the effect of paclobutrazol remained similar throughout the study (Fig. 1G). Lantana height was minimized with 2.7, 2.7, and 3.2 mg·L^{-1} paclobutrazol at 2, 4, and 6 WAT, respectively (Table 1). These paclobutrazol concentrations controlled height by 55, 82, and 87% at 2, 4, and 6 WAT, respectively (Table 1). Lantana diameter (Fig. 1H) was minimized with 2.9, 2.9, and 3.1 mg·L^{-1} paclobutrazol at 2, 4, and 6 WAT, respectively (Table 2). These paclobutrazol concentrations controlled diameter by 36, 68, and 86% at 2, 4, and 6 WAT, respectively (Table 2). The high level of growth control attained for 'New Gold' lantana indicates that paclobutrazol liner soaks may not be appropriate for this cultivar. The lowest concentration of 2 mg·L^{-1} paclobutrazol resulted in significant stunting that nearly halted growth over the 6-week study. It is possible that lower concentrations near 0.5 mg·L^{-1} paclobutrazol could provide beneficial growth control, indicating further studies are required to refine paclobutrazol liner soak recommendations for 'New Gold' lantana.

3.5 New Guinea impatiens

Regression models for 'Sunstanding Fire Red' New Guinea impatiens indicated that low paclobutrazol concentrations were required to control height (Fig. 1I). New Guinea impatiens height was minimized with 0.7, 3.4, and 3.2 mg·L^{-1} paclobutrazol at 2, 4, and 6 WAT, respectively (Table 1). These paclobutrazol concentrations controlled height by 27, 46, and 54% at 2, 4, and 6 WAT, respectively (Table 1). New Guinea impatiens diameter

(Fig. 1J) was minimized with 1.0, 1.6, and 2.1 mg·L^{-1} paclobutrazol at 2, 4, and 6 WAT, respectively (Table 2). These paclobutrazol concentrations controlled diameter by 28, 50, and 62% at 2, 4, and 6 WAT, respectively (Table 2). The relative growth control between the treated and control plants attained at each week increased with time, indicating that the liner soak maintained a high level of efficacy over 6 weeks. Growers wishing to provide moderate growth control to 'Sunstanding Fire Red' New Guinea impatiens should use liner soaks of 0.5–1 mg·L^{-1} paclobutrazol to prevent significant stunting.

3.6 Discussion

One of the primary functions of this study was to observe the trends in PGR effect over time. For the first several weeks, growth was typically similar among all PGR treated plants; however, the PGR effect wore off over time, enabling plants grown with lower paclobutrazol concentrations to attain greater size than plants grown with the highest paclobutrazol concentration. Liner soaks maintained high levels of growth control in some cultivars throughout the entire study, while other cultivars rapidly outgrew the PGR effect. For instance, the percent difference in size between treated and non-treated 'New Gold' lantana broadened over time, while the percent difference for 'Stained Glassworks Molten Lava' coleus was similar at 2 and 6 WAT. This indicates that the liner soak maintained a greater effect for lantana than it did for coleus. If these two cultivars were each treated with a paclobutrazol liner soak and planted in a combination basket, the coleus would likely overcome the PGR effect faster than the lantana, and the coleus would likely dominate the container.

Liner soak concentrations ranging from 0.5–8 mg·L^{-1} paclobutrazol were determined to be optimal for the five cultivars grown in this study. This range was somewhat lower than the optimal concentrations reported by Blanchard and Runkle (2007), who reported optimal concentrations of 4–12 mg·L^{-1} paclobutrazol depending on species. One reason for this difference may be that the cultivars selected for our study were more sensitive to paclobutrazol than the cultivars selected by Blanchard and Runkle (2007). Additionally, the liner soak duration in our study was four times greater than the duration used by Blanchard and Runkle (2007). Both of these factors may have led to lower paclobutrazol liner soak concentrations.

The regression models determined by Blanchard and Runkle (2007) did not indicate that maximum growth control was attained within the range of paclobutrazol concentrations that were used. Similarly, regression models reported by Whipker et al. (2003) demonstrated that paclobutrazol treated plants typically exhibited a linear growth response up to 16 mg·L^{-1} paclobutrazol. By the end of our study, every species except for coleus attained maximum growth control with lower concentrations than 16 mg·L^{-1} paclobutrazol. This may again indicate that the cultivars selected in our study were generally more sensitive to paclobutrazol than those selected in other studies. Additionally, our recommendations were made under the assumption that maximum growth control would be considered excessive by growers, and were therefore based on 50% of the maximum efficacy. This likely led to our recommendations being lower than those suggested in previous studies.

4. Conclusions

Optimal paclobutrazol liner root soak concentrations were determined for several floriculture cultivars. The optimal concentration varied among species, indicating varying levels of sensitivity to paclobutrazol. Fuchsia, lantana, and New Guinea impatiens were all relatively sensitive to the liner soak, and ultimately performed best with ≤1 mg·L^{-1} paclobutrazol. Alternanthera was less sensitive, and could perform well with ≤2 mg·L^{-1} paclobutrazol. Coleus was the least sensitive crop in this study, performing well after receiving a liner soak of ≤8 mg·L^{-1} paclobutrazol. In addition, the regression models determined at earlier growth stages demonstrate how each cultivar responded to different paclobutrazol concentrations over time. This information is particularly useful for combination basket growers that want to use liner soaks to achieve similar levels of vigor in plants that naturally vary in vigor to limit competition and promote uniformity.

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