lower half of containers with layered fertilizer and then grow rapidly to a large size by the time these palms reached a marketable size. If weed biomass in these long term crops had been measured after only a few months of growth, their biomass may have been lower for layered fertilized pots relative to top dressed or incorporated fertilized pots for those palm species that showed no significant differences in weed growth in these experiments.

In conclusion, plant growth response to fertilizer placement varied considerably among species, but with the exception of areca palm, none of the species tested grew best with incorporated fertilizer. Layering of controlled-release fertilizer just below the liner root ball can reduce weed growth and improve plant growth in some species, but potential root injury is an important consideration if the roots are in direct contact with the fertilizer layer.

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Correcting Iron Deficiency in Calibrachoa Grown in a Container Medium at High pH

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SUMMARY. The objective was to evaluate and compare foliar spray and soil drench application methods of iron (Fe) for correcting Fe deficiency in hybrid calibrachoa (*Calibrachoa* ×*hybrida*) grown in a container medium at pH 6.9 to 7.4. Untreated plants showed severe chlorosis and necrosis, stunting, and lack of flowering. An organosilicone surfactant applied at 1.25 mL·L^{-1} (0.160 fl oz/gal) increased uptake of Fe from foliar applications of both ferrous sulfate ($FeSO_4$) and ferric ethylenediamine tetraacetic acid (Fe-EDTA). Foliar sprays at 60 mg·L^{-1} (ppm) Fe were more effective when Fe was applied as Fe-EDTA than $FeSO_4$. Increasing Fe concentration of foliar sprays up to 240 mg·L^{-1} Fe from Fe-EDTA or 368 mg·L^{-1} Fe (the highest concentrations tested) from ferric diethylenetriamine pentaacetic acid (Fe-DTPA) increased chlorophyll content compared with lower spray concentrations, but leaf necrosis at the highest concentrations may have been caused by phytotoxicity. Drenches with ferric ethylenediaminedi(o-hydroxyphenylacetic) acid (Fe-EDDHA) at 20 to 80 mg·L^{-1} Fe were highly effective at correcting Fe-deficiency symptoms, and had superior effects on plant growth compared with drenches of Fe-DTPA at 80 mg·L^{-1} Fe or foliar sprays. Efficacy of Fe-DTPA drenches increased as concentration increased from 20 to 80 mg·L^{-1} Fe. An Fe-EDDHA drench at 20 to 80 mg·L^{-1} Fe was a cost-effective option for correcting severe Fe deficiency at high medium pH.

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Micronutrient deficiency at high medium pH is a common problem for container plant production (Nelson, 1994). Solubility of micronutrients, other than molybdenum, has been shown to decrease as pH increases in organic soils (Lucas and Davis, 1961) and soilless growing media (Peterson, 1981).

Iron is often the nutrient that becomes limiting first for plant growth at high pH in both calcareous field soils (Miller et al., 1984) and greenhouse media (Nelson, 1994). However, plant species differ in their ability at taking up Fe at the same medium pH. The term iron-inefficient species has been used to describe crops such as calibrachoa and petunia (*Petunia* ×*hybrida*) hybrids that are inefficient at taking up Fe into the plant tissue (Argo and Fisher, 2002; Marschner, 1995; Nelson, 1994). The most common problems with Fe deficiency occur when Fe-inefficient plants (with low ability to take up Fe) are grown at high medium pH (with low Fe solubility).

There are a number of strategies for correcting Fe deficiency in plant tissue caused by high medium pH. One approach is to lower medium pH, which increases the solubility of Fe (and other micronutrients) already in the medium and therefore will increase the uptake of Fe by plant roots (Argo and Fisher, 2002; Bailey, 1996). Another strategy is to apply additional Fe to the plant, either using soil drenches or foliar sprays, to reduce the effect of medium pH on Fe nutrition (Argo and Fisher, 2002; Nelson, 1998; Swietlik and Faust, 1984; Wallace et al., 1957).

Efficacy of foliar Fe sprays can be increased by several factors. Surfactants, particularly organosilicones, can improve coverage and uptake of Fe sprays on citrus (*Citrus* spp.), and reduce phytotoxicity (Neumann and Prinz, 1974). Complete spray coverage is important for foliar-applied nutrients, because absorption is more rapid through the abaxial leaf surface which tends to have a thinner cuticle, and the cuticle is the major barrier to uptake (Swietlik and Faust, 1984). Iron chelates are extensively used for foliar applications, and their effectiveness is probably related to their increased mobility within the plant compared with inorganic salts of Fe (Swietlik and Faust, 1984). Even chelated forms of Fe have limited mobility between plant organs, however, and repeated applications of Fe sprays are needed (Swietlik and Faust, 1984; Wallace et al., 1957). Rapid drying of foliar sprays can limit uptake (Marschner, 1995) and in our experience with bedding plants, we have observed increased dark green and necrotic spotting of leaves when Fe spray applications were made at 25 °C (77.0 °F) air temperature. The cuticle is highly permeable to urea (Marschner, 1995). Urea and ammonium nitrate applied at 500 to 1000 $mg \cdot L^{-1}$ (ppm) nitrogen (N) in combination with $FeSO_4$ increased foliar uptake of Fe in corn (*Zea mays*), but urea and ammonium nitrate did not increase uptake of Fe-EDTA (Hsu and Ashmead, 1984).

Iron can also be applied as a corrective drench directly to the growing medium (Nelson, 1998), and at high medium pH (above 6.5) the form of Fe is important in determining solubility (Norvell, 1972). Iron forms most commonly supplied in water-soluble fertilizers for the U.S. greenhouse industry are $FeSO_4$ and Fe-EDTA, with some use of Fe-DTPA and Fe-EDDHA primarily as supplements. In order of increasing solubility at solution pH's above 6.5, Fe forms vary from sulfate < EDTA < DTPA < EDDHA (Norvell, 1972). Fe-EDDHA has therefore been considered as the most effective chelate for correcting Fe deficiency at high soil pH, although its use has been limited by high cost and limited commercial availability compared with other Fe forms (Hagstrom, 1984).

The objective of this study was to compare the effectiveness of foliar versus soil drench applications of Fe for correcting chlorosis at high medium pH in hybrid calibrachoa. Several hypotheses were investigated.

1) Addition of an organosilicone surfactant would increase effectiveness of foliar-applied Fe.

2) Increasing Fe concentration would result in increased chlorophyll content and/or phytotoxicity for foliar sprays.

3) Drenches of Fe-EDDHA would be more effective than Fe-DTPA at pH above 6.5, because of the greater stability of Fe-EDDHA.

Materials and methods

Experiments were conducted using hybrid calibrachoa 'Million Bells Trailing White' planted at either the University of New Hampshire, Durham (UNH) on 11 June 2001 or the Ohio State University, Columbus (OSU) on 7 Sept. 2001. Experimental designs to investigate each hypothesis, with 8 (UNH) or 12 (OSU) replicate plants per treatment in a completely randomized design, were as follows.

1) Organosilicone surfactant. Capsil (Capsil 30; Aquatrols, Cherry Hill N.J.) was applied in an experiment conducted at UNH, at rates of 0, 0.47, or 1.25 $mL \cdot L^{-1}$ (0, 0.060, or 0.160 fl oz/gal). In comparison, U.S. Environmental Protection Agency label rates for this product ranged from 0.47 to 1.25 $mL \cdot L^{-1}$. Capsil concentrations were combined with either deionized water, 60 $mg \cdot L^{-1}$ Fe from Fe-EDTA, or 60 $mg \cdot L^{-1}$ Fe from $FeSO_4$ in a factorial design.

2) Concentration of foliar sprays. Iron was provided at 0, 60, 120, 180, and 240 $mg \cdot L^{-1}$ Fe from Fe-EDTA at UNH, and 0, 46, 92, 184, and 368 $mg \cdot L^{-1}$ Fe from Fe-DTPA at OSU. Capsil was included at 0.47 $mL \cdot L^{-1}$ for all treatments at UNH and 1.25 $mL \cdot L^{-1}$ at OSU.

3) Fe-EDDHA versus Fe-DTPA drenches. 0, 20, 40, and 80 $mg \cdot L^{-1}$ Fe from either Fe-DTPA or Fe-EDDHA were applied as a single drench at UNH and OSU in a factorial design.

Rooted cuttings from an 84-count 25.4 × 50.8-cm (10 × 20-inch) propagation tray were transplanted into 10.2-cm (4-inch) diameter pots, using MetroMix 560 Coir growing medium (Scotts Co., Marysville, Ohio), which included composted pine bark, coconut coir, bark ash, sphagnum peat moss, and perlite. A flowable lime slurry (LimeStone-F; W.A. Cleary Corp., Dayton, N.J.) at 20 $mL \cdot L^{-1}$ (2.6 fl oz/gal) was applied at a rate of 100 mL (3.4 fl oz) per pot at time of planting and 4 d later to increase medium pH, with foliage immediately rinsed to remove a small amount of lime residue.

Plants were irrigated with a complete water-soluble fertilizer including micronutrients [17.0N–2.2P–14.1K–3.0Ca–1.0Mg composed of commercial-fertilizer grade potassium nitrate, calcium nitrate, ammonium nitrate, magnesium nitrate, and ammonium phosphate, Fe-EDTA, manganese sulfate, zinc sulfate, copper sulfate, boric acid, and sodium molybdate, and with a neutral acid reaction, (GreenCare Inc., Chicago, Ill.)] at 150 $mg \cdot L^{-1}$ N throughout the experiment by top-watering, and with near-zero leaching.

Medium pH and electro-conductivity (EC) were measured using the saturated-medium extract method with deionized water as the extractant (Warncke, 1986). Medium pH was measured on 10 destructively sampled containers at 0, 14, and 28 d after planting. Medium pH was measured directly in the saturated medium using a pH meter (model 620; Orion Technologies, Beverly, Mass.) at UNH and a compact pH meter (Horiba Twin B-213; Spectrum Technologies Inc., Plainfield, Ill.) at OSU. Medium EC was measured in the filtered extract using an EC meter (model 130; Orion) at UNH and a conductivity meter (Horiba Twin B-173; Spectrum Technologies Inc.) at OSU.

All foliar spray treatments were applied at 10 mL (0.34 fl oz) per pot on four occasions, 14, 17, 21, and 24 d after planting. Drench treatments were applied once, 14 d after planting at 100 mL/pot with an average of 27 mL (0.91 oz) of solution leached per pot at UNH and 19 mL (0.64 oz) leached at OSU. Containers were arranged randomly on benches in a well-ventilated glass greenhouse. During the experiment, day and night air temperature averaged 26.3 °C (79.34 °F) and 20.1 °C (68.18 °F) at UNH and 23.3 °C (73.94 °F) and 20.6 °C (69.08 °F) at OSU, respectively.

Final data collection occurred on day 28 at OSU and day 37 at UNH. A chlorophyll index meter ([SPAD (soil plant analysis development); Minolta, Ramsey N.J.] was used to measure five leaves per plant randomly selected from the top 2.5 cm (1.0 inch) of shoots. The SPAD meter indirectly measures chlorophyll content in a nondestruc-

Table 1. Analysis of variance (ANOVA) showing effects of Capsil 30 organosilicone surfactant at 0, 0.47, and 1.25 mL·L^{-1} (0, 0.060, and 0.160 fl oz/gal) in combination with different iron (Fe) forms and concentrations [deionized water control, ferrous sulfate ($FeSO_4$) at 60 mg·L^{-1} (ppm) Fe, and ferric ethylenediamine tetraacetic acid (Fe-EDTA) at 60 mg·L^{-1} Fe] on efficacy of foliar sprays for correcting Fe deficiency symptoms in calibrachoa grown at medium pH 7.

	ANOVA effects			0 mL·L^{-1} Capsil			0.47 mL·L^{-1} Capsil			1.25 mL·L^{-1} Capsil		
Parameter	Capsil	Fe	Capsil x Fe	Control	$FeSO_4$	Fe-EDTA	Control	$FeSO_4$	Fe-EDTA	Fe- Control	$FeSO_4$	EDTA
Shoot length (cm)	NS	***	NS	10.4 b[z]	10.4 b	11.5 ab	10.8 b	11.0 b	12.1 ab	10.5 b	10.7 b	13.5 a
Shoot dry wt (g)	NS	***	NS	1.23 b	1.29 ab	1.39 ab	1.15 b	1.23 b	1.41 ab	1.09 b	1.32 b	1.67 a
SPAD chlorophyll index	*	***	NS	15.5 b	18.6 ab	19.9 ab	14.9 b	20.8 ab	22.4 a	15.3 b	24.0 a	24.5 a
Proportion of necrotic leaves (%)	***	***	*	81.4 a	79.6 a	54.7 ab	87.5 a	53.2 ab	34.3 bc	81.1 a	37.2 bc	13.1 c
Number of flower buds	NS	*	NS	0.0 a	3.8 a	2.1 a	0.0 a	1.1 a	1.4 a	1.0 a	2.4 a	3.4 a
Fe concn [μg·g^{-1} (ppm)]	***	***	***	90.0 de	282.0 a	171.4 bc	75.5 de	307.2 a	131.5 cd	63.7 e	211.3 b	150.5 c
Fe uptake into shoot (μg/plant = Fe concn × dry wt)	*	***	***	118.8 de	363.8 a	238.2 bc	86.8 e	377.9 a	185.4 cd	69.4 e	278.9 b	251.3 bc

[z]Letters after values in each column represent mean separation at the 95% level using Tukey's honestly significant difference (HSD) mean comparison method.
NS,*,**,***Nonsignificant or significant at the 95%, 99%, or 99.9% levels, respectively.

tive manner, by comparing the ratio of light transmitted by the leaf at 650 and 940 nm, and has been used to quantify severity of leaf chlorosis associated with Fe deficiency (Peryea and Kammereck, 1997). Before the UNH experiment, SPAD values from 44 plants of calibrachoa 'Million Bells Trailing White' were compared with chlorophyll measurements using a spectrophotometer (in μg·g^{-1} of dried tissue, using a 95% ethanol extraction and measurement protocol based on Lichtenthaler (1987)). The linear relationship was chlorophyll content = –0.2128 + 0.0295*SPAD, with an r^2 of 0.86.

The numbers of leaves at the top 2.5 cm of one shoot per plant with or without necrosis were counted, and the percentage of necrotic leaves/plant was calculated from these data. Shoot length was averaged from three random shoots per plant. Shoots were washed in 0.1 N HCl, followed by a wash with a nonphosphate detergent, followed by a distilled water rinse and then shoot dry weight was measured after tissue was dried at 50 °C (122.0 °F) for 10 d at UNH or 52 °C (125.6 °F) for 5 d at OSU. Total Fe concentration in dried tissue was measured using inductively coupled plasma axial emission spectrometer (ICP, four or three replications at UNH and OSU, respectively). Iron concentration [μg·g^{-1} (ppm)] for each replicate was also multiplied by the average dry weight (grams) per shoot for the corresponding treatment in order to estimate total Fe uptake into the shoot (μg/plant).

SAS Version 8.2 software (SAS Institute, Cary, N.C.) was used for all statistical analyses. Data for hypotheses 1 and 3 were analyzed using analysis of variance (ANOVA) in the General Linear Models procedure. Type III sums of squares were used to test ANOVA effects, and Tukey's honestly significant difference multiple comparison test was used to compare treatment means for hypotheses. Data were combined for both locations (with location treated as a block term) for hypothesis 3. Data for hypothesis 2 were analysed for each location separately (because the Fe forms and Capsil rates differed between locations) using the SAS Regression procedure, and the SAS Stepwise method was used to select between linear and quadratic model terms for Fe concentration.

Results and discussion

Initial medium pH and EC at planting were 6.54 and 1.42 dS·m^{-1} at UNH and 6.1 and 2.3 dS·m^{-1} at OSU. At time of the drench and first foliar application (day 14), after plants had received two flowable lime drenches, medium pH increased to 6.94 (UNH) or 7.06 (OSU) with a medium EC of 1.43 (UNH) or 2.08 dS·m^{-1} (OSU). Most new tissue showed severe chlorosis by day 14. At UNH when final data were collected (day 37), pH and EC for nondrench treatments were 7.19 and 1.28 dS·m^{-1}, compared with 7.38 and 2.41 dS·m^{-1} at OSU on day 28. By the end of the experiment, 84% (UNH) or 31% (OSU) of upper leaves were necrotic on plants that did not receive Fe foliar or drench applications.

ORGANOSILICONE SURFACTANT. Addition of Capsil had a positive effect on increasing the SPAD chlorophyll index in plants, and also reduced leaf necrosis for treatments that included $FeSO_4$ or Fe-EDTA (Table 1). The highest shoot length, dry weight, and SPAD index and fewest necrotic leaves occurred following Fe-EDTA sprays, particularly in combination with Capsil. Plants that did not receive $FeSO_4$ or Fe-EDTA, regardless of whether Capsil was included, showed severe stunting, chlorosis, and leaf damage. Both $FeSO_4$ and Fe-EDTA sprays resulted in a higher flower bud count than sprays with water, but flower number was low (up to four buds per plant) in all treatments, and there was no effect of Capsil on flower number.

Iron concentration measured using ICP, and also Fe uptake (concentration × dry weight), were highest for $FeSO_4$ sprays (Table 1). Adding Capsil to $FeSO_4$ caused a decrease in measured Fe concentration and Fe uptake. Iron measurements for each treatment were therefore poorly correlated with effects on plant growth. Previous researchers have also reported a poor correlation between Fe concentration and chlorosis following Fe foliar sprays (for example, Neumann and Prinz, 1974). This lack of correlation may arise because not all of the Fe in foliage is physiologically active (Marschner, 1995), and the leaf surface may have been contaminated with Fe residue despite acid-washing. Based on growth responses from Table 1, therefore, the most effective treatment was Fe-EDTA in combination with the high rate (1.25 mL·L^{-1}) of Capsil.

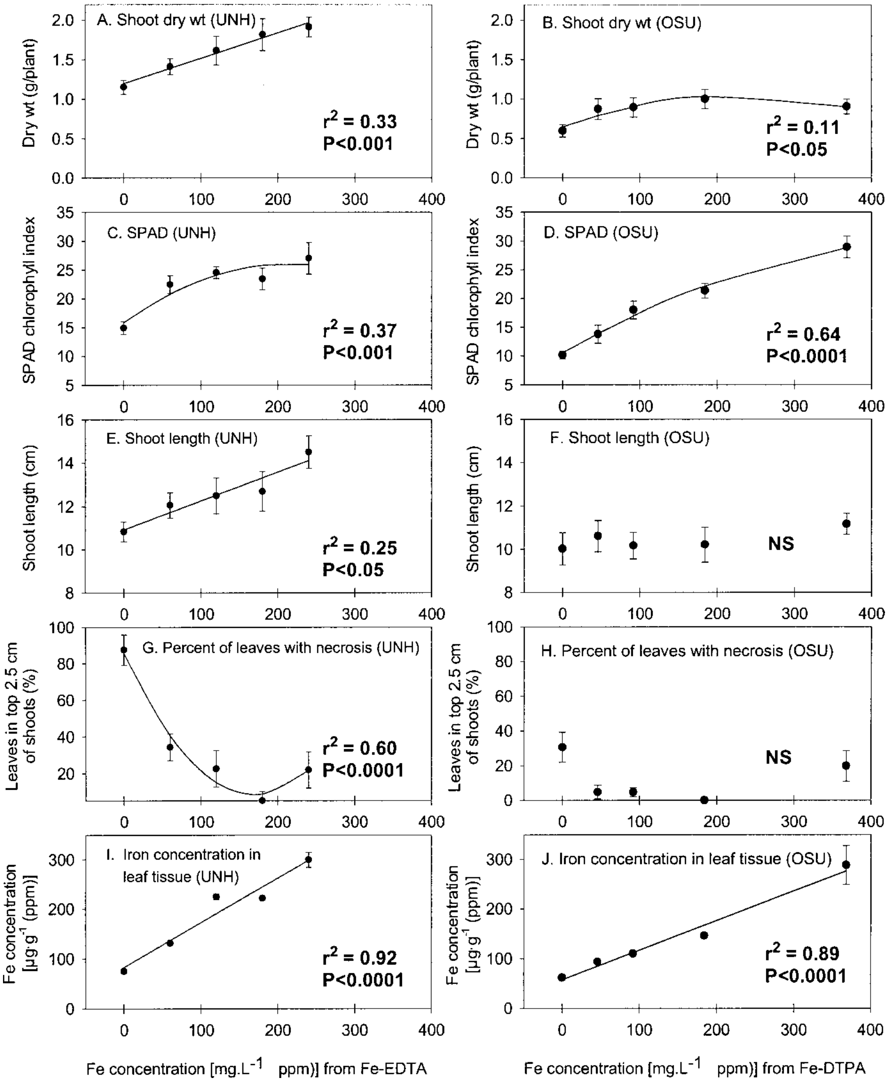

Fig. 1. Effect of iron (Fe) concentration from ferric ethylenediamine tetraacetic acid (Fe-EDTA) [University of New Hampshire, Durham (UNH)] or ferric diethylenetriamine pentaacetic acid (Fe-DTPA) [Ohio State University, Columbus (OSU)] applied as repeated foliar sprays 14, 17, 21, and 24 d after planting to calibrachoa grown at medium pH 7. Data were collected 35 d after planting at UNH and after 28 d at OSU. Line represents quadratic regression curve fit using the stepwise selection method, which was not significant for stem length or leaf necrosis at OSU. Symbols represent averages of 8 (UNH) or 12 (OSU) replicate plants ± SE; 28.35 g = 1.0 oz, 2.54 cm = 1.0 inch.

CONCENTRATION OF FOLIAR SPRAYS. At UNH, increasing foliar Fe concentration from 0 to 240 mg·L^{-1} positively affected dry weight, SPAD chlorophyll index, and shoot length, and greatly reduced leaf necrosis (Fig. 1). There was a strong positive correlation between Fe concentration and SPAD chlorophyll index at OSU (Fig. 1). Dry weight at OSU increased as Fe concentration increased from 0 to 184 mg·L^{-1}; however, dry weight did not increase from 184 to 368 mg·L^{-1}. The lack of response in terms of stem length and leaf necrosis at OSU compared with UNH may have been because of differences in Fe form (Fe-EDTA versus Fe-DTPA) and Capsil concentration (higher at OSU), and because final data were collected after only 14 d at OSU compared with 23 d at UNH (Fig. 1). It was not possible to differentiate between leaf necrosis from Fe deficiency or spray phytotoxicity in this experiment, and phytotoxicity may have increased leaf necrosis at the highest spray concentrations at UNH and OSU.

Iron levels measured in tissue increased from 76 to 300 µg·g^{-1} at UNH and from 62 to 288 µg·g^{-1} at OSU as foliar spray concentration increased from the control to highest concentration (Fig. 1I, 1J). The increase in both tissue concentration (both locations) and dry weight (at UNH) as foliar spray concentration increased resulted in a positive correlation between spray concentration and total Fe uptake (Fe concentration × dry weight) in both locations. Because of the potential Fe contamination on the leaf surface, however, these data should be interpreted with caution.

Nelson (1998) recommended 30 mg·L^{-1} of Fe from Fe-DTPA or 62 mg·L^{-1} from $FeSO_4$ for foliar applications to correct Fe deficiency in floricultural crops. Cox (2000) and the EPA label for a commercial Fe-DTPA formulation (Sprint 330; Becker Underwood, Inc., Ames, Iowa) recommended Fe-DTPA at 60 mg·L^{-1} Fe, with Cox (2000) suggesting repeat applications every 3 to 4 weeks if needed. Foliar label rates for a micronutrient blend that includes sulfate salts (STEM Soluble Trace Element Mix; Scotts Co., Marysville, Ohio), correspond to 24 to 100 mg·L^{-1} Fe.

Results from this experiment indicate that commonly recommended rates would be inadequate to correct severe Fe deficiency in calibrachoa and that growth response would be improved at spray concentrations above 60 mg·L^{-1} Fe. This research, industry literature, and the authors' observations, have reported phytotoxicity from foliar Fe sprays. If foliar applications of Fe are to be used, then the risk of phytotoxicity should be weighed against the apparent benefits of applying higher concentrations than is commonly recommended (60 mg·L^{-1}).

SOIL DRENCHES OF FE-EDDHA AND FE-DTPA. Fe-EDDHA at concentrations from 20 to 80 mg·L^{-1} Fe consistently resulted in a marked improvement in all measured aspects of plant growth compared with the control (Table 2). There were no significant differences in response between 20, 40, or 80 mg·L^{-1} Fe from Fe-EDDHA. As Fe concentration increased in Fe-DTPA drenches, there was an increasing improvement in plant growth compared with the control, and the 80 mg·L^{-1} Fe rate was superior than lower Fe-DTPA concentrations in terms of shoot dry weight and SPAD chlorophyll index. At the end of the experiment, plants receiving Fe-EDDHA drenches consistently had a healthy appearance that was horticulturally acceptable in terms of leaf color, size, and flower number. Iron levels measured in

Table 2. Analysis of variance (ANOVA) showing effects of iron (Fe) form [ferric diethylenetriamine pentaacetic acid (Fe-DTPA) and ferric ethylenediaminedi(o-hydroxyphenylacetic) acid (Fe-EDDHA)] and concentration [0, 20, 40, and 80 mg·L^{-1} (ppm) Fe] on efficacy of soil drenches applied to correct Fe deficiency symptoms in calibrachoa grown at medium pH 7.

	ANOVA effects[z]				Fe-DTPA				Fe-EDDHA			
	Fe form	Concn	Fe form × concn	Location	0	20	40	80	0	20	40	80
Shoot length (cm)	**	***	***	***	11.4b cd[y]	11 cd	12.7 abc	13.6 ab	10.2 d	14.6a	14.4 a	14.3 a
Shoot dry wt (g)	***	***	***	***	1.0 d	1.4 cd	1.7 c	2.0 ab	1.0 d	2.5 a	2.4 a	2.3 a
SPAD chlorophyll index	***	***	***	NS	12.7 c	14.9 c	12 c	23.5 b	12.6 c	30.1 a	31.2 a	33.1 a
Proportion of necrotic leaves (%)	***	***	***	***	61.3 a	48.4 a	22.9 b	2.3 b	55.3 a	1.9 b	1.9 b	1.9 b
Number of flower buds	***	***	***	NA[x]	0 b	2.3 b	18.8 b	11 b	0 b	47 a	52.7 a	45.8 a
Medium pH	NS	NS	NS	**	7.2 a	7.3 a	7.2 a	7 a	7.1a	7.2 a	7.3 a	7.3 a
Fe concn [μg·g^{-1} (ppm)]	*	**	NS	**	72.2 b	82.6 ab	63.1 b	82.6 ab	73.5 b	82.8 ab	84.3 ab	106.7 a
Fe uptake into shoot (μg,/plant = Fe concn × dry wt)	***	***	**	***	61.2 d	90.7 d	108.7 cd	180.8 bc	67.7 d	222.8 ab	223.4 ab	294.4 a

[z]Fe form = Fe-DTPA or Fe-EDDHA, Concn = concentration of Fe in mg·L^{-1}, Location = is the location of the experiment [University of New Hampshire, Durham (UNH) or Ohio State University, Columbus (OSU)].
[y]Letters after values in each column represent mean separation at the 95% level using Tukey's honestly significant difference (HSD) mean comparison method.
[x]NA = number of flower buds was counted only at UNH.
NS,*,**,***Nonsignificant or significant at the 95%, 99%, or 99.9% levels, respectively.

tissue and Fe uptake were higher for Fe-EDDHA than for Fe-DTPA, and Fe measurements from drench treatments did not have the potential confounding effect of residue on tissue.

Location differences in shoot length and dry weight arose because plants were larger and older at UNH compared with OSU, temperatures were warmer at UNH, and there was a greater amount of leaf necrosis in control plants at UNH. There was a location difference in final medium pH (7.3 at UNH compared with 7.1 at OSU), but drench treatments did not affect medium pH. Overall, Fe concentrations were slightly lower at OSU compared with UNH but trends in Fe concentration and uptake were similar.

Results from these UNH and OSU trials found that calibrachoa responded better to a 20 mg·L^{-1} Fe application from Fe-EDDHA compared with up to 80 mg·L^{-1} Fe from Fe-DTPA, but that Fe-DTPA at 80 mg·L^{-1} was also an effective Fe supplement. In comparison, Nelson (1998) recommended corrective drenches of 30 mg·L^{-1} of Fe from Fe-DTPA or 62 mg·L^{-1} from $FeSO_4$ for correction of Fe deficiency, and Cox (2000) recommended a drench of Fe-DTPA at 60 mg·L^{-1}.

Conclusions

The best strategy for managing Fe deficiency is to avoid the problem in the first place, and this requires appropriate pH management for the given crop. For example, our research (Smith et al., 2001) has shown that when calibrachoa is grown with a medium pH between 5.5 and 6.0, no special applications of Fe outside of normal fertility management were necessary to produce horticulturally acceptable plants. When pH management fails, application of Fe as a foliar spray or drench can be an effective tool for maintaining plant health until the crop is shipped.

A comparison between foliar and drench technologies for correcting Fe deficiency on bedding plants is summarized in Table 3. Foliar sprays are easier to apply, but multiple foliar applications are likely to be needed and

Table 3. Summary of costs and benefits of foliar versus drench application of iron (Fe) to correct Fe deficiency.

Foliar	Drench
Free of complex soil reactions	Availability and uptake can be dependent on pH for forms other than ethylenediaminedi(o-hydroxyphenylacetic) acid (Fe-EDDHA), as well as concentration of other nutrients (e.g., phosphorus, manganese)
Root uptake not required	Active growth, healthy root system needed
Materials: 31,300 10.2-cm (4-inch) diameter pots treated per $1.00 for 10 mL (0.34 oz) of 60 mg·L^{-1} (ppm) Fe from ferric ethylenediamine tetraacetic acid (Fe-EDTA)[z]	Materials: 940 10.2-cm-diameter pots treated per $1.00 for 100 mL (3.38 oz) of 20 mg·L^{-1} Fe from Fe-EDDHA[z]
Low labor cost for application per pot	More labor-intensive to apply
Multiple applications needed	Single application sufficient for the 21 d duration of this experiment
Phytotoxicity more likely	Phytotoxicity less likely
No residual Fe left in medium	Residual Fe could be a problem in long-term if less soluble forms of drench are applied at a high rate [e.g. ferric diethylenetriamine pentaacetic acid (Fe-DTPA), Fe-EDTA, or ferrous sulfate ($FeSO_4$)], especially after pH drops

[z]2002 retail prices for northeastern U.S. (Blackmore Co., Belleville, Mich.).

phytotoxicity is more likely than for a single drench application.

In comparing the foliar and drench treatments for calibrachoa reported in these trials, a drench of 20 mg·L^{-1} Fe from Fe-EDDHA, a drench of 80 mg·L^{-1} Fe from Fe-DTPA, four foliar sprays of 240 mg·L^{-1} Fe from Fe-EDTA, or four foliar sprays of 368 mg·L^{-1} of Fe from Fe-DTPA represented 2, 8, 9.6, and 14.7 mg Fe (28,350 mg = 1.0 oz) applied per plant. Drench application of 20 mg·L^{-1} Fe from Fe-EDDHA was therefore more effective per milligram Fe applied than foliar treatments or a drench of Fe-DTPA. Drenches of Fe-EDDHA may be less likely to cause nutrient imbalances compared with more concentrated drenches of less-soluble Fe forms, particularly if medium pH drops and Fe solubility increases.

Given the high crop value of floricultural crops, and the low material cost of Fe-EDDHA drenches when only 20 mg·L^{-1} is applied (Table 3), cost is not the determining factor in selecting between technologies. In cases of severe Fe deficiency, Fe drenches with Fe-EDDHA or Fe-DTPA are preferred over foliar applications.

Further research is needed to improve correction of micronutrient deficiencies in floricultural crops. The existing nutrient solubility charts rely on research with organic soils (Lucas and Davis, 1961) and one container medium (Peterson, 1981), in both cases without plants. There is a lack of knowledge about the differences in nutrient uptake between plant species, as well as to the relationship between micronutrient solubility and medium pH for different substrates and fertilizer forms used in container plant production. Information is also needed to quantify which nutrients are limiting to plant growth at high medium pH — manganese, copper, zinc, boron, and phosphorus may be limiting for some species or in certain situations—and technologies should be evaluated to best correct those problems. Research on several practical aspects of corrective nutrient applications would benefit greenhouse managers, including efficacy of sprays for different species, ways to increase uptake and reduce phytotoxicity for sprays (Fe form, surfactants, solution pH, and environmental factors), and efficacy of combination drench and foliar sprays (sprenches) that can be applied with a boom to reduce labor costs of hand drenching.

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