Fertilization Strategy Affects Production and Postproduction Performance of Petunia

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ADDITIONAL INDEX WORDS. controlled-release fertilizer, nitrogen, post-harvest, pulse fertilization

SUMMARY. The amount of fertilizer applied during the commercial production of bedding plants has decreased in recent years because of increasing concerns about environmental impacts and the need to minimize production costs. However, reduced fertilization affects plant growth and flowering during production and in the postproduction environment. Plants grown with lower nutrient levels may perform satisfactorily during greenhouse production, but they may possess insufficient nutrients to sustain further growth in the postproduction environment, where fertilizer application is frequently lacking. This study examined conventional and alternative fertilizer delivery strategies that produce high-quality petunia (*Petunia ×hybrida*) during greenhouse production and continue to support plant growth and flowering in the postproduction environment. The fertilizer treatments during production consisted of four constant liquid fertilization (CLF) treatments of 0, 50, 100, or 200 ppm nitrogen (N) and three controlled-release fertilization (CRF) treatments (0, 4, or 8 lb/yard³). Three pulse fertilization (PF) treatments (0, 300, or 600 ppm N) were applied immediately before moving the plants to the postproduction environment. During production, petunia growth and development increased as CLF increased from 0 to 200 ppm N, but the addition of CRF resulted in the increase occurring at a declining rate. During postproduction, the interactive effects of CLF and CRF continued in a similar pattern as that seen in the production environment. The additional PF treatments resulted in further increases in plant growth. Across all CLF and CRF treatments, the leaf area increased from 466 to 540 cm² as PF increased from 0 to 300 ppm N, and the leaf area increased further to 631 cm² as PF increased from 300 to 600 ppm N. Based on our findings, two alternative strategies are possible. First, 0 to 50 ppm N CLF can be combined with 4 lb/yard³ CRF. The second strategy maintains the standard commercial practice of applying 100 ppm N CLF treatment and then applying a 300- to 600-ppm N PF treatment. These results suggest that a relatively low CLF rate can be used to achieve the desired production characteristics while reducing the cost of plant growth regulation, and that additional plant nutrition can be provided with CRF and/or PF to enhance the postproduction performance.

The high value and relatively short production schedules of bedding plants demand intensive production methods such as frequent fertigation (Roude et al., 1991). Historically, commercial greenhouse growers in the United States have applied relatively high nutrient concentrations (e.g., 250–350 ppm N) to maximize growth and reduce the

production time of crops, such as petunia (*Petunia ×hybrida*), that are considered to be “heavy feeders” (Dole et al., 2002; Zhang et al., 2012). Additionally, fertilizer is relatively inexpensive; therefore, growers have tended to err by applying excess fertilizer to avoid nonoptimal growth and nutritional deficiencies. However, excessive fertilizer application results

in nutrient runoff, which has become an increasingly important environmental concern because of the potential nitrate and phosphate contamination of groundwater (Klock-Moore and Broschat, 1999). Moreover, the amount of N applied to greenhouse crops is typically greater than those used for field crops on an area basis (Martín et al., 2007).

Growers have been motivated to reduce the amount of fertilizer applied to their crops because excess nutrients do not necessarily translate to higher profits for ornamental production (Cardarelli et al., 2010). Nutrient concentrations of 100 to 150 ppm N are now quite common in commercial bedding plant production. An additional benefit of reduced fertilization rates is the reduction in plant growth rates, which means that the amount of plant growth regulator applied to bedding plants can be reduced. Although these trends in greenhouse production are typically viewed as positive, one recent observation is that consumer performance has been negatively impacted (M. Kramer, personal communication). For example, plant growth after retail purchase is often limited because consumers frequently fail to fertilize their plants. Lower fertilization rates during production reduce consumer performance because of the lack of nutrients in the plant and the growing substrate at the point of sale.

In this study, we propose solutions that growers have the ability to control and implement because changing consumer practices and knowledge is a daunting task. Petunia was chosen as the subject of the experiment because it is one of the most popular bedding plants. Approximately 25 million pots of petunias were sold in 2015 in the United States; petunia ranks fourth among bedding/garden

Received for publication 19 Nov. 2020. Accepted for publication 24 Feb. 2021.

Published online 18 March 2021.

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Technical Contribution No. 6947 of the Clemson University Experiment Station.

This material is based on work supported by National Institute of Food and Agriculture/U.S. Department of Agriculture under project number SC-1700585.

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<https://doi.org/10.21273/HORTTECH04764-20>

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
2.54	inch(es)	cm	0.3937
6.4516	inch ²	cm ²	0.1550
645.1600	inch ²	mm ²	0.0016
0.4536	lb	kg	2.2046
0.5933	lb/yard ³	kg·m ⁻³	1.6856
1	mmho/cm	mS·cm ⁻¹	1
28.3495	oz	g	0.0353
28,350	oz	mg	3.5274 × 10 ⁻⁵
11.1612	oz/inch	g·cm ⁻¹	0.0896
1	ppm	mg·kg ⁻¹	1
1	ppm	mg·L ⁻¹	1
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

plants, followed by geranium, pansy, and impatiens (U.S. Department of Agriculture, 2016). Three fertilizer delivery strategies were assessed for their potential to maintain adequate growth of petunia during greenhouse production while improving plant growth during the postproduction environment. The fertilizer delivery strategies used included CLF, CRF, and PF treatments. Constant liquid fertilization is the standard industry practice for greenhouse production, whereas CRF and PF provide alternative approaches. Controlled-release fertilizer refers to a fertilizer designed to gradually release nutrients to the growing substrate over time and is most often used for production outdoors, where CLF is not practical because of the lack of control over water supplied during rainfall events (Medina et al., 2008; Tian and Saigusa, 2002). Pulse fertilization refers to a one-time fertigation application performed before placing the plants in a postproduction environment and at a higher rate than the CLF rates applied during production. Both the CRF and PF methods have the potential advantage of providing nutrients to the plant after the greenhouse production phase, thus improving postproduction performance compared with the conventional CLF method. The objective of this research was to evaluate the effects of CLF, CRF, and PF on petunia growth and flowering in the production and subsequent postproduction environments.

Materials and methods

Plug seedlings [288 cells/flat, three and four flats for replication (Rep.) 1 and 2, respectively] of 'Pretty Grand Red' petunia were obtained from a commercial grower and transplanted to six-pack plastic containers (six cells/container, 175 g/cell, 108 and 144 six-packs for Rep. 1 and 2, respectively) filled with a standard growing substrate that was custom-formulated without a fertilizer starter charge (Fafard 3B; Sun Gro Horticulture, Anderson, SC). The plants were placed in a glass greenhouse, and the initial irrigation event was performed with tap water after transplanting the seedlings.

Two replications of the following experiment were conducted during two consecutive growing seasons: Spring [Rep. 1 (28 Apr. to 30 June 2018)] and Fall [Rep. 2 (6 Oct. to 14 Dec. 2018)]. The experiment was

divided into two phases, the production phase and the postproduction phase. The production phase consisted of the time from transplantation to when at least five out of the six plants in each six-pack container had at least one open flower, which occurred 20 d after transplant (DAT) for Rep. 1 and 31 DAT for Rep. 2. This difference was due to the difference in maturity of the plugs received from the commercial plug producer. Air temperatures averaged 72.8 ± 2.2 or 72.1 ± 3.2 °F, and daily light integral averaged 17.8 ± 3.5 or 10.9 ± 2.6 mol·m⁻²·d⁻¹ for Rep. 1 and 2, respectively. The postproduction phase began by placing the flowering plants in the dark at 71.6 °F for 2 d to simulate a shipping environment and then placing the plants in a greenhouse under a 50% light transmission shade curtain for 1 week to simulate a retail garden center environment. The temperatures during the simulated retail environment averaged 76.4 ± 1.2 or 67.6 ± 0.4 °F for Rep. 1 and 2, respectively. Then, plants were transplanted to 6-inch-diameter containers (1 kg volume) with one plant per container and 6-inch spacing between the containers. The same growing substrate was used during the production phase and postproduction phase. Plants were located in the same greenhouse as those in the simulated retail environment, but the shade curtain was removed. No additional fertilizer was provided during the postproduction phase, which lasted for 30 or 24 d for Rep. 1 and 2, respectively. Air temperature averaged 77.4 ± 1.6 °F and daily light integral averaged 17.5 ± 4.2 mol·m⁻²·d⁻¹ for Rep. 1 and 67.4 ± 0.4 °F and 8.5 ± 3.5 mol·m⁻²·d⁻¹ for Rep. 2 during the postproduction phase.

FERTILIZATION TREATMENTS. Plants were fertigated throughout the greenhouse production phase with a CLF solution of 17N–2.2P–14.1K–3Ca–1Mg [4.9% ammonium–N, 12.1% nitrate–N (Plantex Solutions; Master Plant-Prod, Brampton, ON, Canada)] to deliver solutions containing 0, 50, 100, or 200 ppm N. Micronutrient concentrations were adjusted using a micronutrient blend [7% iron (Fe), 3.5% manganese (Mn), 3.5% zinc (Zn), 1.75% boron (B), 1.75% copper (Cu), and 0.7% molybdenum (Mo); Greencare Water-Soluble Micronutrient Blend; Blackmore Co.,

Belleville, MI] so that all treatments received 1 ppm Fe with each fertigation application. The container capacity was 103 g/cell, which was determined by irrigating a container until the substrate was completely saturated and water stopped dripping from the container. Then, the substrate was placed in an oven at 70 °C for 1 week before re-weighing the substrate to calculate the weight of water held by the substrate at the container capacity. The six-pack containers were checked daily and manually fertigated when the substrate color started to turn a lighter brown (every ≈ 3 –4 d) during the production phase. The fertigation volume was targeted to reach 80% of container capacity to minimize leaching of nutrients from the container. To accomplish this, the plant-container-substrate-water weight was measured at each fertigation event. The volume of solution to be added was calculated by subtracting the weight of the plastic, dry substrate, and plant from the total weight of the plant-container-substrate-water weight, assuming the substrate was at container capacity. The plant weight changed weekly; therefore, a representative plant was removed from the substrate each week and weighed to account for this change. The volume of fertilizer solution applied at each irrigation to bring the container up to 80% container capacity was recorded for each six-pack container at each irrigation event. The wholesale cost for the 17N–2.2P–14.1K–3Ca–1Mg fertilizer was \$14.75/25 lb.

For the CRF treatments, microprills were incorporated in the growing substrate before planting using a 3- to 4-month release formulation of 16N–2.2P–9.1K–0Ca–1.2Mg [8.5% ammonium–N, 7.5% nitrate–N (Florikan, Sarasota, FL)]. Incorporation rates were 0, 4, and 8 lb/yard³ for the control group, the medium label rate, and the high label rate, respectively. The wholesale cost for the 16N–2.2P–9.1K–0Ca–1.2Mg fertilizer was \$55.00/50 lb.

At the end of the production phase, the plants received PF treatments that consisted of a one-time fertilizer application at 0, 300, or 600 ppm N at 48 h before the plants were placed in the simulated shipping environment. The PF treatment was applied using the same fertilizer as

that used for the CLF treatments at a volume of 87 g/cell. No additional fertilizer was applied after the PF treatment, and the growing substrate used during the postproduction phase lacked a fertilizer starter charge.

DATA COLLECTION. The chlorophyll content of the petunia leaves was estimated weekly (Chlorophyll Meter; Apogee Instruments, Logan, UT). The leaves sampled were the largest uppermost leaves that would fit in the meter (64 mm²). Substrate pH and electrical conductivity (EC) were measured weekly (Oakton PC 700 pH/conductivity meter; Cole-Parmer, Vernon Hills, IL) using the substrate occupied by two plants per treatment. The plants in the containers sampled for pH and EC were discarded. Substrate EC was obtained using the 1:2 (growth substrate:deionized water, v/v) method by adding 100 g of deionized water to a 50-g substrate sample. The date of the first open flower was recorded for each plant during the production phase. A destructive harvest was performed at the end of the production phase (20 or 31 DAT) and another was performed at the end of the postproduction phase (62 or 67 DAT) for each of the two experimental replications. Plant height and flower number per plant were measured on three plants per treatment at each harvest date at the end of the production phase and on four plants per treatment at the end of the postproduction phase. Plant height was determined as the distance from the surface of the substrate to the base of the calyx of the uppermost flower. The number of flowers per plant included senesced flowers and buds displaying flower color.

A tissue nutrient analysis was performed for the entire above-ground shoot, including the leaf, stem, and flowers, of plants harvested at the end of the production and postproduction phases. The dried and ground tissues were analyzed to determine the following nutrients: N, phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), and Fe (USDA-Agricultural Research Service Laboratory, Toledo, OH). For Rep. 1, shoot fresh weight was measured at these two harvest dates. For Rep. 2, a substrate nutrient analysis was performed in addition to the tissue analysis; the leaf area

(LI-3100 area meter; LI-COR, Lincoln, NE) and root fresh weight were also measured. Two plants were measured per treatment at each data collection date. Plant fullness was defined as shoot fresh weight divided by plant height. This parameter was considered a reasonable measure of plant quality because it reflects the density of the plant canopy and a compact, well-branched plant is usually perceived as having improved ornamental characteristics.

EXPERIMENTAL DESIGN AND DATA ANALYSIS. The fertilizer treatments

applied to the plants were defined by a 4 × 3 × 3 factorial combination of four CLF concentrations (0, 50, 100, or 200 ppm N), three CRF concentrations (0, 4, or 8 lb/yard³), and three PF concentrations (0, 300, or 600 ppm N). The experimental design was a completely randomized design with four and five containers (six cells/container) per treatment for Rep. 1 and 2, respectively. Among these, six plants per treatment were used to collect weekly substrate pH/EC data during the production phase (3 weeks × 2 plants/week). Two

Table 1. Growth and development measurements of petunia recorded at the end of the production phase [20 or 31 d after transplantation for replication (Rep.) 1 and 2, respectively] for petunia treated with 0, 50, 100, or 200 ppm nitrogen (N) constant liquid fertilization (CLF) and 0, 4, or 8 lb/yard³ controlled-release fertilization (CRF). Plants were grown from 28 Apr. to 30 June 2018 for Rep. 1, and from 6 Oct. to 14 Dec. 2018 for Rep. 2. Leaf area data are presented for Rep. 2. The other data are the means of Rep. 1 and 2.

CLF (ppm N) ^z	CRF (lb/yard ³) ^z			CLF avg	ANOVA	
	0	4	8		Source	Significance ^y
Flowers (no.) (n = 6)						
0	1.0 h ^x	4.9 e	5.3 de	3.7 C ^w	CLF	***
50	2.8 g	5.3 de	6.6 ab	4.9 B	CRF	***
100	3.8 f	6.1 bc	6.0 bcd	5.3 B	CLF × CRF	***
200	5.6 cde	6.2 bc	7.1 a	6.3 A		
CRF avg	3.3 C ^v	5.6 B	6.2 A			
Plant ht (cm) ^z (n = 6)						
0	2.3 f	9.2 c	9.5 bc	7.0 C	CLF	***
50	5.3 e	9.7 bc	10.2 ab	8.4 B	CRF	***
100	7.7 d	10.7 a	10.6 a	9.7 A	CLF × CRF	***
200	9.3 bc	10.8 a	10.1 abc	10.1 A		
CRF avg	6.1 B	10.1 A	10.1 A			
Shoot fresh wt (g) ^z (n = 4)						
0	1.2 f	9.8 de	11.5 cde	7.5 C	CLF	***
50	4.3 f	13.0 bcd	15.2 ab	10.8 B	CRF	***
100	8.0 e	14.9 abc	15.2 ab	12.7 B	CLF × CRF	**
200	15.0 abc	15.4 ab	16.6 a	15.6 A		
CRF avg	7.1 B	13.3 A	14.6 A			
Leaf area (cm ²) ^z (n = 2)						
0	15 ^u	197	219	143 D	CLF	***
50	69	255	315	213 C	CRF	***
100	159	331	318	283 B	CLF × CRF	NS
200	349	347	386	361 A		
CRF avg	148 B	282 A	320 A			
Chlorophyll (μmol·m ⁻²) (n = 4)						
0	10.6 d	26.7 ab	27.7 ab	21.6 A	CLF	NS
50	20.8 bc	30.6 a	26.4 ab	25.9 A	CRF	***
100	25.1 ab	22.7 b	21.2 bc	23.0 A	CLF × CRF	**
200	14.9 cd	24.4 ab	31.0 a	23.4 A		
CRF avg	17.8 B	26.1 A	26.6 A			

^z1 ppm = 1 mg·L⁻¹; 1 lb/yard³ = 0.5933 kg·m⁻³; 1 cm = 0.3937 inch; 1 g = 0.0353 oz; 1 cm² = 0.1550 inch².

^yNS, **, *** Nonsignificant or significant at *P* < 0.01 or 0.001, respectively.

^xMeans within columns and rows having different lowercase letters are significantly different according to Tukey's honestly significant difference (HSD), *P* < 0.05.

^wMain effect means within columns having different uppercase letters are significantly different according to Tukey's HSD, *P* < 0.05.

^vMain effect means within rows having different uppercase letters are significantly different according to Tukey's HSD, *P* < 0.05.

^uNo statistical comparison is provided when interactions were nonsignificant.

plants per treatment were used for the first destructive harvest, and another two plants per treatment were used for the tissue/substrate nutrient analysis. Four plants per treatment (one plant per container) were transplanted for the postproduction phase. Among these, two plants per treatment were used for the second destructive harvest, and another two plants per treatment were used for the tissue/substrate nutrient analysis. Data were analyzed using an analysis of variance with Tukey's honestly significant difference test using statistical software (JMP Pro version 13; SAS Institute, Cary, NC). Correlations with $P < 0.05$ were considered statistically significant.

Results

PRODUCTION PHASE. Flower number, plant height, and shoot fresh weight measured at the end of the production phase responded similarly to the interaction of CLF and CRF (Table 1). Plant growth and development increased as CLF increased, but that increase occurred at a decreasing rate as CRF increased. For example, at low CLF (0–50 ppm N), increasing CRF from 0 to 4 lb/yard³ resulted in a large increase in the measured growth and development responses, but the response to CRF was small or nonsignificant when CRF was increased from 4 to 8 lb/yard³. More specifically, shoot fresh weight

increased from 1.2 to 15.0 g with the increase of CLF from 0 to 200 ppm N when no CRF was applied, whereas shoot fresh weight increased from 11.5 to 16.6 g with the increase of CLF from 0 to 200 ppm N when CRF was applied at a high rate (8 lb/yard³).

The leaf area increased as CLF increased from 0 to 200 ppm N and as CRF increased from 0 to 4 lb/yard³; no interaction was observed (Table 1). Chlorophyll measurements increased as CRF increased from 0 to 4 lb/yard³, whereas responses to CLF were greater at a CRF of 0 lb/yard³ than at the higher CRF treatments. Chlorophyll readings $\geq 20 \mu\text{mol}\cdot\text{m}^{-2}$ were considered of acceptable commercial quality; therefore, the only unacceptable treatments were the 0 and 200 ppm N CLF $\times$ 0 lb/yard³ CRF treatments. Time to flower was delayed by 1 to 2 d for the 0 to 50 ppm N CLF rate and 0 lb/yard³ CRF treatment compared with the other fertilization treatment combinations (data not shown).

The amount of N applied during the production phase ranged from 0 to 100.4 mg/plant (Table 2). The amount of water applied during the fertigation events also varied among the CLF treatments because of differences in the plant size and substrate EC. Water delivered increased as the leaf area increased, but the treatments with the highest substrate EC

displayed a reduction in the amount of water required to adequately irrigate the treatment. The amounts of N, P, and K remaining in the substrate after the production phase were not different among the 0 lb/yard³ CRF treatments, suggesting that plants were using all of these nutrients made available from the CLF treatments from 0 to 200 ppm N CLF. The amount of N remaining in the substrate at the end of the production phase approximately doubled as CRF increased from 0 to 8 lb/yard³. Additionally, the substrate EC at the end of the production phase increased as the CRF rate increased from 0 to 8 lb/yard³. These results demonstrate that the CRF treatments continued to have significant levels of N, P, and K available at the beginning of the postproduction environment. Substrate pH ranged from 5.3 to 5.8 among treatments with no clear trends (data not shown).

A shoot tissue analysis showed that the CLF $\times$ CRF treatments that provided $\geq 6.2\%$ N were not significantly different, suggesting that the plants had reached the maximum tissue concentration (Table 3). Only four treatments had significantly lower tissue N levels, namely the 0 ppm CLF $\times$ 0 or 4 lb/yard³ CRF and 50 or 100 ppm CLF $\times$ 0 lb/yard³ CRF. Tissue P levels followed a similar trend as N, with treatments yielding $\geq 0.6\%$ P (not significantly different).

Table 2. Substrate nutrient analysis performed at the end of the production phase (31 d after transplantation). *Petunia* was treated during the production phase with 0, 50, 100, or 200 ppm nitrogen (N) constant liquid fertilization (CLF) and 0, 4, or 8 lb/yard³ controlled-release fertilization (CRF). Plants were grown from 6 Oct. to 14 Dec. 2018. The amounts of N and water applied and the growing substrate electrical conductivity (EC) are noted for each of the 12 CLF $\times$ CRF treatments. A substrate nutrient analysis was performed for N, phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), and iron (Fe).

CLF (ppm N) ^z	CRF (lb/ yard ³) ^z	N applied (mg/ plant) ^z	Water applied (g/plant) ^z	Substrate EC (mS·cm ⁻¹) ^z	Substrate nutrient analysis						
					N	P	K	Ca	Mg	S	Fe
					(% dry wt)						(mg·kg ⁻¹) ^z
0	0	0.0	138	0.09	0.7 b ^y	0.01 b	0.02 b	3.5 a	2.0 a	0.13 d	995 b
0	4	34.1	161	0.13	1.0 ab	0.06 b	0.12 b	0.9 d	0.6 d	0.25 cd	1562 ab
0	8	68.3	174	0.52	1.5 a	0.18 ab	0.43 ab	2.3 b	1.3 ab	0.49 ab	2306 ab
50	0	7.4	148	0.03	0.7 b	0.02 b	0.02 b	2.5 ab	1.5 ab	0.13 d	938 b
50	4	42.3	163	0.13	1.1 ab	0.05 b	0.11 b	1.0 cd	0.6 cd	0.23 cd	1808 ab
50	8	76.8	171	0.40	1.5 a	0.29 a	0.66 a	2.3 b	1.3 b	0.57 a	2843 a
100	0	12.7	127	0.03	0.8 b	0.02 b	0.02 b	1.9 bcd	1.1 bcd	0.12 d	981 b
100	4	52.9	188	0.19	1.0 ab	0.13 ab	0.32 ab	2.2 b	1.2 bc	0.33 c	1754 ab
100	8	84.7	164	0.50	1.4 a	0.15 ab	0.32 ab	1.9 bc	1.1 bcd	0.35 bc	1256 b
200	0	29.5	147	0.07	0.8 b	0.03 b	0.02 b	1.6 bcd	1.0 bcd	0.12 d	1028 b
200	4	67.4	166	0.30	1.1 ab	0.09 b	0.16 b	1.9 bcd	1.0 bcd	0.22 cd	1069 b
200	8	100.4	161	0.68	1.4 a	0.13 ab	0.32 ab	2.0 b	1.1 bcd	0.31 c	1384 ab

^z1 ppm = 1 mg·L⁻¹; 1 lb/yard³ = 0.5933 kg·m⁻³; 1 mg = 3.5274 $\times$ 10⁻⁵ oz; 1 g = 0.0353 oz; 1 mS·cm⁻¹ = 1 mmho/cm; 1 mg·kg⁻¹ = 1 ppm.

^yMeans within columns having different letters are significantly different according to Tukey's honestly significant difference, $P < 0.05$ ($n = 2$).

The highest K tissue levels were only achieved with the 200 ppm CLF treatments. The Ca, Mg and Fe levels in the shoot tissue were unaffected by the fertilization treatments. Although Fe and Mg were well within the target tissue levels for petunia (reported as 0.36% to 1.37% Mg and 84 to 168 ppm Fe) (Mills and Jones, 1996), Ca was on the low end of the target range (1.2% to 2.8%) across all treatments.

POSTPRODUCTION PHASE. After the greenhouse production phase, no additional fertilization was provided. However, the responses of petunia shoot growth and flowering to the CLF and CRF treatments continued to be significant (Table 4). All growth and development parameters recorded at the end of the postproduction phase displayed an

interactive response to CLF and CRF. Growth and development increased as CLF increased, but the addition of CRF resulted in the increase occurring at a declining rate (Fig. 1A–L). The PF treatment applied at the end of the greenhouse production phase also influenced plant growth and development during the postproduction phase (Table 4). For example, across all CLF and CRF treatments, the leaf area increased from 466 to 540 cm² as PF increased from 0 to 300 ppm N, and the leaf area increased further to 631 cm² as PF increased from 300 to 600 ppm N (Fig. 1J–L).

Plant fullness, defined as shoot fresh weight divided by plant height, increased with increasing CLF, CRF, and PF (Fig. 1M–O). At the end of

the postproduction phase, the maximum plant fullness was observed with the 100 ppm N CLF × 8 lb/yard³ CRF × 600 ppm N PF treatment, which was nearly double the value of the industry standard treatment of 100 ppm N CLF.

At the end of the postproduction phase, root fresh weight increased as CLF increased (Fig. 1P–R). High CRF (8 lb/yard³) reduced root fresh weight, whereas high PF (600 ppm N) increased root fresh weight. At the end of the postproduction phase, the root-to-shoot ratio decreased as CLF increased only when no CRF and no PF were applied (data not shown). When CRF and PF were added, the root-to-shoot ratio remained low and was negatively correlated with CRF rates. The substrate EC (0.04

Table 3. Tissue nutrient analysis measured at the end of the production phase [20 or 31 d after transplant for replication (Rep.) 1 and 2, respectively]. Petunia was treated during the production phase with 0, 50, 100, or 200 ppm nitrogen (N) of constant liquid fertilization (CLF) and 0, 4, or 8 lb/yard³ of controlled-release fertilization (CRF). Plants were grown from 28 Apr. to 30 June 2018 for Rep. 1 and from 6 Oct. to 14 Dec. 2018 for Rep. 2. Tissue nutrient analysis was performed for N, phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), and iron (Fe).

CLF (ppm N) ^z	CRF (lb/yard ³) ^z	N	P	K	Ca	Mg	S	Fe (mg·kg ⁻¹) ^z
(% dry wt)								
0	0	2.1 e ^y	0.12 e	2.3 f	1.1 a	0.9 a	0.29 de	173 a
0	4	5.4 bc	0.46 cd	3.3 ef	1.0 a	1.1 a	0.42 abc	123 a
0	8	6.3 ab	0.69 ab	4.8 de	1.1 a	1.1 a	0.47 a	151 a
50	0	3.8 d	0.40 d	3.9 def	1.1 a	1.1 a	0.36 bcd	101 a
50	4	6.3 ab	0.60 abc	4.4 de	1.0 a	1.1 a	0.49 a	208 a
50	8	6.7 a	0.68 ab	4.8 de	1.1 a	1.2 a	0.42 abc	196 a
100	0	5.0 c	0.57 bc	4.9 cde	1.1 a	1.2 a	0.33 cde	112 a
100	4	6.2 ab	0.65 ab	5.1 bcd	1.2 a	1.3 a	0.42 abc	115 a
100	8	6.5 a	0.67 ab	5.3 bcd	1.1 a	1.2 a	0.42 abc	132 a
200	0	6.6 a	0.74 ab	7.1 a	0.9 a	1.0 a	0.23 e	101 a
200	4	6.8 a	0.75 a	6.7 ab	1.1 a	1.0 a	0.41 abc	132 a
200	8	6.7 a	0.76 a	6.6 abc	1.1 a	1.0 a	0.46 ab	149 a

^z1 ppm = 1 mg·L⁻¹; 1 lb/yard³ = 0.5933 kg·m⁻³; 1 mg·kg⁻¹ = 1 ppm.

^yMeans within columns having different letters are significantly different according to Tukey's honestly significant difference, $P < 0.05$ ($n = 4$).

Table 4. Statistical analysis of petunia growth and development parameters recorded at the end of the postproduction phase [62 or 67 d after transplantation for replication (Rep.) 1 and 2, respectively]. Plants were treated during the production phase with 0, 50, 100, or 200 ppm nitrogen (N) constant liquid fertilization (CLF), 0, 4, or 8 lb/yard³ controlled-release fertilization (CRF), and 0, 300, or 600 ppm N pulse fertilization (PF). Petunia was grown from 28 Apr. to 30 June 2018 for Rep. 1, and from 6 Oct. to 14 Dec. 2018 for Rep. 2 (1 ppm = 1 mg·L⁻¹, 1 lb/yard³ = 0.5933 kg·m⁻³).

Measurement	CLF	CRF	PF	CLF×CRF	CLF×PF	CRF×PF	CLF×CRF×PF
Flower no.	***	***	***	***	NS	NS	NS
Plant ht	***	***	***	***	NS	NS	NS
Shoot fresh wt	***	***	***	***	NS	NS	NS
Leaf area	***	***	***	**	NS	NS	NS
Chlorophyll	***	***	NS	***	NS	NS	NS
Plant fullness	***	***	***	***	NS	NS	**
Root fresh wt	***	*	***	***	NS	NS	**
Root to shoot ratio	***	***	***	***	***	***	***

NS, *, **, ***Nonsignificant or significant at $P < 0.05$, 0.01, or 0.001, respectively, according to the analysis of variance.

Pulse fertilization rate

Fig. 1. Flower number (A–C), plant height (D–F), shoot fresh weight (G–I), leaf area (J–L), plant fullness (shoot fresh weight/plant height) (M–O), and root fresh weight (P–R) recorded at the end of the postproduction phase [62 or 67 d after transplant for replication (Rep.) 1 and 2, respectively]. Petunia was treated with 0, 50, 100, or 200 ppm nitrogen (N) constant liquid fertilization (CLF), 0, 4, or 8 lb/yard³ controlled-release fertilization (CRF), and 0, 300, or 600 ppm N pulse fertilization (PF). Plants were grown from 28 Apr. to 30 June 2018 for Rep. 1, and from 6 Oct. to 14 Dec. 2018 for Rep. 2. Lines indicate significant linear or quadratic effects; $P < 0.05$ ($n = 8$). Leaf area and root fresh weight data are presented for Rep. 2 only. Error bars represent $\pm$ SE; 1 ppm = 1 mg·L⁻¹; 1 lb/yard³ = 0.5933 kg·m⁻³; 1 cm = 0.3937 inch; 1 g = 0.0353 oz; 1 cm² = 0.1550 inch²; 1 g·cm⁻¹ = 0.0896 oz/inch.

Table 5. Cost analysis for the 36 fertilizer treatments. Petunia was treated during the production phase with 0, 50, 100, or 200 ppm nitrogen (N) constant liquid fertilization (CLF), 0, 4, or 8 lb/yard³ controlled-release fertilization (CRF), and 0, 300, or 600 ppm N pulse fertilization (PF). Plants were grown from 28 Apr. to 30 June 2018 for replication (Rep.) 1, and from 6 Oct. to 14 Dec. 2018 for Rep. 2.

CLF (ppm N) ^z	CRF (lb/yard ³) ^z	Fertilizer cost (\$0.01/six-pack)		
		PF (ppm N)		
		0	300	600
0	0	0.00	0.12	0.24
	4	0.31	0.43	0.55
	8	0.62	0.74	0.86
50	0	0.04	0.16	0.28
	4	0.35	0.47	0.59
	8	0.66	0.78	0.90
100	0	0.07	0.19	0.31
	4	0.38	0.50	0.62
	8	0.69	0.81	0.93
200	0	0.15	0.27	0.39
	4	0.46	0.58	0.70
	8	0.77	0.89	1.01

^z1 ppm = 1 mg·L⁻¹, 1 lb/yard³ = 0.5933 kg·m⁻³.

mS·cm⁻¹) and pH (5.5) at the end of the postproduction phase were not significantly different among the treatments (data not shown).

The chlorophyll measurements at the end of the postproduction phase showed that the 0 ppm N CLF × 0 lb/yard³ CRF treatment resulted in the lowest chlorophyll value (9 μmol·m⁻²; data not shown). Although all other treatments exhibited similar chlorophyll measurements between 20 and 28 μmol·m⁻², there was a downward trend in the chlorophyll concentration as CLF increased. Chlorophyll at the end of the postproduction phase was unaffected by the PF treatments (Table 4).

Tissue and substrate analyses at the end of the postproduction phases showed no significant differences among the fertilization treatments (data not shown). The mean tissue concentrations measured across all fertilization treatments were 3.4% N, 0.31% P, 2.5% K, 1.3% Ca, 0.92 Mg, 0.45% S, and 108 ppm Fe. The mean growing substrate nutrient concentrations were 0.75% N, 0.02% P, 0.015% K, 0.94% Ca, 0.57% Mg, 0.13% S, and 825 ppm Fe.

The cost analysis demonstrated that the fertilizer cost for the industry standard treatment is \$0.0007/six-pack (Table 5). The CRF treatment provided an additional cost of \$0.0024/six-pack and \$0.0055/six-pack for the 4 and 8 lb/yard³

treatments, respectively. The PF treatment provided an additional cost of \$0.0005/six-pack and \$0.0017/six-pack for the 300 and 600 ppm N treatments, respectively.

Discussion

During the past two decades, the standard industry fertilization practice for petunia production has been reduced from ≥200 to 100 to 150 ppm N CLF, and CRF has not been used commonly in greenhouse production. Here, we refer to the 100 ppm N CLF × 0 ppm N CRF treatment as the standard industry practice. Compared with the industry standard, adding CRF at the 4 lb/yard³ rate resulted in a 39% increase in plant height and an 86% increase in shoot fresh weight. No further increases were observed with the 8 lb/yard³ CRF rate. Compared with the industry standard, increasing the CLF rate up to 200 ppm N resulted in a 21% increase in plant height and an 86% increase in shoot fresh weight.

Lower CLF rates (<100 ppm N) produce unacceptably small or slow-growing plants. Higher CLF rates or the addition of CRF result in additional shoot growth that does not necessarily improve the ornamental appearance of the crop in the retail environment; however, it dictates the use of additional plant growth regulation methods. In other words, commercial growers have gradually

reduced their CLF practices to the point of providing the minimal acceptable fertilizer levels. This approach is ideal from an environmental perspective because nutrient waste is minimized. Because lower rates of plant growth regulators are delivered, the consumer is more likely to purchase a plant that will not have significant plant growth regulator residual activity. However, from a postproduction performance perspective, delivering a plant with minimal nutrient levels can be problematic if the consumer fails to provide additional plant nutrition after the plant is purchased. The growth and development responses in the postproduction environment reported here underscore this dilemma.

This work suggests alternative methods of delivering plant nutrients before the postproduction period that simultaneously meet the goals of minimizing the application of excess nutrients during production while maximizing the growth potential in the postproduction environment. First, the use of CRF provides nutrients during both the production and postproduction environments, and second, the implementation of the PF technique provides a significant dose of nutrients as the plants are transitioning from the production to the postproduction environment. Based on our findings, two alternative strategies are possible. First, 0 to 50 ppm N CLF can be combined with 4 lb/yard³ CRF to produce growth similar to that of the industry standard while supplying additional nutrition during the postproduction environment. The second strategy is using the standard 100 ppm N CLF treatment to achieve the desired production characteristics, and then applying a 300 to 600 ppm N PF treatment to supplement the nutrients available for growth in the postproduction environment. With this second method, improved postproduction performance can be achieved without the need to change production methods.

This study provides insight into the potential use of two alternative methods of improving postproduction performance of petunia while maintaining the recent progress that bedding plant growers have achieved through the reduction of fertilizer and plant growth regulator application

during production. The cost of the proposed alternative fertilization treatments would add <\$0.01/six-pack; therefore, these options should be considered economically viable means of improving postproduction performance that will likely improve consumer satisfaction.

Literature cited

- Cardarelli, M., Y. Roupael, E. Rea, A. Salerno, and G. Colla. 2010. Nutrient solution concentration and growing season affect growth and quality of potted petunia in a recirculating subirrigation and drip-irrigation system. *J. Food Agr. Environ.* 8:312–320, doi: 10.1234/4.2010.1516.
- Dole, J.M., B.E. Whipker, and P.V. Nelson. 2002. Producing vegetative petunias and calibrachoa. 18 Feb. 2021. <<https://gpnmag.com/article/producing-vegetative-petunias-and-calibrachoa/>>.
- Klock-Moore, K.A. and T.K. Broschat. 1999. Differences in bedding plant growth and nitrate loss with a controlled-release fertilizer and two irrigation systems. *HortTechnology* 9:206–209, doi: 10.21273/HORTTECH.9.2.206.
- Martín, I., N. Alonso, M.C. López, and M. Prieto. 2007. Estimation of leaf, root, and sap nitrogen status using the SPAD-502 chlorophyll meter for ornamental shrubs. *Commun. Soil Sci. Plant Anal.* 38:1785–1803, doi: 10.1080/00103620701435555.
- Medina, L.C., T.A. Obreza, J.B. Sartain, and R.E. Rouse. 2008. Nitrogen release patterns of a mixed controlled-release fertilizer and its components. *HortTechnology* 18:475–480, doi: 10.21273/HORTTECH.18.3.475.
- Mills, H.A. and J.B. Jones, Jr. 1996. Plant analysis handbook: A practical sampling, preparation, analysis, and interpretation guide. MicroMacro Publ., Athens, GA.
- Roude, N., T.A. Nell, and J.E. Barrett. 1991. Longevity of potted chrysanthemums at various nitrogen and potassium concentrations and NH₄:NO₃ ratios. *HortScience* 26:163–165, doi: 10.21273/HORTSCI.26.2.163.
- Tian, X. and M. Saigusa. 2002. Merits, utilization, perspectives of controlled-release nitrogen fertilizers. *Tohoku J. Agr. Res.* 52:39–55.
- U.S. Department of Agriculture. 2016. Floriculture crops: 2015 Summary. 24–31. 18 Feb. 2021. <<https://downloads.usda.library.cornell.edu/usda-esmis/files/0p0966899/pz50gz655/8910jx14p/FlorCrop-04-26-2016.pdf>>.
- Zhang, W., X. Li, F. Chen, and J. Lu. 2012. Accumulation and distribution characteristics for nitrogen, phosphorus and potassium in different cultivars of *Petunia hybrida* Vilm. *Scientia Hort.* 141:83–90, doi: 10.1016/j.scienta.2012.04.010.