Comparing the Adequacy of Controlled-release and Water-soluble Fertilizers for Bedding Plant Production

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Abstract. Four complete water-soluble fertilizer (WSF) formulations including micronutrients applied at 200 mg·L⁻¹ nitrogen (N) at each irrigation [Peters Excel (21N–2.2P–16.5K), Daniels (10N–1.8P–2.5K), Peters Professional (15N–1.3P–20.8K), and Jack's Professional (20N–1.3P–15.7K)] were compared with two controlled-release fertilizer (CRF) products (also containing micronutrients) substrate incorporated at transplant at a rate of 3000 g·m⁻³ of substrate [Osmocote Plus (15N–4P–9.9K, 90 to 120 days longevity at 21 °C) and Osmocote Bloom (12N–3.1P–15K, 60 to 90 days longevity at 21 °C)] in the greenhouse production of four commonly produced bedding plant species with high alkalinity irrigation water (pH 7.1, 280 mg·L⁻¹ CaCO₃ equivalent). Species included *Argyranthemum frutescens* (L.) Sch. Bip. 'Madeira Cherry Red' and iron-inefficient *Calibrachoa* Cerv. hybrid 'Cabaret Pink Hot', *Diascia barberae* Hook. f. 'Wink Coral', and *Sutera cordata* Roth 'Abunda Giant White'. Additional treatments included a combination of 100 mg·L⁻¹ Excel and 2100 g·m⁻³ Osmocote Plus and an Osmocote Plus treatment irrigated with reduced alkalinity water (acidified to pH 6.3, 92 mg·L⁻¹ CaCO₃ equivalent). Bedding plants were evaluated at the end of a finish or market stage (3 or 5 weeks depending on species) for shoot dry mass (SDM) and root dry mass (RDM), tissue nutrient concentrations, and visual quality rating (0 to 4). At 3 weeks, there were no significant differences in SDM and RDM between fertilizer treatments for any of the four species. Shoot dry mass significantly increased at 5 weeks in the WSF and combination treatments over the three CRF only treatments for *Argyranthemum* and over the non-acidified Osmocote Plus treatment only for *Calibrachoa*. At finish, 3 weeks for *Sutera* and *Diascia* and 5 weeks for *Argyranthemum* and *Calibrachoa*, visual quality rating for all species was lowest when using Osmocote Plus with or without acidified irrigation water compared with the WSF treatments, except the Daniels treatment in *Argyranthemum*, which also resulted in a low visual quality rating. Leaf tissue N for all species and phosphorus (P) for all except *Diascia* were below the recommended range for bedding plant crops in the CRF treatments, which was reflected by the lower substrate electrical conductivity (EC) for the CRF alone and combination treatments. Leaf tissue N and P were related to visual quality rating for all species, leaf tissue potassium (K) for *Argyranthemum* and *Calibrachoa* only, and leaf tissue iron (Fe) for *Diascia* only.

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Potted annual bedding and garden plants represented a \$1.33 billion wholesale value in the 15 top-producing states [U.S. Department of Agriculture (USDA), 2012]. New varieties have been released at a rapid rate motivated by the 48% market share bedding and garden plants have of the total floriculture crop sales in the United States (USDA, 2012). Breeders have released many new varieties to feed the market-driven demand for designer colors in flower and foliage, modified growth habit, and improved garden performance for the increasingly inexperienced gardener (Abate and Peterson, 2005). This presents challenges to bedding and garden plant producers, because production problems can be coupled with these desirable marketing qualities.

Inefficient Fe uptake is one such characteristic documented in the genus of *Calibrachoa*, *Diascia*, *Petunia*, *Sutera*, and others, occurring at substrate pH above 6.2 (Fisher and Argo, 2002). High alkalinity irrigation water (at 150 mg·L⁻¹ CaCO₃ equivalent or greater) (Nelson, 2003) is conducive to an increase in substrate pH. The median alkalinity value for irrigation water in the United States is estimated at 130 mg·L⁻¹ CaCO₃ equivalent with four of the five top floriculture-producing states having a median value exceeding this (Argo et al., 1997; USDA, 2012). Regionally, the Great Lakes states of Illinois, Michigan, and Ohio had the highest median alkalinity (187 mg·L⁻¹ CaCO₃ equivalent) (Argo et al., 1997), yet accounted for a wholesale annual bedding plant value of ≈\$331 million in 2011 (USDA, 2012). Growers have the options of using a substrate with a lower lime charge, acidifying irrigation water, or using a fertilizer that is acidifying in reaction or contains Fe in a highly soluble form (Fe-EDDHA) to avoid Fe deficiency-induced chlorosis (Fisher and Argo, 2002). Irrigation water acidification and using multiple substrates and fertilizer formulations are particularly difficult for smaller growers. Economics, including the cost of acidifying water, and number and types of crops grown dictate which approach is used. Environmental conditions influence outcome and Fe deficiency-induced chlorosis may not be a significant issue every production cycle. Avoidance is preferable to corrective procedures because value is typically lost by the time deficiency symptoms are observed (Argo and Fisher, 2009).

Coinciding with the genetic changes in bedding plant material are environmental concerns in regard to fertilizer runoff from inefficient fertilizer delivery systems and excess application (Evans et al., 2007). Volatility in fertilizer costs (Silva, 2011), together with the environmental impacts of WSF application rates that err on the side of overapplication, have driven advances in coating technologies for CRF products. Complex polymer coatings that release nutrients to the substrate as a slow, continuous dose at a rate more compatible with uptake have the potential to decrease the environmental impact of excess N, P, and K (Hulme, 2012). Nutrient release rates in polymer-coated CRF products are temperature-dependent and the CRFs are formulated for different longevitys (nutrient release period at a standard temperature). In addition, micronutrients can be incorporated to provide the full array of elements necessary for production in soilless substrates. The objective of this study was to compare two formulations of polymer-coated CRFs containing micronutrients (differing slightly in N–P–K ratio and in longevity) applied at the recommended N rate to four WSF options suitable for production with high alkalinity water and one combination CRF and WSF treatment for the production of *Argyranthemum* and iron-inefficient *Calibrachoa*, *Diascia*, and *Sutera*. In addition, species were chosen to represent a range of nutrient requirements, including *Argyranthemum*

and *Calibrachoa* as heavy feeders, *Sutera*, moderate to heavy, and *Diascia* moderate (Hamrick, 2003) to determine if the CRF products could provide adequate nutrition across a range of species with different nutrient requirements. Because the WSFs were chosen for their potential to lower substrate pH due to high alkalinity irrigation water, a CRF treatment irrigated with acidified water was added for evaluation of CRF under more ideal conditions.

Materials and Methods

On 9 Mar. 2011, 54 rooted cuttings each of *Argyranthemum frutescens* 'Madeira Cherry Red', *Calibrachoa* 'Cabaret Pink Hot', *Diascia barberae* 'Wink Coral', and *Sutera cordata* 'Abunda Giant White' were transplanted from 105-cell plug trays to 12.7-cm plastic containers that were filled with a commercial soil-less substrate composed of 80% Sphagnum peatmoss and 20% perlite, starter nutrients (108, 29, and 125 g·m⁻³ of N, P, and K, respectively) and 3 to 3.6 g·kg⁻¹ dolomitic limestone (Fafard Custom 1P Mix; Fafard, Inc., Agawam, MA) at Purdue University in West Lafayette, IN (lat. 40° N). The plants were grown in a polycarbonate greenhouse with a double-layer polyethylene roof, exhaust fan and evaporative-pad cooling, and radiant hot-water heating controlled by an environmental computer (Wadsworth EnviroSTEP climate control computer; Wadsworth Control Systems, Inc., Arvada, CO). The average greenhouse air and substrate temperatures during the study were 21.4 and 22.6 °C, respectively. Plants were grown under ambient light and photoperiod with an average daily light integral of 17.6 mol·m⁻²·d⁻¹. Plants were hand-irrigated as necessary with ≈150 to 200 mL (20% to 25% leaching fraction) of either a fertilizer solution or clear irrigation water, which was non-acidified (pH 7.1; 280 mg·L⁻¹ CaCO₃ equivalent), except for one treatment, which was acidified (A) by addition of 93% sulfuric acid (Ulrich Chemical, Indianapolis, IN) at 0.08 mL·L⁻¹ to an acceptable level of alkalinity as suggested by Nelson (2003) of 92 mg·L⁻¹ CaCO₃ equivalent, pH

6.3. Irrigation water acidification increased calcium (Ca) from 70 to 89 mg·L⁻¹ (possible dissolution of CaCO₃ precipitate in plumbing) and sulfur (S) from 28 to 72 mg·L⁻¹. A total of ≈900 mL and 1800 mL irrigation water was applied per container during the 3- and 5-week intervals, respectively.

Fertilizer treatments (described in Tables 1 and 2) consisted of an unfertilized control (C), four water-soluble fertilizers [coded EX (Excel), D (Daniels), P-Fe (Peters Professional), J-Fe (Jack's Professional)] applied at each irrigation, and four CRF treatments [using OP (Osmocote Plus) and OB (Osmocote Bloom)] incorporated in the substrate at transplant. Water-soluble fertilizer was applied at a uniform rate of 200 mg per L N but differed in N composition and concentration of all other nutrients (Table 1). Two WSFs (P-Fe and J-Fe) were selected because of their high Fe concentration (1.0 mg·L⁻¹) compared with EX (0.50 mg·L⁻¹) and D (0.10 mg·L⁻¹). Fertilizer rate for OP and OB was (3000 g·m⁻³) of substrate (2120 mg per container). The two CRFs differed in release rate (OP 90 to 120 d and OB 60 to 90 d). One OP treatment (OP-A) was irrigated with acidified water, whereas OP was irrigated with non-acidified water (as were the other fertilizer treatments). Osmocote Plus was also applied at a reduced rate (2100 g·m⁻³; 1490 mg per container) in combination with a WSF (EX at 100 mg per L N; coded OP/EX).

Substrate pH and EC and tissue analysis of recently matured leaves (Everris Testing Laboratory, Lincoln, NE) were conducted at 3 weeks (all species, finish for *Diascia* and *Sutera*) and at 5 weeks (finish for *Argyranthemum* and *Calibrachoa*). Substrate pH and EC were measured by the PourThru method (Cavins et al., 2000). Plant tissue was harvested (shoots dissected from roots at substrate surface and substrate washed from roots) when plants were considered marketable (finish) and dried in a forced-air oven (Sheldon Manufacturing, Inc., Cornelius, OR) at 70 °C for 72 h, and SDM and RDM were measured. Two of the six replications were combined to provide an adequate sample for a total of three replicates analyzed. Nitrogen

in dried plant tissue was determined after digestion in concentrated H₂SO₄ at 360 °C for ≈1.5 h and the NH₄⁺ in solution was measured with a Lachat QuikChem 8500 flow-injection analyzer. Other tissue nutrients [Ca, magnesium (Mg), K, P, manganese (Mn), Fe, zinc, copper, boron (B), S, molybdenum] were quantified with inductively coupled plasma atomic emission spectroscopy (Perkin Elmer 4300 DV spectrometer) after digestion in concentrated HNO₃ at 90 °C followed by three small additions of 30% H₂O₂ with a total digestion time of ≈1 h.

A visual quality rating of 0 to 4 was used. Visual quality rating was as follows: 0 indicated the plant was not marketable; 1 = poor size and quality; 2 = fair size and quality; 3 = plant-filled container, foliage color appropriate; and 4 = substrate not visible due to vigorous plant cover, overall appearance excellent. The visual quality rating for all plants was determined by visual evaluation of randomized containerized plants by one individual for consistency.

Four species and six replications (individual plant as experimental unit) per harvest date were randomized within each fertilizer treatment. All statistical analyses were conducted with SAS (SAS Institute Inc., Cary, NC). Analysis of variance was conducted using PROC MIXED, and pairwise comparisons between treatments were performed using Tukey's honest significant difference test. Shoot dry mass at finish was correlated with tissue nutrient concentrations with PROC REG. A linear plateau model was fit with PROC NLIN to describe the relationship between visual quality rating and tissue nutrient concentrations. The predicted tissue concentration associated with maximum quality was presented if convergence criteria were met and the model was significant ($P \geq 0.05$).

Results and Discussion

Shoot and root dry mass accumulation. Low nutrient availability may be reflected in reduced biomass accumulation. Shoot dry mass for all species at 3 weeks was not

Table 1. Quantity of ammonium (NH₄-N), urea, nitrate (NO₃-N), organic nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), boron (B), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn) present in the water-soluble and controlled-release fertilizer treatments.

Fertilizer	Code	Elemental mg·L ⁻¹ applied when applying 100 mg of N													
		NH ₄ -N	Urea	NO ₃ -N	Org-N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
Control—no fertilizer	C														
Peters Excel [®] 21–5–20	EX	34.8	5.2	60.0	0.0	10.4	79.4	0.0	0.0	0.0	0.125	0.125	0.5	0.25	0.05
Daniels [®] 10–4–3	D	37.0	36.5	19.0	7.5	17.5	24.8	0.1	0.5	10.0	0.020	0.01	0.1	0.05	0.003
Peters Professional [®] 15–3–25	P-Fe	26.7	0.0	73.3	0.0	8.7	138.9	0.0	16.7	6.7	0.125	0.125	1.0	0.25	0.05
Jack's Professional [®] 20–3–19	J-Fe	59.8	0.0	40.2	0.0	6.5	78.9	0.0	6.7	0.0	0.100	0.05	1.0	0.25	0.05
Osmocote [®] Plus ^z 15–9–12/Peters Excel [®] 21–5–20	OP/EX	56.0	0.0	44.0	0.0	26.2	66.1	0.0	8.7	40.0	0.126	0.33	3.1	0.40	0.13
Osmocote [®] Plus 15–9–12	OP-A	56.0	0.0	44.0	0.0	26.2	66.1	0.0	8.7	40.0	0.126	0.33	3.1	0.40	0.13
90 to 120 d at 21 °C															
Osmocote [®] Plus 15–9–12	OP	56.0	0.0	44.0	0.0	26.2	66.1	0.0	8.7	40.0	0.126	0.33	3.1	0.40	0.13
90 to 120 d at 21 °C															
Osmocote [®] Bloom ^z 12–7–18	OB	55.8	0.0	44.2	0.0	25.5	124.0	0.0	8.3	62.5	0.208	0.0	2.9	0.42	0.17
60 to 90 d at 21 °C															

^zEverris NA, Inc., Dublin, OH.

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significantly greater for the WSF treatments over the CRF treatments (Table 3, data not shown for *Argyranthemum* and *Calibrachoa*). At finish (5 weeks) for *Argyranthemum* and *Calibrachoa*, SDM was greater in fertilized plants compared with the unfertilized control and generally greater for the WSF treatments alone or in combination with a CRF over CRF alone. This may indicate that nutrient availability was limiting for the CRF fertilizers in the 35-d production cycle over that of the 21 d in which nutrients in the cuttings and starter charge were available (Table 3). Additionally,

by 5 weeks, more total N had been applied per container for WSF treatments (Table 2). Increased SDM at finish was correlated with increased shoot tissue N concentration for *Argyranthemum* ($r = 0.90$; $P = 0.0008$), *Calibrachoa* ($r = 0.88$; $P = 0.002$), *Diascia* ($r = 0.72$; $P = 0.03$), and *Sutera* ($r = 0.82$; $P = 0.007$). Van Iersel et al. (1998) reported a similar correlation between SDM and N in four species of bedding plant plugs, including *Petunia*. Shoot dry mass at finish was correlated with tissue K concentration for *Argyranthemum* ($r = 0.72$; $P = 0.03$) and

with tissue P concentration for *Calibrachoa* ($r = 0.85$; $P = 0.004$) and *Sutera* ($r = 0.68$; $P = 0.04$).

Direct comparisons were made between specific fertilizer treatments for *Diascia* and *Sutera* at 3 weeks and *Argyranthemum* and *Calibrachoa* at 5 weeks (finish), because fertilizer treatments were diverse (Table 3). At 3 weeks for *Diascia* and 5 weeks for *Calibrachoa*, SDM increased when the irrigation water was acidified (OP-A) over the non-acidified OP treatment. The combination (OP/EX) of CRF (OP; 2100 g·m⁻³ N) and

Table 2. Approximate total quantity (mg per container) of ammonium nitrogen (NH₄-N), urea, nitrate nitrogen (NO₃-N), soluble nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), boron (B), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn) applied over 3 (*Diascia* and *Sutera*) or 5 weeks (*Argyranthemum* and *Calibrachoa*).

Fertilizer ^z	N concn ^y	Code	Approximate quantity applied through week 3 (values should be doubled for soluble fertilizer through week 5) (milligrams/container)														
			Total N				P	K	Ca	Mg	S	B	Cu	Fe	Mn	Mo	Zn
			NH ₄ -N	Urea	NO ₃ -N	Org-N											
Control		C															
Peters Excel [®] x 21–5–20	200	EX	62.6	9.4	108.0	0	18.7	142.9	0	0	0	0.23	0.23	0.90	0.45	0.09	0.45
Daniels [®] w 10–4–3	200	D	66.6	65.7	34.2	13.5	31.5	44.6	0.18	0.90	18.0	0.04	0.02	0.18	0.09	0.01	0.07
Peters Professional [®] x 15–3–25	200	P-Fe	48.1	0	131.9	0	15.7	250.0	0	30.0	12.0	0.23	0.23	1.8	0.45	0.09	0.45
Jack's Professional [®] v 20–3–19	200	J-Fe	107.6	0	72.4	0	11.7	142.0	0	12.0	0	0.18	0.09	1.8	0.45	0.09	0.45
Osmocote [®] Plus ^x 15–9–12/ Peters Excel [®] 21–5–20	2100/100	OP/EX	156.5	4.7	152.3	0	67.9	219.2	0	19.4	89.4	0.39	0.85	7.38	1.12	0.34	0.96
Osmocote [®] Plus 15–9–12 90 to 120 d at 21 °C	3000	OP-A	178.1	0	139.9	0	83.3	210.2	0	27.7	127.2	0.40	1.05	9.86	1.27	0.41	1.05
Osmocote [®] Plus 15–9–12 90 to 120 d at 21 °C	3000	OP	178.1	0	139.9	0	83.3	210.2	0	27.7	127.2	0.40	1.05	9.86	1.27	0.41	1.05
Osmocote [®] Bloom ^x 12–7–18 60–90 d at 21 °C	3000	OB	142.0	0	112.4	0	64.9	315.5	0	21.1	159.0	0.53	0	7.38	1.07	0.43	0

^zNA = non-acidified irrigation water (280 mg·L⁻¹ CaCO₃ equivalent) and A = irrigation water acidified with sulfuric acid at 0.08 mL·L⁻¹ which reduced alkalinity to 92 mg·L⁻¹ CaCO₃ equivalent

^yWater-soluble fertilizer N conc. expressed in mg·L⁻¹, controlled-released fertilizer as g·m⁻³ substrate.

^xEverris NA, Inc., Dublin, OH.

^vBall Horticultural Company, West Chicago, IL.

^wJ. R. Peters, Inc., Allentown, PA.

Table 3. Shoot (SDM) and root (RDM) dry mass (after 3 weeks of fertilizer treatments) for *Diascia* 'Wink Coral' and *Sutera* 'Abunda Giant White' and after 5 weeks with various fertilizer treatments for *Argyranthemum* 'Madeira Cherry Red' and *Calibrachoa* 'Cabaret Pink Hot'.

Treatment ^z	SDM (grams/container)				RDM (grams/container)			
	<i>Diascia</i>	<i>Sutera</i>	<i>Argyranthemum</i>	<i>Calibrachoa</i>	<i>Diascia</i>	<i>Sutera</i>	<i>Argyranthemum</i>	<i>Calibrachoa</i>
C	1.30 c ^y	2.50 b	2.73 d	2.25 d	0.62 a	0.47 bc	1.52 c	0.69 c
EX	2.54 ab	4.22 a	9.82 a	11.39 a	0.42 bc	0.60 abc	2.25 abc	0.84 abc
D	2.57 ab	4.56 a	7.81 b	11.00 a	0.43 bc	0.44 c	1.86 bc	0.72 c
P-Fe	2.43 ab	4.15 a	8.13 b	9.84 ab	0.42 bc	0.48 bc	1.83 abc	0.76 bc
J-Fe	2.52 ab	4.44 a	9.08 ab	10.96 a	0.40 c	0.53 abc	1.76 abc	0.87 abc
OP/EX	2.67 a	4.31 a	7.70 b	9.11 ab	0.39 c	0.67 a	2.57 a	1.11 a
OP-A	2.62 ab	3.41 ab	5.41 c	7.53 bc	0.53 ab	0.59 abc	2.08 ab	1.08 ab
OP	1.94 bc	3.54 ab	4.89 c	5.31 c	0.45 bc	0.52 abc	1.94 abc	0.92 abc
OB	2.62 ab	4.24 a	5.94 c	8.30 b	0.46 bc	0.65 ab	2.54 abc	0.91 abc
Comparisons	-----Level of significance-----							
OP-A vs. OP	**	NS	NS	**	*	NS	NS	NS
OP vs. OP/EX	**	*	***	***	NS	NS	***	**
OP/EX vs. EX	NS	NS	***	**	NS	NS	NS	*
OP vs. OB	**	NS	NS	***	NS	*	*	NS

^zControl (C), Excel (EX), Daniels (D), Peters Professional (P-Fe), Jack's Professional (J-Fe), Osmocote Plus/Excel (OP/EX), Osmocote Plus-acidified water (OP-A), Osmocote Plus (OP), Osmocote Bloom (OB).

^yValues within columns with the same letter are not significantly different by Tukey's honestly significant difference test at $P \geq 0.05$.

NS = nonsignificant. *, **, *** = significant comparison at $P = 0.05, 0.01, 0.001$, respectively.

WSF (EX; 100 mg per L N) resulted in less SDM for *Argyranthemum* than when WSF (EX; 200 mg per L N) was applied alone, suggesting that nutrient availability from this CRF limited plant growth at the rate applied. The other CRF used in this study (OB) had a release rate of 60 to 90 d compared with 90 to 120 d for OP and resulted in greater SDM production than OP in *Calibrachoa* and *Diascia*, indicating that the release rate of OP may have been too slow to support maximum plant growth of this crop.

Root dry mass of fertilized plants was equivalent to or greater than the unfertilized control for *Sutera* (3 weeks), *Argyranthemum* (5 weeks), and *Calibrachoa* (5 weeks). However, RDM of *Diascia* was reduced by addition of nutrients compared with the control with the exception of the OP-A treatment (Table 3).

Visual quality rating. The OP and OP-A treatments resulted in plants that had a significantly lower visual quality rating than the other fertilizer treatments at 3 weeks for *Sutera* (2.0 vs. an average of 3.5) but not for *Diascia* (Table 4). *Argyranthemum* and *Calibrachoa* fertilized with OP had a visual quality rating of 2.3 and 2.2, respectively, significantly less than the 3.6 average for the other seven fertilizer treatments after 5 weeks. In a study with *Impatiens hawkeri* W. Bull., Ostrom (2011) found consumer preference ratings for foliage, vigor, and uniformity (when averaged over the three application rates) were higher for conventional WSF and soybean-based fertilizer (Daniels; Ball Horticultural Company) over the slow-release fertilizer and CRF used in their study. When flower number was included in the rating, the average rating for CRF equaled that of the WSF. Flower number was not factored into our study because only *Argyranthemum* was not in flower before fertilizer treatments were applied, and there was no observable difference. The largest plants (greatest SDM) were not consistently correlated with the highest visual quality rating in our study or with highest consumer preference rating in Ostrom (2011).

When plants received irrigation water of pH 7.1 (OP and OB treatments), those fertilized with OB were assigned a significantly higher visual quality rating than the OP fertilized plants for all species with the exception of *Diascia* (Table 4). There was a significant increase in quality rating using acidified water (OP-A treatment) compared with the OP treatment in *Argyranthemum* only. There was little or no increase in visual quality in the production phase when using Excel (EX) at 200 mg·L⁻¹ N alone over a combination of OP and EX (Table 4).

Tissue analysis. Visual quality rating at finish was most closely related to leaf tissue N and P in all species and to K for *Argyranthemum* and *Calibrachoa* only (Fig. 1). *Argyranthemum*, *Calibrachoa*, and *Sutera* are most sensitive to N and Fe deficiencies, whereas *Sutera* is also susceptible to Mn and S deficiencies (Gibson et al., 2007). This information has not been reported for *Diascia*, except for sensitivity

to Fe deficiency. Leaf tissue analyses at finish indicated that there was an interaction between fertilizer treatment and species for N, P, K, Ca, Fe, Mg, B, Mn, and S. Tissue analysis data for N, P, K, and Fe only are included in Table 5, because Mg, B, Mn, and S were not highly related to visual quality rating for any species by visual assessment of correlation graphs. Leaf tissue Fe was related to visual quality rating for only *Diascia* but was included for its relevance to the species studied. Sufficiency ranges used were those of the Everris Testing Laboratory for bedding plants in general, which were similar to the recommended range for *Argyranthemum*, *Calibrachoa*, and *Sutera* reported by Gibson et al. (2007), with the exception of higher N concentration recommended for *Argyranthemum* (65 to 73 vs. 35 to 46 mg·g⁻¹) and lower Fe concentration recommended for *Argyranthemum* and *Sutera* (56 to 66 vs. 90 to 250 mg·kg⁻¹) in Gibson et al. (2007).

Table 4. Visual quality rating (rated on a scale of 0 to 4) at finish (after 3 weeks of fertilizer treatments) for *Diascia* 'Wink Coral' and *Sutera* 'Abunda Giant White' and (after 5 weeks with various fertilizer treatments) for *Argyranthemum* 'Madeira Cherry Red' and *Calibrachoa* 'Cabaret Pink Hot'.

Treatment ²	Visual quality rating			
	<i>Diascia</i>	<i>Sutera</i>	<i>Argyranthemum</i>	<i>Calibrachoa</i>
C	0.8 c ³	0.0 d	0.0 e	0.0 c
EX	4.0 a	3.5 ab	4.0 a	3.8 a
D	3.8 ab	4.0 a	3.0 c	4.0 a
P-Fe	4.0 a	4.0 a	4.0 a	4.0 a
J-Fe	4.0 a	3.5 ab	4.0 a	4.0 a
OP/EX	3.8 ab	3.2 b	3.7 ab	3.7 a
OP-A	3.2 b	2.0 c	3.2 bc	2.5 b
OP	3.5 ab	2.0 c	2.3 d	2.2 b
OB	3.8 ab	3.0 b	3.0 c	3.8 a

Comparisons	Level of significance			
OP-A vs. OP	NS	NS	***	NS
OP vs. OP/EX	NS	***	NS	***
OP/EX vs. EX	NS	NS	*	NS
OP vs. OB	NS	***	***	***

²Control (C), Excel (EX), Daniels (D), Peters Professional (P-Fe), Jack's Professional (J-Fe), Osmocote Plus/Excel (OP/EX), Osmocote Plus-acidified water (OP-A), Osmocote Plus (OP), Osmocote Bloom (OB).

³Values within columns with the same letter are not significantly different by Tukey's honestly significant difference test at $P \geq 0.05$.

NS = nonsignificant. *, **, *** = significant comparison at $P = 0.05, 0.001$, respectively.

Fig. 1. Visual quality rating (scale of 0 to 4) at finish (after 3 weeks of fertilizer treatments) for *Diascia* 'Wink Coral' (black symbol) and *Sutera* 'Abunda Giant White' (dark gray) and (after 5 weeks of fertilizer treatments) for *Argyranthemum* 'Madeira Cherry Red' (light gray) and *Calibrachoa* 'Cabaret Pink Hot' (white) with leaf tissue nitrogen (N), phosphorus (P), and potassium (K). Individual points represent means for each species across all treatments. Indicated treatment and species keys apply to all three plots.

Table 5. Tissue nitrogen, phosphorus, potassium and iron concentration at finish (after 3 weeks of fertilizer treatments) for *Diascia* 'Wink Coral' and *Sutera* 'Abunda Giant White' and (after 5 weeks of fertilizer treatments) for *Argyranthemum* 'Madeira Cherry Red' and *Calibrachoa* 'Cabaret Pink Hot'.

Treatment ^z	<i>Diascia</i>	<i>Sutera</i>	<i>Argyranthemum</i>	<i>Calibrachoa</i>
Nitrogen (mg·g ⁻¹)				
C	21.0 e ^y	14.3 g	13.1 g	8.5 g
EX	49.9 b	51.1 b	51.7 b	41.6 b
D	56.0 a	56.7 a	57.8 a	46.4 a
P-Fe	48.2 b	45.4 c	47.1 c	37.8 c
J-Fe	49.2 b	50.2 bc	48.7 bc	41.2 bc
OP/EX	45.3 b	34.6 d	33.8 d	26.9 d
OP-A	30.7 d	20.7 f	22.2 f	12.9 f
OP	33.1 d	20.8 f	20.8 f	15.4 ef
OB	38.9 c	26.4 e	27.2 e	16.8 e
Phosphorus (mg·g ⁻¹)				
C	3.5 f	2.5 e	2.2 g	1.6 f
EX	7.6 ab	6.0 a	6.8 b	4.4 a
D	8.7 a	6.9 a	10.4 a	4.2 a
P-Fe	7.0 bc	5.0 b	5.7 c	4.0 ab
J-Fe	5.2 de	4.4 bc	4.3 de	3.3 bc
OP/EX	6.0 cd	3.7 cd	4.1 def	2.8 cd
OP-A	4.6 ef	3.2 de	3.3 ef	1.8 ef
OP	4.5 ef	2.9 de	3.2 fg	2.0 ef
OB	5.2 de	3.1 de	4.6 d	2.3 de
Potassium (mg·g ⁻¹)				
C	21.7 e	20.2 b	20.9 e	13.9 e
EX	40.2 ab	42.2 a	53.4 b	33.4 ab
D	21.9 e	18.9 b	27.8 cd	16.3 de
P-Fe	45.6 a	44.8 a	72.2 a	36.7 a
J-Fe	39.1 ab	43.4 a	51.3 b	31.3 b
OP/EX	36.4 bc	26.4 b	31.0 c	22.9 c
OP-A	24.1 de	22.3 b	24.4 de	15.1 de
OP	23.3 de	19.3 b	24.1 de	17.6 de
OB	30.6 cd	23.6 b	31.6 c	18.8 cd
Iron (mg·kg ⁻¹)				
C	69.4 b	110.4 bc	56.9 a	62.5 a
EX	94.2 ab	123.5 b	63.7 a	76.3 a
D	102.8 a	86.6 c	53.7 a	65.0 a
P-Fe	101.4 a	109.1 bc	59.9 a	72.1 a
J-Fe	107.7 a	196.1 a	68.7 a	77.3 a
OP/EX	87.0 ab	87.6 c	54.4 a	57.9 a
OP-A	73.9 b	89.0 c	54.5 a	52.0 a
OP	86.2 ab	85.2 c	56.8 a	51.2 a
OB	84.4 ab	107.8 bc	67.4 a	50.6 a

^zControl (C), Excel (EX), Daniels (D), Peters Professional (P-Fe), Jack's Professional (J-Fe), Osmocote Plus/Excel (OP/EX), Osmocote Plus-acidified water (OP-A), Osmocote Plus (OP), Osmocote Bloom (OB).

^yFor each nutrient within-column means followed by different lower-case letters are significantly different by Tukey's honestly significant difference test at $P \leq 0.05$.

Tissue N was greater with WSF treatments than with CRF for all species (Table 5). Visual quality rating increased with increasing leaf tissue N for all species up to a point (Fig. 1). Maximum quality was attained at N concentrations of 24, 18, 34, and 26 mg·g⁻¹ for *Argyranthemum*, *Calibrachoa*, *Diascia*, and *Sutera*, respectively (Table 6). All species attained maximum quality near or below the previously defined sufficiency range (35 to 46 mg·g⁻¹) for bedding plant crops (Everris Testing Laboratory). This value corresponds to the low end of the sufficiency range of 38 to 76 mg·g⁻¹ reported for *Petunia* × *hybrida* Vilm. (Mills and Jones, 1996), an Fe-inefficient crop in which much research has been conducted and closely related to *Calibrachoa*.

Deficiency symptoms, purple pigmentation in older leaves and dark green foliage, were observed in the OP and OP-A treatments

for *Sutera* and the OB treatment for *Calibrachoa*. Tissue P was related to visual quality rating with increases in visual quality rating with increasing leaf tissue P dependent on species (Fig. 1). Tissue P concentrations related to maximum visual quality were 3.6, 2.2, 4.8, and 3.5 mg·g⁻¹ for *Argyranthemum*, *Calibrachoa*, *Diascia*, and *Sutera*, respectively (Table 6). Mills and Jones (1996) reported a survey range of 4.7 to 9.3 mg·g⁻¹ for *Petunia* × *hybrida* Vilm. and Everris Testing Laboratory uses a sufficiency range of 4.0 to 6.7 mg·g⁻¹ for bedding plants in general.

For leaf tissue K, values for the Daniels, OP, OP-A, and OB treatments were significantly lower than for the EX, P-Fe, and J-Fe treatments for all species at 3 and 5 weeks (Table 5). Nelson et al. (2010) reported leaf tissue K concentrations with six bedding plant species and petunia fertilized with Daniels

fertilizer were below those for conventional fertilizer with no K deficiency symptoms observed as was the case in this study. Leaf tissue K levels were within the sufficiency range of 20 to 88 mg·g⁻¹ (Everris Testing Laboratory) and 31 to 66 mg·g⁻¹ (Mills and Jones, 1996) in *Calibrachoa* for the EX, P-Fe, and J-Fe treatments only. Leaf tissue K was related to visual quality rating for *Argyranthemum* and *Calibrachoa* but not *Diascia* and *Sutera* (Fig. 1C). Leaf K concentrations at maximum visual quality were 28 and 18 mg·g⁻¹ for *Argyranthemum* and *Calibrachoa*, respectively (Table 6). Fertilizer nutrient concentration values presented in Table 1 show twice as much K was supplied (although not necessarily available) in the OB over OP treatments and three to five times as much K in the three WSF fertilizers compared with Daniels.

Tissue Fe concentration was related to visual quality rating only for *Diascia* (data not shown). Maximum quality rating occurred at a Fe concentration of 75 mg·kg⁻¹. The linear plateau model explaining the relationship was: quality = $-36.2133 + 0.53333 \times (\text{Fe, mg·kg}^{-1})$ at $\text{Fe} < 75 \text{ mg·kg}^{-1}$, 3.8 thereafter ($R^2 = 0.98$; $P < 0.0001$). Suboptimal Fe concentrations in *Diascia* only occurred with the control and OP-A treatments. Leaf tissue Fe levels in the control plants in the other three species studied ranged from 57 to 110 mg·kg⁻¹ and were sufficient for maximum visual quality although below the sufficiency range of 90 to 250 mg·kg⁻¹ (Everris Testing Laboratory). Visual deficiency symptoms are often not correlated with tissue Fe concentrations (Mills and Jones, 1996). Iron provided to the rooted cuttings before transplant may be a factor in lack of tissue response to Fe in the fertilizer treatments during finish. Because N is considered the most likely nutrient to affect plant growth and development, release rates, and thus longevity for CRFs are based on N release rate. In a nutrient leaching study, release rate in seven different CRFs was greatest for N, intermediate for P and K, and very slow for Mg, Mn, and Fe (Broschat and Moore, 2007). Providing Fe and other micronutrients through CRFs alone could result in Fe deficiencies in Fe-inefficient species in cropping cycles under 5 weeks, particularly if grown from seed.

Although the total quantity of each nutrient applied was high for the CRFs in our study (Table 2), the proportion available in the short 21- to 35-d period to finish these rapidly growing bedding plant crops was likely much less. Longevity influences release rate (Hasse et al., 2007) with OB (60 to 90 d) likely releasing nutrients more rapidly than OP (90 to 120 d). Continued release of nutrients after the 35-d production period would also contribute to crop viability during transport, retail sale, and garden performance, benefits not measured in this study.

Substrate electrical conductivity and pH. Substrate EC is often used to assess nutrient availability (Nelson, 2003). Average substrate EC was typically greater for the conventional water soluble EX, P-Fe, and J-Fe

Table 6. Parameters for linear plateau models (see Fig. 1) relating visual quality rating (0 = lowest quality to 4 = highest quality) to tissue concentration of nitrogen (N), phosphorus (P), and potassium (K) at finish (after 3 weeks of fertilizer treatment) for *Diascia* 'Wink Coral' and *Sutera* 'Abunda Giant White' and at finish (after 5 weeks of fertilizer treatment) for *Argyranthemum* 'Madeira Cherry Red' and *Calibrachoa* 'Cabaret Pink Hot'.

Species	Intercept	Slope	Joint point	R ²	Prob>F
----- Level of significance -----					
Tissue N (mg·g ⁻¹) vs. visual quality rating (0–4)					
<i>Argyranthemum</i>	–4.40909	0.33382	24.0422	0.90	0.001
<i>Calibrachoa</i>	–3.28278	0.40357	17.7983	0.93	0.0004
<i>Diascia</i>	–4.0048	0.23012	34.3504	0.99	<0.0001
<i>Sutera</i>	–4.43307	0.31002	25.6963	0.94	0.0003
Tissue P (mg·g ⁻¹) vs. visual quality rating (0–4)					
<i>Argyranthemum</i>	–5.88694	2.66216	3.56988	0.89	0.001
<i>Calibrachoa</i>	–8.33333	5.5	2.22121	0.90	0.0009
<i>Diascia</i>	–7.54595	2.39189	4.78531	0.98	<0.0001
<i>Sutera</i>	–8.67826	3.56522	3.45512	0.88	0.002
Tissue K (mg·g ⁻¹) vs. visual quality rating (0–4)					
<i>Argyranthemum</i>	–8.42605	0.4342	28.0195	0.79093	0.009
<i>Calibrachoa</i>	–7.9291	0.64255	18.3474	0.64842	0.04
<i>Diascia</i>	NA ^z	NA	NA	NA	0.16
<i>Sutera</i>	NA	NA	NA	NA	0.35

^zNA = not applicable because model not significant ($P \geq 0.05$).

treatments over D and the CRF products for all species at both sampling dates (data not shown). The conventional WSFs provided a medium (2.6 to 4.6 dS·m⁻¹) level of fertility (average of 2.7 dS·m⁻¹ across species and dates) as compared with a light feed (1.0 to 2.6 dS·m⁻¹) from the other products (average of 1.3 dS·m⁻¹ across species and dates) (using the scale in Whipker et al., 2003). The OP treatment EC value was significantly lower than for the OP-A or OB treatments at 3 weeks but not at 5 weeks. Newman et al. (2006) found that in a pH-neutral substrate without plant material, the concentration of NH₄-N and NO₃-N present in the leachate of four different polymer-coated fertilizers increased at ≈5 weeks, indicating that the lower EC observed with the CRF treatments in our study at 3 and 5 weeks may be the result of release rate, especially for the OP treatment (90- to 120-d longevity). There were species differences in EC at 3 weeks with *Diascia* and *Sutera* being significantly higher than *Calibrachoa* and *Argyranthemum*, the species requiring higher fertilizer inputs. *Calibrachoa* and *Argyranthemum* maintained similar EC values from 3 to 5 weeks.

Substrate differences in pH were observed at 3 weeks with values above the recommended range for these species (5.5 to 6.2) (Gibson et al., 2007) for the C, D, and OP treatments for all species (data not shown). At 5 weeks, substrate pH increased for *Argyranthemum* and *Calibrachoa* from an average of 6.1 to 6.6. The relatively short (3- to 5-week) production period resulting from ideal light and temperature conditions allowed finishing of crops before Fe or Mn nutrient deficiency symptoms as a result of high pH developed.

Conclusions

Although cost per unit of N in a CRF is higher than for WSF, a reduction in labor

resulting from a single fertilizer application and controlled-release rate of nutrients, which reduces losses through leaching, have made CRFs a useful technology for high-value horticulture crops. However, under the conditions in our study, WSFs alone or in combination with a CRF resulted in bedding plants with a higher visual quality rating than those fertilized with CRF alone. The combination treatment (2100 g·m⁻³ OP and 100 mg·L⁻¹ EX) resulted in plants with a high visual quality rating, a potential for reduced N loss, and post-production provision of nutrients. Species should be considered in any fertilizer management approach because there can be significant differences in response in as little as 3 weeks.

The Osmocote Bloom (12–7–18, 60 to 90 d, 220 prills/g) treatment resulted in plants with a higher visual quality rating at finish over the Osmocote Plus (15–9–12, 90 to 120 d, 40 prills/g) treatment for all species except *Diascia*, in which they were the same. Tissue analysis indicated differences only in leaf tissue N, which could be attributable to release rate or improved distribution resulting from smaller prill size, because N form is similar for the two products and OB contains 3% less N than OP. Reduced prill size and shorter longevities would appear to be beneficial for the short-term production of bedding plants in small containers, especially in species requiring greater fertilizer inputs such as *Argyranthemum* and *Calibrachoa*.

The reduced SDM with CRFs in *Argyranthemum* may reduce need for a plant growth regulator (PGR) application; however, the growth habit of *Calibrachoa*, *Diascia*, and *Sutera* may still require a PGR application to produce the compact plants desired regardless of reduction in SDM. Maximum SDM was not correlated with maximum visual quality rating for any species.

We were able to use discretion in hand irrigation for a total application of ≈900 mL per container in a 3-week period. Water use

in an automated irrigation system in a commercial greenhouse operation would likely result in larger inputs of water and thus WSF, so the total amount of nutrients applied by WSF would more closely align with that of CRFs (Table 2).

For the short production cycle (less than 5 weeks) in this study, marketable iron-inefficient bedding plant species without deficiency symptoms were produced using acidifying WSF with high alkalinity irrigation water (pH 7.1, 280 mg·L⁻¹ CaCO₃ equivalent). However, by Week 5, pH was not maintained in the recommended range and another management approach is recommended.

Future work could include a study comparing multiple application rates of several WSF formulations to CRFs because the WSF rate used in this study resulted in leaf tissue N concentrations above the threshold associated with a high visual quality rating and the CRF rate resulted in leaf tissue N concentrations below the threshold. Work with additional commercially important species could verify if the N, P, and K thresholds associated with a high visual quality rating in this study hold true. Established threshold leaf tissue nutrient concentrations could then be used to determine fertilizer application rates above which no additional profit can be expected despite increased growth or quality. Current nutrient application rates based on established leaf tissue nutrient sufficiency ranges have not been related to wholesale or retail value, and the ability to do so has the potential to maximize profit and minimize nutrient waste. Creating a model that could assess this by crop would be a useful tool in maximizing fertilizer efficiency. Our study focused on production only. Additional studies including a post-production shrinkage component would be necessary in making a complete economic benefit comparison between the WSF and CRF nutrient delivery systems.

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