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# Identifying the Temporal Sensitivity of Poinsettia Flowering to High Temperatures

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***Abstract.*** **The objective of this study was to identify the specific weeks and night lengths when poinsettia (*Euphorbia pulcherrima* Willd. ex Klotzsch) flowering is most sensitive to high temperatures. One experiment was conducted in greenhouses under natural daylength (ND) conditions at lat. 34.7°N starting on 4 Sep, and a second experiment was conducted in growth chambers with an initial night length (NL) of 11 hours 01 minutes that was increased by 2 min/d to simulate ND conditions through September and October. Each week, one group of plants was moved from a moderate-temperature environment [22 °C average daily temperature (ADT)] to a high-temperature environment 28 °C ADT. Each group of plants spent 1 week in the high-temperature environment before returning to the moderate-temperature environment. The temperature treatments lasted for 7 or 8 weeks for the growth chamber and greenhouse studies, respectively. Additional groups of plants were kept in either the moderate- or high-temperature environment for the entire treatment period as controls. Four cultivars were used in the greenhouse study: Advent Red, Freedom Red, Prestige Red, and Tikal Red; only Prestige Red was used in the growth chamber study. Advent Red was identified as the most heat-tolerant cultivar followed by Tikal Red, Freedom Red, and Prestige Red. 'Advent Red's' period of sensitivity to high temperatures ranged from 4 Sep to 1 Oct. 'Tikal Red's' period of sensitivity to high temperature ranged from 11 Sep to 8 Oct. 'Freedom Red' had a longer period of high-temperature sensitivity: from 11 Sep to 22 Oct. 'Prestige Red' had the longest period of sensitivity to high temperatures encompassing 4 Sep to 29 Oct, and 11 hours 01 minute to 12 hours 37 minutes NL for the greenhouse and growth chamber studies, respectively. Within periods of sensitivity to high temperatures, time to visible bud and anthesis were most affected by high temperatures in earlier weeks, and final bract color development and time to first bract color were more affected by high temperatures during the latter weeks. As cultivars varied in their duration of sensitivity to high temperatures, duration, as well as magnitude of response to high temperature, should be considered in future breeding projects.**

Poinsettia is a short day (SD) plant with an estimated critical NL between 11 h 0 min and 11 h 45 min depending on temperature and cultivar (Larson and Langhans 1962). Therefore, floral initiation typically occurs between mid-September and early-October under ND conditions in the contiguous United States (lat. 24.5°N to 49.4°N). High temperatures during the production season can cause delays to flowering, a phenomenon known as heat delay (Ecke et al. 2004). As a contemporary symbol of Christmas, the poinsettia wholesale market is concentrated to a relatively brief period from early-November through early-December. This narrow sales window puts poinsettia growers at risk to delays in flowering, especially because climate change is creating unusual weather patterns (Horton et al. 2016). Therefore, it is increasingly important for growers to know the precise time in the production season that their crop is susceptible to heat delay to mitigate its impact.

Schnelle et al. (2005) grew several poinsettia cultivars at either a 13-h NL or natural SDs (lat. 29.7°N) starting on 30 Sep. For the first 28 d of the inductive photoperiod, plants were provided either a high-temperature [28 °C day temperature (DT)/24 °C night temperature (NT)] or a moderate-temperature (24/21 °C DT/NT) environment. High temperatures caused significant delays to visible bud, bract color formation, and anthesis in mid- to late-season cultivars, such as Prestige Red and Success Red, whereas early-season cultivars such as Early Freedom Red and Orion were not delayed by the high-temperature treatments. An additional experiment was performed in which 'Prestige Red' and 'Freedom Red' were exposed to the same high-temperature environment (28/24 °C DT/NT) for 7, 14, or 21 d starting 22 Sep, after which they were finished in a moderate-temperature environment (24/21 °C DT/NT). 'Prestige Red' experienced delays to anthesis of 3, 6, and 10 d from plants receiving 7, 14, or 21 d of high temperatures, respectively, whereas shorter delays were experienced by 'Freedom Red'. Because floral initiation generally occurs within the first 2 to 3 weeks of receiving an inductive photoperiod (Goddard 1960; Miller and Kiplinger 1962; Struckmeyer and Beck 1960), the delays observed in these experiments are due to a high-temperature inhibition of floral initiation and early stages of floral development.

Schnelle (2008) exposed plants under ND conditions (29.7°N), starting on 1 Sep, to a high-temperature treatment (29/24 °C DT/NT) for 2, 3, or 4 weeks at different points between 12 Sep and 8 Nov. A 28-d period of sensitivity to high temperatures was identified from 12 Sep to 10 Oct. High-temperature treatments provided after this window of sensitivity did not negatively affect time to flower. However, because high-temperature treatments lasted for at least 2 weeks and often overlapped, it is unclear what specific weeks contributed to heat delay.

The objective of this study was to identify specific weeks and NLs of sensitivity to high temperatures for several cultivars grown under ND conditions. Our hypothesis was that sensitivity to high temperatures coincides with floral initiation and that 1 day of high temperatures causes 1 day of delayed flowering.

## Materials and Methods

*General practices.* Cuttings were propagated in a foam medium (Oasis Rootcubes Plus Wedge; Smithers-Oasis, Kent, OH, USA) for 4 weeks under night-interruption lighting (2200 HR to 0200 HR) consisting of LED bulbs that delivered 1.2 ± 0.2 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Cuttings were then transplanted into 1.33-L pots containing a peat-based growing medium (Fafard 3B; Sun Gro, Anderson, SC, USA). One week after

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transplant, plants were pinched to five nodes, and after an additional 2 weeks, lateral shoots were removed so that two uniform shoots remained on each plant.

The plants were continuously fertigated with Peters Excel Cal-Mag Special (15N–5$P_2O_5$–15$K_2O$) at 150 mg·$L^{-1}$ N for the duration of the experiment. Temperature measurements were collected every 15 s and averaged into 15-min increments by a weather station (Silent Sentinel; Apogee Instruments, North Logan, UT, USA) placed at canopy height. Photosynthetic photon flux density and daily light integrals (DLI) were measured with a full-spectrum quantum sensor (SQ-500-SS; Apogee Instruments) connected to a datalogger (μCache Bluetooth Micro Logger; Apogee Instruments) placed at canopy height. Before the start of experimental treatments, two fungicide drenches, azoxystrobin and etridiazole, were applied as preventive measures for controlling rhizoctonia stem rot and pythium root rot, respectively, while cyantraniliprole, dinotefuran, thiamethoxam, and pymetrozine were used for whitefly control.

*Cultivars.* Four cultivars were used in this study: Advent Red, Tikal Red, Freedom Red, and Prestige Red. Advent Red was chosen as it is a very early season cultivar, ready to market ~3 Nov under ND conditions. It is also considered in the industry to be tolerant to high temperatures. 'Tikal Red', a sibling variety to 'Advent Red', was chosen as it has a similar phenotype as 'Advent Red' but flowers ~10 d later. It is considered slightly more sensitive to high temperatures than 'Advent Red' but relatively tolerant to high temperatures. 'Freedom Red' was first introduced in the early 1990s and is still grown in south Florida due to reliable performance in this high-temperature climate. It has a similar response time to Tikal Red, and both cultivars are categorized as early-season cultivars. 'Prestige Red' was chosen as it is considered to be highly sensitive to high temperatures. It also has the longer response time than the other three cultivars, and thus is categorized as a late-season cultivar.

*Greenhouse experiment (Expt. 1).* A total of 200 cuttings of each cultivar were propagated then thinned to two shoots per plant as per the general practices stated previously. The most uniform 110 plants from each cultivar were then selected. The experiment was conducted twice under ND conditions in Clemson, SC (lat. 34.7°N), in two glass greenhouses; one greenhouse was set to provide an ADT of 22 °C (the actual ADT averaged 21.8 ± 2 °C during the 8-week treatment period), and the other greenhouse was set at an ADT of 28 °C (the actual ADT averaged 27.8 ± 1.6 °C during the 8-week treatment period). These two greenhouses are referred to as the moderate- and high-temperature greenhouses, respectively. Temperatures and DLIs delivered during both replications were not significantly different, so means are reported.

Black plastic (thickness of 6 mil) was used to cover the vertical greenhouse walls (4.3 m) to prevent light pollution from affecting the ambient photoperiod. An average DLI of 10.5 ± 4.8 mol·$m^{-2}$·$d^{-1}$ was recorded during the 8-week treatment period, and an average DLI of 9.6 ± 2.8 mol·$m^{-2}$·$d^{-1}$ was recorded in the subsequent finishing period (as DLI data were not significantly different between the two replications, DLI data were averaged between the two replications). Beginning on 4 Sep, one group of plants was moved each week from the moderate-temperature greenhouse to the high-temperature greenhouse for 8 weeks. Each group of plants remained in the high-temperature greenhouse for 1 week before being returned to the moderate-temperature greenhouse (Table 1). One additional group of control plants was kept in either the moderate- or high-temperature greenhouse for the entire 8-week period.

Table 1. In the greenhouse experiment, poinsettia cultivars Advent Red, Tikal Red, Freedom Red, and Prestige Red were exposed to eight, 1-week, high-temperature treatments as well as a moderate- (22 °C) and high-temperature (28 °C) control from 4 Sep to 29 Oct. This table shows each of the 10 temperature treatments (columns) and the temperatures applied during each week of the experiment (rows). The high-temperature treatments are highlighted for clarity. Values are in °C.

| | | Week of high-temperature treatment | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Dates | 22 °C Control | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 28 °C Control |
| 4–10 Sep | 22 | 28 | 22 | 22 | 22 | 22 | 22 | 22 | 22 | 28 |
| 11–17 Sep | 22 | 22 | 28 | 22 | 22 | 22 | 22 | 22 | 22 | 28 |
| 18–24 Sep | 22 | 22 | 22 | 28 | 22 | 22 | 22 | 22 | 22 | 28 |
| 25 Sep–1 Oct | 22 | 22 | 22 | 22 | 28 | 22 | 22 | 22 | 22 | 28 |
| 2–8 Oct | 22 | 22 | 22 | 22 | 22 | 28 | 22 | 22 | 22 | 28 |
| 9–15 Oct | 22 | 22 | 22 | 22 | 22 | 22 | 28 | 22 | 22 | 28 |
| 16–22 Oct | 22 | 22 | 22 | 22 | 22 | 22 | 22 | 28 | 22 | 28 |
| 23–29 Oct | 22 | 22 | 22 | 22 | 22 | 22 | 22 | 22 | 28 | 28 |

For the year 1 replication, each treatment consisted of eight plants, and 10 plants/treatment were used for year 2 replication. Treatments were grouped into complete, randomized blocks consisting of one plant per treatment group per cultivar with each greenhouse bench containing two to three complete blocks. After the 8-week treatment period, all plants were moved to a glass greenhouse to finish flowering at 22 °C ADT (the actual ADT averaged 22.2 ± 2.0 °C).

*Growth chamber experiment (Expt. 2).* A total of 100 cuttings of 'Prestige Red' were propagated by the method described previously and thinned to one or two primary shoots for replication one or two, respectively. Forty-five uniformly sized plants were then selected. Two growth chambers were used, one moderate-temperature growth chamber was set at 22 °C ADT (the actual ADT averaged 23.1 ± 1.5 °C), and the high-temperature growth chamber was set at 28 °C ADT (the actual ADT averaged 27.8 ± 1.1 °C). Note that temperatures and DLIs delivered during both replications were not significantly different, so means are reported. Both growth chambers had LED fixtures (Fluence Bioengineering RAZR 97W LED, Austin, TX, USA) providing a photosynthetic photon flux density of 175 ± 25 μmol·$m^{-2}$·$s^{-1}$ at canopy level. An NL of 11 h 01 min was provided at the start of the experiment and increased by 2 min/d to simulate natural conditions at lat. 34.7°N. Once an NL of 13 h 30 min was reached, the NL was kept at a constant 13 h 30 min until the end of the experiment.

Each week for 7 weeks, one treatment group of five plants was placed in the high-temperature growth chamber. Treatment groups spent 1 week in the high-temperature growth chamber before returning to the moderate-temperature growth chamber (Table 2). In addition to the seven, 1-week, high-temperature treatments, a group of plants was kept in either the moderate- or high-temperature growth chamber for the entire 7-week period to serve as controls. Treatments were completely randomized in both the growth chamber and greenhouse environments. After the 7-week treatment period, all plants were moved to a glass greenhouse to finish flowering at moderate temperatures (21.9 ± 2.5 °C ADT). Night lengths continued to increase by 2 min/d by using a combination of blackout curtains, which provided a consistent 14-h NL, and LED lights that

Table 2. In the growth chamber experiment, poinsettia cultivar Prestige Red was exposed to seven, 1-week, high-temperature treatments as well as a moderate- (22 °C) and high-temperature (28 °C) control over a period of 7 weeks. A night length of 11 h 01 min was provided at the start of the experiment and increased by 2 min/d to simulate natural daylength conditions at lat. 34.7°N. The table shows each of the nine temperature treatments (columns), the temperatures applied during each week of the experiment (rows), and the actual night length (HR:MIN) delivered during each week. The high-temperature treatments are highlighted for clarity. Values are in °C.

| | | Week of high-temperature treatment | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Night length (HR:MIN) | 22 °C Control | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 28 °C Control |
| 11:01–11:13 | 22 | 28 | 22 | 22 | 22 | 22 | 22 | 22 | 28 |
| 11:15–11:27 | 22 | 22 | 28 | 22 | 22 | 22 | 22 | 22 | 28 |
| 11:29–11:41 | 22 | 22 | 22 | 28 | 22 | 22 | 22 | 22 | 28 |
| 11:43–11:55 | 22 | 22 | 22 | 22 | 28 | 22 | 22 | 22 | 28 |
| 11:57–12:09 | 22 | 22 | 22 | 22 | 22 | 28 | 22 | 22 | 28 |
| 12:11–12:23 | 22 | 22 | 22 | 22 | 22 | 22 | 28 | 22 | 28 |
| 12:25–12:37 | 22 | 22 | 22 | 22 | 22 | 22 | 22 | 28 | 28 |

shortened the NL to the appropriate length for each given day of the experiment. An average DLI of 8.6 ± 3.8 mol·m$^{-2}$·d$^{-1}$ was recorded during the finishing period.

*Data collection and analysis.* Dates of first bract color (when 100% of one bract was covered with red pigmentation), visible bud (primary bracts unfolded to reveal the primary cyathium in the shoot apex), and anthesis (pollen visible on one stamen of the primary cyathium) were recorded. In addition, the three primary bracts and five subtending stem bracts were rated at the time of anthesis using a qualitative scale ranging from 0 to 4, where 0 = no red pigmentation, 1 = 1% to 25% red pigmentation, 2 = 26% to 75% red pigmentation, 3 = 76% to 99% red pigmentation, and 4 = 100% red pigmentation. Statistical data analysis was performed using JMP Pro (version 16.0; SAS Institute Inc., Cary, NC, USA) and analysis of variance tests were conducted. Least square means were calculated for each treatment × cultivar for each flowering response, for example, time from start of experiment to visible bud, first bract color, and anthesis, as well as an average color rating of the uppermost five bracts on each stem (the three primary bracts and the two uppermost stem bracts). Significance of treatment means relative to the moderate-temperature control were calculated using Fisher's least significant difference Student's *t* test ($P < 0.05$).

## Results

*Greenhouse experiment (Expt. 1).* Data from years 1 and 2 of the experiment were averaged based on three observations. First, although year was statistically significant, interaction plots revealed that the treatment means between year 1 and year 2 of the experiment had the same trend. Second, the F ratio of the effect of year and its interactions were smaller relative to the other effects (e.g., temperature and cultivar). Last, when treatment means were calculated as means relative to the moderate-temperature control, year was not a significant factor.

Bract color rating, time to visible bud, first bract color, and anthesis had a significant response to the cultivar × temperature treatment interaction (Table 3). Cultivars differed with regard to the specific treatment weeks and the number of weeks significantly affected by the high-temperature treatment. Compared with the moderate-temperature control, time to visible bud for 'Advent Red' was delayed by 4, 8, and 26 d from high-temperature treatments provided from 4 to 10 Sep, 11 to 17 Sep, and the high-temperature control, respectively (Fig. 1A). The other treatment periods did not cause a significant delay in time to visible bud. High-temperature treatments which occurred on 4 to 10 Sep, 11 to 17 Sep, 18 to 24 Sep, and the high-temperature control significantly delayed time to first bract color by 3, 6, 7, and 24 d, respectively (Fig. 2A). Time to anthesis was significantly delayed 6 and 21 d from high-temperature treatments that occurred on 11 to 17 Sep and the high-temperature control, respectively (Fig. 3A). High-temperature treatments that occurred on 18 to 24 Sep and 25 Sep to 1 Oct significantly reduced bract color ratings relative to the moderate-temperature control (Fig. 4A).

Table 3. In the greenhouse experiment, poinsettia cultivars Advent Red, Tikal Red, Freedom Red, and Prestige Red were exposed to eight, 1-week, high-temperature treatments as well as a moderate- (22 °C) and high-temperature (28 °C) control from 4 Sep to 29 Oct. The analysis of variance table shows the significance of each main effect, including cultivar (Cvr), temperature (Temp), and their interactions for four flowering responses: days from start of the experiment (4 Sep) to first bract color, visible bud, and anthesis and bract color rating.

| | First bract color | | Visible bud | | Anthesis | | Bract color rating | |
|---|---|---|---|---|---|---|---|---|
| Effect | F ratio | Sign. | F ratio | Sign. | F ratio | Sign. | F ratio | Sign. |
| Cvr | 210.1 | *** | 385.7 | *** | 267.0 | *** | 62.1 | *** |
| Temperature | 49.7 | *** | 192.5 | *** | 82.3 | *** | 23.1 | *** |
| Cvr × Temp | 2.2 | *** | 7.6 | *** | 4.5 | *** | 7.1 | *** |

***Significant at $P < 0.001$.

For 'Tikal Red', time to visible bud was significantly delayed by 5, 9, 3, and 21 d from high-temperature treatments that occurred on 11 to 17 Sep, 18 to 24 Sep, 25 Sep to 1 Oct, and the high-temperature control, respectively (Fig. 1B). High-temperature treatments that occurred on 11 to 17 Sep, 18 to 24 Sep, 25 Sep to 1 Oct, 2 to 8 Oct, and the high-temperature control significantly delayed time to first bract color by 6, 6, 8, 6, and 18 d, respectively (Fig. 2B). Time to anthesis was significantly delayed 7, 9, 6, and 20 d from high-temperature treatments that occurred on 11 to 17 Sep, 18 to 24 Sep, 25 Sep to 1 Oct, and the high-temperature control (Fig. 3B). High-temperature treatments that occurred on 25 Sep to 1 Oct and 2 to 8 Oct significantly reduced bract color ratings relative to the moderate-temperature control (Fig. 4B).

Time to visible bud for 'Freedom Red' was significantly delayed by 5, 9, 6, 4, and 33 d from high-temperature treatments that occurred on 11 to 17 Sep, 18 to 24 Sep, 25 Sep to 1 Oct, 2 to 8 Oct, and the high-temperature control, respectively (Fig. 1C). High-temperature treatments that occurred on 11 to 17 Sep, 18 to 24 Sep, 25 Sep to 1 Oct, 2 to 8 Oct, and the high-temperature control significantly delayed time to first bract color by 3, 8, 10, 8, and 24 d, respectively (Fig. 2C). Time to anthesis was significantly delayed 5, 10, 9, 8, 5, and 32 d from high-temperature treatments that occurred on 11 to 17 Sep, 18 to 24 Sep, 25 Sep to 1 Oct, 2 to 8 Oct, 9 to 15 Oct, and the high-temperature control, respectively (Fig. 3C). High-temperature treatments that occurred on 25 Sep to 1 Oct, 2 to 8 Oct, 9 to 15 Oct, and 16 to 22 Oct significantly reduced bract color ratings relative to the moderate-temperature control (Fig. 4C).

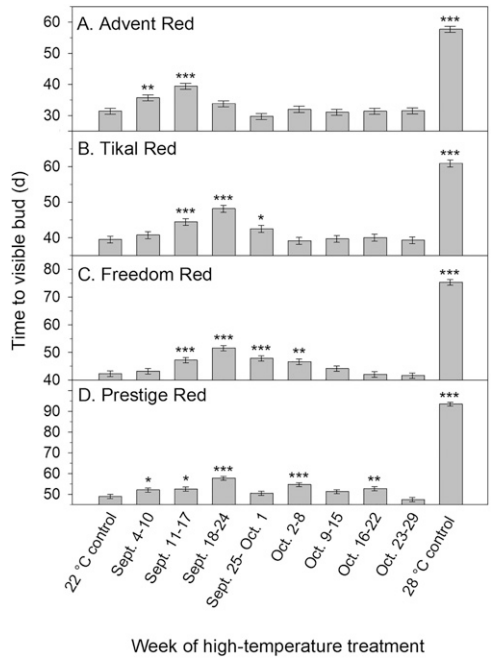


Fig. 1. In the greenhouse experiment, poinsettia cultivars Advent Red (**A**), Tikal Red (**B**), Freedom Red (**C**), and Prestige Red (**D**) were exposed to eight, 1-week, high-temperature treatments as well as a moderate- (22 °C) and high-temperature (28 °C) control from 4 Sep to 29 Oct. Average number of days from the start of the experiment (4 Sep) to visible bud are reported for the 10 temperature treatments for each of the four cultivars. *, *** indicate *P* values of <0.05 and <0.001, respectively, in relation to the moderate-temperature control. Error bars represent ±1 *SE*.

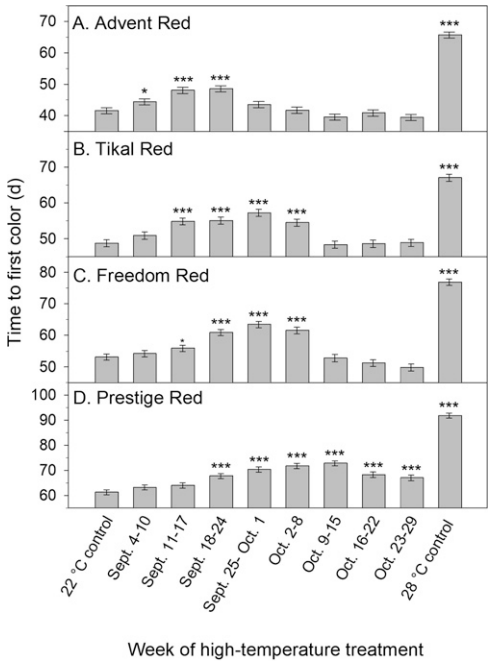


Fig. 2. In the greenhouse experiment, poinsettia cultivars Advent Red (**A**), Tikal Red (**B**), Freedom Red (**C**), and Prestige Red (**D**) were exposed to eight, 1-week, high-temperature treatments as well as a moderate- (22 °C) and high-temperature (28 °C) control from 4 Sep to 29 Oct. Average number of days from the start of the experiment (4 Sep) to first bract color are reported for the 10 temperature treatments for each of the four cultivars. *, *** indicate $P$ values of <0.05 and <0.001, respectively, in relation to the moderate-temperature control. Error bars represent ±1 *SE*.

Conversely, the high-temperature control treatment had a significantly higher bract color rating compared with the moderate-temperature control.

For 'Prestige Red', time to visible bud was significantly delayed 3, 4, 9, 6, 4, and 45 d from high-temperature treatments that occurred on 4 to 10 Sep, 11 to 17 Sep, 18 to 24 Sep, 2 to 8 Oct, 16 to 22 Oct, and the high-temperature control, respectively (Fig. 1D). High-temperature treatments that occurred on 18 to 24 Sep, 25 Sep to 1 Oct, 2 to 8 Oct, 9 to 15 Oct, 16 to 22 Oct, 23 to 29 Oct, and the high-temperature control

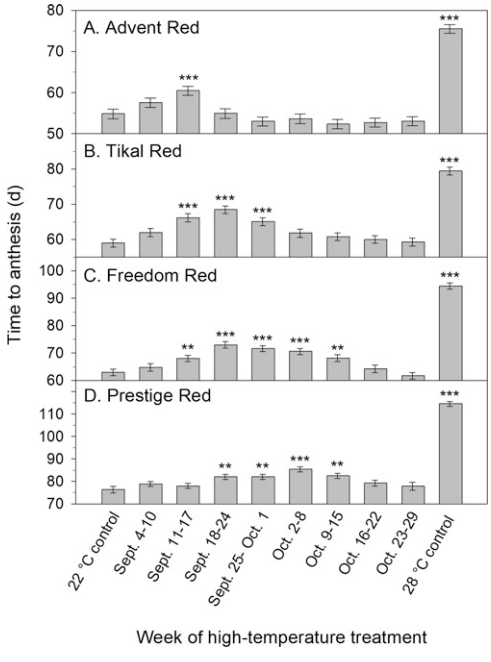


Fig. 3. In the greenhouse experiment, poinsettia cultivars Advent Red (**A**), Tikal Red (**B**), Freedom Red (**C**), and Prestige Red (**D**) were exposed to eight, 1-week, high-temperature treatments as well as a moderate- (22 °C) and high-temperature (28 °C) control from 4 Sep to 29 Oct. Average number of days from the start of the experiment (4 Sep) to anthesis are reported for the 10 temperature treatments for each of the four cultivars. **, *** indicate $P$ values of <0.01 and <0.001, respectively, in relation to the moderate-temperature control. Error bars represent ±1 *SE*.

significantly delayed time to first bract color by 6, 9, 10, 12, 7, 6, and 31 d, respectively (Fig. 2D). Time to anthesis was significantly delayed 6, 6, 9, 6, and 38 d from high-temperature treatments that occurred on 18 to 24 Sep, 25 Sep to 1 Oct, 2 to 8 Oct, 9 to 15 Oct, and the high-temperature control, respectively (Fig. 3D). High-temperature treatments that occurred on 25 Sep to 1 Oct, 2 to 8 Oct, 9 to 15 Oct, 16 to 22 Oct, and 23 to 29 Oct significantly reduced bract color ratings relative to the moderate-temperature control (Fig. 4D). In contrast, the 18 to 24 Sep and high-temperature control treatments had significantly higher bract color ratings compared with the moderate-temperature control.

'Freedom Red' and 'Tikal Red' experienced delays to anthesis of >1 d per day of high-temperature treatment during the peak week of high-temperature sensitivity (e.g., 18 to 24 Sep for both cultivars) (Fig. 5). However, during the nonpeak weeks of high-temperature sensitivity, ≤1 d of delay per day of high temperature was experienced. For 'Advent Red' and 'Prestige Red', the flowering delay was always ≤1 d of delay per day of high-temperature treatment.

*Growth chamber experiment (Expt. 2).* Bract color rating, time to visible bud, first bract color, and anthesis were significantly affected by temperature treatment (Table 4). No significant differences occurred between the two replications of the experiment and thus results were averaged. Compared with the moderate-temperature control, time to visible bud was significantly delayed by 5, 7, 7, 5, and 25 d from high-temperature treatments that occurred when NLs were 11 h 15 min to 11 h 27 min (week 2), 11 h 29 min to 11 h 41 min (week 3), 11 h 43 min to 11 h 55 min (week 4), 11 h 57 min to 12 h 09 min (week 5), and 11 h 01 to 12 h 37 min (high-temperature control), respectively (Fig. 6A). High-temperature treatments that occurred when NLs were 11 h 15 min to 11 h 27 min (week 2), 11 h 29 min to 11 h 41 min (week 3), 11 h 43 min to 11 h 55 min (week 4), 11 h 57 min to 12 h 09 min (week 5), 12 h 11 min to 12 h 23 min (week 6), 12 h 25 min to 12 h 37 min (week 7), and 11 h 01 to 12 h 37 min (high-temperature control) significantly delayed time to first bract color by 4, 6, 8, 9, 12, 12, and 18 d, respectively, relative to the moderate-temperature control (Fig. 6B).

Time to anthesis was significantly delayed by all high-temperature treatments provided. Delays of 4, 5, 8, 9, 5, 4, 5, and 23 d were observed from high-temperature treatments applied when NLs were 11 h 01 min to 11 h 13min (week 1), 11 h 15 min to 11 h 27 min (week 2), 11 h 29 min to 11 h 41 min (week 3), 11 h 43 min to 11 h 55 min (week 4), 11 h 57 min to 12 h 09 min (week 5), 12 h 11 min to 12 h 23 min (week 6), 12 h 25 min to 12 h 37 min (week 7), and 11 h 01 min to 12 h 37 min (high-temperature control), respectively (Fig. 6C). Finally, high-temperature treatments that occurred when NLs were 11 h 43 min to 11 h 55 min (week 4), 11 h 57 min to 12 h 09 min (week 5), 12 h 11 min to 12 h 23 min (week 6), and 12 h 25 min to 12 h 37 min

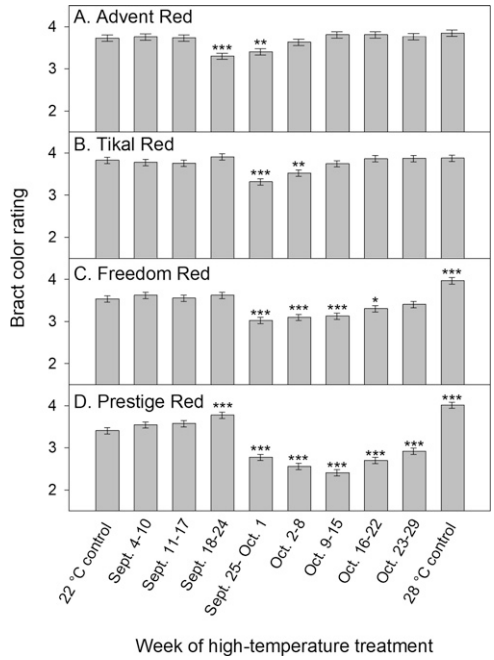


Fig. 4. In the greenhouse experiment, poinsettia cultivars Advent Red (**A**), Tikal Red (**B**), Freedom Red (**C**), and Prestige Red (**D**) were exposed to eight 1-week high-temperature treatments as well as a moderate- (22 °C) and high-temperature (28 °C) control from 4 Sep to 29 Oct. Upon reaching anthesis, the three primary bracts and the uppermost two stem bracts of each plant were rated using a qualitative rating going from 0 to 4, where 0 = no red pigmentation, 1 = 1% to 25% red pigmentation, 2 = 26% to 75% red pigmentation, 3 = 76% to 99% red pigmentation, and 4 = 100% red pigmentation. *, **, *** indicate *P* values of <0.05, <0.01, <0.001, respectively, in relation to the moderate-temperature control. Error bars represent ±1 *SE*.

(week 7) significantly reduced bract color ratings relative to the moderate-temperature control (Fig. 6D).

'Prestige Red' displayed >1 d of delayed flowering per day of high-temperature treatment during the NL where peak sensitivity occurred, 11 h 43 min to 11 h 55 min NL (Fig. 7). During the nonpeak NLs that occurred before or after the peak NL of sensitivity, the delay in flowering was ≤1 d per day of high temperature.

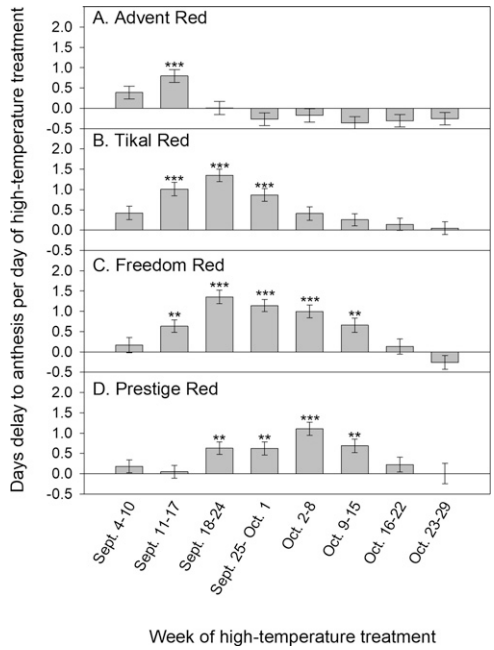


Fig. 5. In the greenhouse experiment, poinsettia cultivars Advent Red (**A**), Tikal Red (**B**), Freedom Red (**C**), and Prestige Red (**D**) plants were exposed to eight, 1-week, high-temperature treatments as well as a moderate- (22 °C) and high-temperature (28 °C) control from 4 Sep to 29 Oct. The number of days delay to anthesis per day of high-temperature treatment was calculated by subtracting the time to anthesis of the moderate-temperature control from the time to anthesis of each weekly high-temperature treatment and then dividing by the number of days of exposure to the high-temperature treatment (e.g., 7 d). The horizontal dashed lines identify the response of >1 d delay per day of high-temperature treatment. *, **, *** indicate *P* values of <0.05, <0.01, and <0.001, respectively, in relation to the moderate-temperature control. Error bars represent ±1 *SE*.

## Discussion

Discrete periods of sensitivity to high temperatures, specific to individual cultivars, were identified. Although specific periods of sensitivity to high temperatures varied between cultivar, sensitive periods generally overlapped with the 12 Sep to 10 Oct period of sensitivity identified by Schnelle (2008). Sensitive periods for the growth chamber experiment were estimated based on the time of photoperiod perception that occurs between sunrise/sunset and civil twilight (unpublished data). The sensitive periods were as follows for time to visible bud, first bract color, anthesis, and bract color rating sensitivity: 17 Sep to 13 Oct, 17 Sep to 26 Oct, 10 Sep to 26 Oct, and 1 to 26 Oct. The overlap between sensitive periods identified for 'Prestige Red' in the growth chamber and greenhouse experiments serves to validate the identified periods of sensitivity to high temperatures.

Sensitivity to high temperatures changed as the season progressed. Plants were relatively insensitive to high-temperature treatments early in the season, presumably due to NLs being insufficiently long to induce floral initiation. Sensitivity to high temperatures then increased as the season progressed, with peak sensitivity to high temperatures occurring earlier for the early-season cultivar (Advent Red) and progressively later for mid- (Tikal Red and Freedom Red) and late-season (Prestige Red) cultivars (Figs. 1–4). After this peak, sensitivity to high temperatures declined, with high-temperature treatments in later weeks having progressively less impact on floral development. This decline in sensitivity to high temperatures in later weeks of the growing season could be attributed to increased rates of floral development associated with longer NLs (Alden and Faust 2021; Grueber and Wilkins 1994; Miller and Kiplinger 1962).

Delays to visible bud and anthesis generally occurred from high-temperature treatments in earlier weeks within this sensitive period, whereas delays to first bract color and a reduction in bract color tended to occur from high-temperature treatments in later weeks within the overall sensitive time frame. This pattern of cyathium development being affected by high-temperature treatments in earlier weeks and bract color development being affected by high-temperature treatments in later weeks was likely because the primary cyathium initiation and development occurs before bract color formation. In this series of experiments, visible bud was reached before first bract color across all cultivars. In addition, previous research has also indicated that initiation of the primary cyathium generally occurs at least 2 weeks before visible bud (Goddard 1960; Miller and Kiplinger 1962; Struckmeyer and Beck 1960). Therefore, cyathium development began several weeks before

Table 4. In the growth chamber experiment, poinsettia 'Prestige Red' plants were exposed to seven, 1-week, high-temperature treatments as well as a moderate- (22 °C) and high-temperature (28 °C) control. A night length of 11 h 01 min was provided at the start of the experiment and increased by 2 min/d to simulate natural daylength conditions at lat. 34.7°N. The analysis of variance table shows the significance of the main effect, temperature, across four floral responses: days from start of the experiment to first bract color, visible bud, and anthesis and bract color rating.

| | First bract color | | Visible bud | | Anthesis | | Bract color rating | |
|---|---|---|---|---|---|---|---|---|
| Effect | F ratio | Sign. | F ratio | Sign. | F ratio | Sign. | F ratio | Sign. |
| Temperature | 65.1 | *** | 21.2 | *** | 31.4 | *** | 24.3 | *** |

***Significant at $P < 0.001$.

bract color formation and thus was susceptible to high temperatures earlier in the growing season.

For all four cultivars in the greenhouse study, the high-temperature control was the most delayed treatment regarding visible bud, first bract color, and anthesis. However, for 'Advent Red' and 'Tikal Red' the high-temperature control treatment did not significantly affect the bract color rating. For 'Freedom Red' and 'Prestige Red', the high-temperature control treatment had significantly higher bract color ratings compared with the moderate-temperature control. A possible explanation for these results is that during the 8 continuous weeks of high temperatures, floral development was effectively halted for much of this period resulting in large delays to visible bud, first bract color, and anthesis. However, at the end of this 8-week period, the high-temperature control group plants were placed into moderate temperatures and resumed floral development under relatively longer NLs. Thus, although delayed, this treatment eventually developed equal to, or greater bract color compared with the moderate-temperature control. This conclusion is supported by previous studies that have shown reported increased bract color development with NLs >12 h (Alden and Faust 2022; Langhans and Larson 1959; Langhans and Miller 1959).

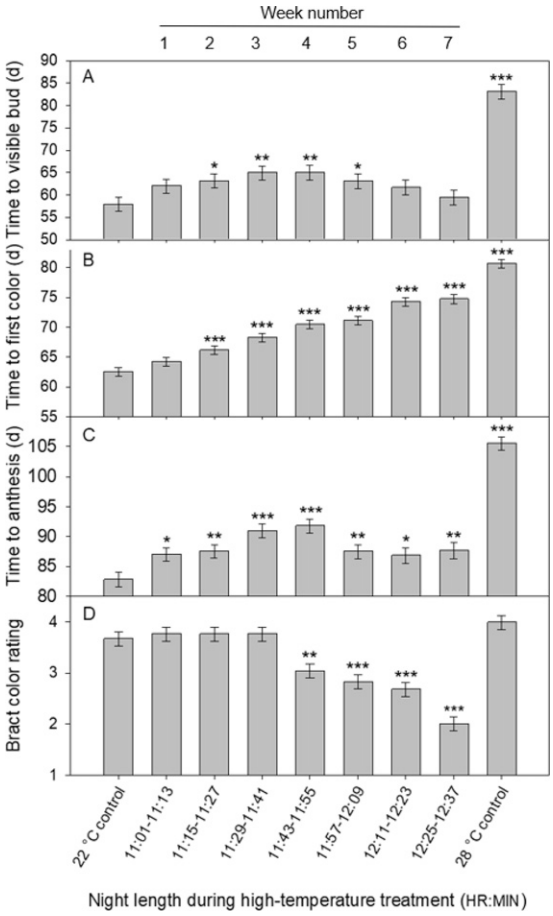


Fig. 6. In the growth chamber experiment, poinsettia 'Prestige Red' plants were exposed to seven, 1-week, high-temperature (28 °C) treatments as well as a moderate- and high-temperature control. A night length of 11 h 01 min was provided at the start of the experiment and increased by 2 min/d to simulate natural conditions at lat. 34.7°N. Upon reaching anthesis, the three primary bracts and the uppermost two stem bracts of each plant were rated using a qualitative rating going from 0 to 4, where 0 = no red pigmentation, 1 = 1% to 25% red, 2 = 26% to 75% red, 3 = 76% to 99% red, and 4 = 100% red. Average time (in days) from the start of the experiment to visible bud (**A**), first bract color (**B**), and anthesis (**C**) are also reported for the nine temperature treatments. *, **, *** indicate $P$ values of <0.05, <0.01, and <0.001, respectively, in relation to the moderate-temperature control. Error bars represent ±1 *SE*.

Our hypothesis was that 1 day of high temperatures would cause 1 day of delayed flowering. The data reveal a much more complex situation. During the peak time of high-temperature sensitivity in both the greenhouse and growth chamber studies, >1 d of delay was observed per day of heat stress (Figs. 5 and 7). This suggests a residual effect of high temperature during peak periods of sensitivity. In contrast, during the less-sensitive time periods, <1 d of delay was observed per day of heat stress. Therefore, accurate prediction of heat delay with temperature data requires one to know the relative heat sensitivity for a given cultivar during the weeks of flower initiation and the early stages of flower development. These data also reveal how 1 week of high temperatures can have varying effects on different cultivars depending on each cultivar's unique sensitivity during that specific week. This could result in a misleading or inaccurate assessment of a cultivar's overall sensitivity to high temperatures. For example, if high temperatures were experienced on 11 Sep to 17 Sep, Advent Red will appear to be a more high-temperature-sensitive cultivar than Prestige Red; however, one would draw the opposite conclusion if high temperatures were experienced from 18 Sep through 29 Oct.

Knowing specific periods in the growing season when plants are most sensitive to high temperatures allows growers to make informed decisions regarding greenhouse temperature management and allows for a more accurate ability to predict flowering times. However, using cultivars that are tolerant to high temperatures remains the most practical solution for growers to address heat delay. 'Advent Red' demonstrated tolerance of high temperatures in that it showed a lower magnitude of response to high temperatures as well as a shorter window of sensitivity to high temperatures (4 Sep to 1 Oct). 'Tikal Red', 'Freedom Red', and 'Prestige Red' all experienced a relatively higher magnitude of delay compared with 'Advent Red'; however, these cultivars differed in the overall length of their sensitive period to high temperatures (Figs. 1–4). Prestige Red, considered a sensitive cultivar to high temperatures, had the longest window of sensitivity to high temperatures (4 Sep to 29 Oct), followed by Freedom Red (11 Sep to 22 Oct) and Tikal Red (11 Sep to 8 Oct). Thus, relative tolerance of high temperatures from highest to lowest for the cultivars tested would be as follows: Advent Red, Tikal Red, Freedom Red, and Prestige Red. In future breeding efforts, duration of sensitivity to high temperatures as well as magnitude of response to high temperatures should be considered when selecting for heat-tolerant cultivars.

A potential method breeders can use to screen new introductions for tolerance to high temperatures would be to use blackout curtains to obtain a 12-h NL to control the starting date for flower initiation. Three temperature treatments

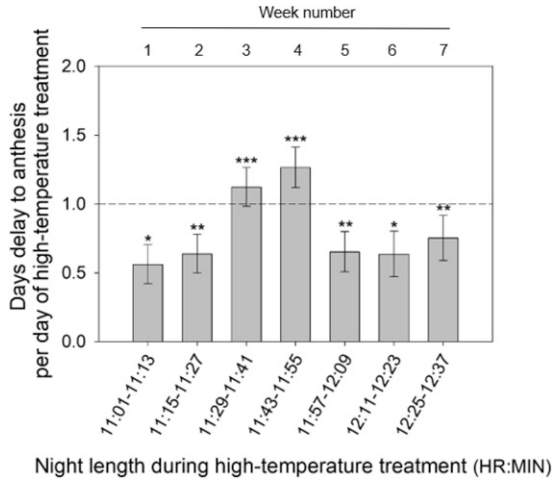


Fig. 7. In the growth chamber experiment, poinsettia cultivar Prestige Red plants were exposed to seven, 1-week, high-temperature treatments as well as a moderate- (22 °C) and high-temperature (28 °C) control. A night length of 11 h 01 min was provided at the start of the experiment and increased by 2 min/d to simulate natural conditions at lat. 34.7°N. The number of days of delay to anthesis per day of high-temperature treatment was calculated by subtracting the time to anthesis of the moderate-temperature control from the time to anthesis for each weekly high-temperature treatment and then dividing by the number of days of exposure to the high-temperature treatment (e.g., 7 d). *, **, *** indicate $P$ values of $<0.05$, $<0.01$, and $<0.001$, respectively, in relation to the moderate-temperature control. The horizontal dashed lines identify the response of $>1$ d delay per day of high-temperature treatment. Error bars represent ±1 *SE*.

would then be applied at the start of the SD treatment: a moderate-temperature control treatment of 18 to 22 °C, a high-temperature treatment of 28 °C applied during the first 2 weeks of SD, and a high-temperature treatment of 28 °C applied in weeks 3 and 4 of the inductive 12-h NL. With these treatments, the breeder would be able to identify the magnitude of response to high temperatures by comparing finishing times between the high-temperature treatments and the moderate-temperature control. The breeder would also be able to identify the duration of sensitivity to high temperatures of a cultivar by comparing the two high-temperature treatments with each other. This screening method would allow breeders to screen for tolerance of high temperatures considering both the magnitude of response and the duration of the period of sensitivity, while not requiring extensive greenhouse space or an overly complex array of treatments.

Additional research will be required to more fully understand the dynamics of temporal sensitivity to high temperatures in poinsettia. For instance, in natural conditions, high temperatures occur sporadically, rather than in continuous week-long periods, and they fluctuate diurnally. Research investigating the impact of high temperatures delivered continuously compared with intermittent high temperatures and with diurnal temperature patterns would allow for a more accurate ability to predict the effects of high temperatures on poinsettia flowering. In addition, the impact of supra-optimal temperatures above and below 28 °C should be investigated.

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