Irrigation Water Acidification to Neutralize Alkalinity for Nursery Crop Production: Substrate pH, Electrical Conductivity, Nutrient Concentrations, and Plant Nutrition and Growth

Joseph P. Albano
U.S. Horticultural Research Laboratory, USDA-ARS, Fort Pierce, FL 34945

James Allland
Application Technology Research Unit, USDA-ARS, Wooster, OH 44691

Donald J. Merhaut
University of California-Riverside, Riverside, CA 92521

Sandra B. Wilson and P. Chris Wilson
Institute of Food and Agricultural Science, University of Florida, Gainesville, FL 32611

Additional index words. carbonate, bicarbonate, controlled-release fertilizer (CRF), runoff, water quality, thyrallis, Galphimia glauca, Galphimia gracilis

Abstract. Liming agents (LAs) in irrigation water, typically associated with carbonates and bicarbonates of calcium (Ca) and magnesium (Mg), contribute to water alkalinity. Repeated application of LA to container crops can cause media-solution pH to rise overtime, that uncorrected, can lead to a nutrient availability imbalance that may be suboptimal for plant-growth due to nutrient disorder(s). To correct high levels of LA in irrigation water, growers can inject acid into their irrigation system to neutralize alkalinity. Therefore, a 52-week study was conducted using irrigation water, substrate, and plants from a commercial nursery in Florida that has a history of poor water quality and plant production problems related to high alkalinity irrigation water. The objectives of the study were to assess substrate pH, electrical conductivity (EC), and nutrients, and plant nutrition and growth for thyrallis (Galphimia gracilis Bartl.) to irrigation water acidification. Treatments consisted of irrigation water acidified with sulfuric acid (H₂SO₄) to neutralize 0% (control), 40%, or 80% of calcium carbonates (CaCO₃) yielding a CaCO₃ (meq L⁻¹) / pH levels of 5 [High Alkalinity (H-A)]/7.37, 3 [Medium Alkalinity (M-A)]/6.37, and 1 [Low Alkalinity (L-A)]/4.79, respectively. Substrate analysis by the 1:2 dilution method at the end of the study was significant (P < 0.05) for pH 6.2, 5.2, and 4.7 for the H-A, M-A, and L-A treatments, respectively, and for nutrients Ca, Mn, and Zn. Foliar nutrient levels were statistically significant (P < 0.05) for alkalinity treatment for Fe, K, Mn, P, and Zn. Alkalinity treatment was significant (P < 0.05) for growth, leaf greenness (by SPAD), and quality (by survey) with the M-A treatment producing more biomass, having greener leaves, and the highest aesthetic quality value than the H-A or L-A treatments. A qualitative survey of root systems at harvest showed that the M-A and L-A treatment root systems were greater than the H-A treatment based on visual side-wall root development. These data demonstrate that irrigation water acidification does alter substrate pH and nutrients and plant tissue nutrient levels and growth over a long-term production cycle typical for nursery crops.

Dissolved carbonates and bicarbonates are major contributors to irrigation water alkalinity. Irrigation water alkalinity (i.e., buffering capacity), not pH, has the major influence on substrate (the term "substrate" is interchangeable with "media" for purposes of this article) solution chemistry (Ruter, 2013). Groundwater sources in Florida are typically characterized with a pH > 7.0 and high levels of carbonates (CO₃²⁻) and bicarbonates (HCO₃⁻) of calcium (Ca), magnesium (Mg), and possibly other cations like potassium (K) and sodium (Na). Such water is typically derived from a surficial (≥ 9.14–82.30 m (30–270 ft)) limestone aquifer, especially as you move south through the state (Fish and Stewart, 1991; Li and Zhang, 2002; Reese and Cunningham, 2000). Repeated application of high alkalinity water may cause substrate solution pH to rise overtime, subsequently altering substrate nutrient availability/balance to an extent that nutrient disorders develop, especially for micronutrients, and a reduction in plant growth (Bell et al., 1993; Coulombre et al., 1984; De la Guardia and Aycinárt, 2002; Kuehny and Morales, 1998; Li and Zhang, 2002; Roosta, 2011; Valdez-Aguilar and Reed, 2007). Current recommendations for correcting high alkalinity irrigation water are to either neutralize to an end-point alkalinity (80% neutralization of bases is recommended), or to an end-point pH (pH 5.8 is recommended) by acidification with sulfuric, nitric, or phosphoric acid (Baily, 1996; Kidder and Hanlon Jr., 1997). Surprisingly, little information outside of technical bulletins is available for assessing the long-term effects of irrigation water acidification on nursery crops. A commercial nursery located in Fort Pierce, FL (27.4467°N, 80.3256°W), that identified production problems related to high alkalinity was selected to be the source for plants, substrate, and water for the study. Affected plants at this nursery developed a general pattern of interveinal chlorosis on leaves of plants in 11.4-L containers after several months in production (Fig. 1). Corrective measures included supplemental fertilizer applications [fertilizer products varied (personal communication with grower)]. Preliminary analysis of affected plants revealed a foliar micronutrient imbalance and a pH greater than 6.0 for substrate extracts (data not shown). The irrigation water source for this nursery also contained a high level of carbonates and bicarbonates (> 200 ppm (mg L⁻¹) as CaCO₃). To investigate this problem, we conducted a long-term (52-week) study to assess irrigation water chemistry, the effects of alkalinity level/irrigation water acidification on substrate chemistry and on plant nutrition and growth for thyrallis

Fig. 1. Thyrallis plants collected at the same nursery that was the focus of the study. (A) Leaves showing nutrient disorder and (B) affected plant with general chlorosis and poor growth.
grown under near-normal commercial nursery-crop production conditions.

Materials and Methods

Plant, substrate, and irrigation water source. Thyrallis plants, substrate, and irrigation water were acquired from a commercial nursery in Fort Pierce, FL, reporting production problems because of high alkalinity irrigation water. Plants were received in 11.36-L pots and had been in this size pot and substrate for ≈4 months. Plants were ≈1-year-old from cuttings having been stepped up from 10.16 cm to 3.79-L containers before transplant into 11.36-L containers. Substrate was composed of Florida peat, aged pine bark, sand, and other amendments as described in Table 1. Water used for irrigation (i.e., treatments) was collected from an 18.29-m well on the same nursery. There is some debate on the correct species for thyrallis with some sources referring to it as *Galphima glauca* Cav., commonly called “Rain-of-Gold” (Gilman, 1999); and some referring to it as *Galphima gracilis* Bartl., commonly called “Slender Goldshower” (USDA, NRCS, 2016). The latter, *Galphima gracilis*, is becoming generally accepted, but, however, “thyrallis” is used for both species.

Growing conditions. Plants were grown for 52 weeks in a greenhouse maintained at venting/heating temperatures of 29.4/23.3 °C. Because controlled-release fertilizers (CRF) longevity is often based on temperature, a detailed record of environmental conditions during the course of the 52-week study is presented in Fig. 2. Plants were arranged on a greenhouse bench spaced 45.7 cm on the center. For more consistent growth measurements over the 52-week study, the north side of pots were marked, and plants maintained the same directional orientation on the bench throughout the study (Fig. 3A). Osmocote 19–5–8–9 (N–P–K–Mg) (Physical and Aggregate Properties, Alkalinity: Titration, 1998). For comparison, the alkalinity level was also estimated indirectly (indirect method) by calculation based on the concentration [mg L⁻¹ (ppm)] of Ca and Mg in irrigation water as determined by inductively couple plasma-optical emission spectroscopy [ICP-OES (IRIS 1000 HR Duo; Thermo Elemental, Franklin, MA)]. (Physical and Aggregate Properties, Alkalinity: Hardness by Calculation, 1998). Treatments consisted of irrigation water without neutralization [high alkalinity (H-A) (control, not acidified)] or irrigation treated with acid to neutralize alkalinity at two levels: medium alkalinity (M-A) or low alkalinity (L-A). Treatments H-A, M-A, and L-A had CaCO₃ meq L⁻¹ levels of 5, 3, and 1, respectively. Treatments (800–1000 mL) were applied every other day or as needed with an average collected leachate volume of 255 mL ±12.4 mL (standard error of the mean), corresponding to a leaching fraction of 0.32. Irrigation water to prepare treatments was collected from the nursery for each treatment.

Plant growth and quality. Plants were sheared/pruned to the side of pots and to height from the substrate surface to 25.4, 30.5, 40.6, 25.4, 35.6, and 45.7 cm on days 58, 120, 181, 241, 304, and 358 of the study, respectively. Treatments (800–1000 mL) were applied every other day or as needed with an average collected leachate volume of 255 mL ±12.4 mL (standard error of the mean), corresponding to a leaching fraction of 0.32. Irrigation water to prepare treatments was collected from the nursery for each treatment.

Preparation of irrigation water treatments. Alkalinity level was determined directly (direct method) by titration to a pH end-point of 4.0 using 0.1 N sulfuric acid [H₂SO₄ 36 N (Fisher Scientific, Pittsburgh, PA, A-304)] and the indicator bromocresol green (Fisher Scientific, SI14-500) (Physical and Aggregate Properties, Alkalinity: Titration, 1998). For comparison, the alkalinity level was also estimated indirectly (indirect method) by calculation based on the concentration [mg L⁻¹ (ppm)] of Ca and Mg in irrigation well-water as determined by inductively couple plasma-optical emission spectroscopy [ICP-OES (IRIS 1000 HR Duo; Thermo Elemental, Franklin, MA)]. (Physical and Aggregate Properties, Alkalinity: Hardness by Calculation, 1998). Treatments consisted of irrigation water without neutralization [high alkalinity (H-A) (control, not acidified)] or irrigation treated with acid to neutralize alkalinity at two levels: medium alkalinity (M-A) or low alkalinity (L-A). Treatments H-A, M-A, and L-A had CaCO₃ meq L⁻¹ levels of 5, 3, and 1, respectively. Treatments (800–1000 mL) were applied every other day or as needed with an average collected leachate volume of 255 mL ±12.4 mL (standard error of the mean), corresponding to a leaching fraction of 0.32. Irrigation water to prepare treatments was collected from the nursery for each treatment.

**Table 1. Substrate components, amendments, and formulation that plants were growing in when received from the nursery.**

| Media composition | Physical components |
|-------------------|---------------------|
| **Pear** | 45% |
| **Bark** | 45% |
| **Sand** | 10% |
| **Amendments (kg·m⁻²)** |  |
| Osmocote 20–5–9 | 8.90 |
| Harrells minors | 1.19 |
| Dolomite | 2.37 |
| Calcium hydrate | 5.93 |
| Talstar | 1.19 |
| **Formulated pH** | 5.8–6.0 |

Florida peat.

Aged pine bark. Time bark was “aged” and was undefined on substrate invoice.

Department of Transportation course grade sand (aggregate size undefined on substrate invoice).

Osmocote, The Scotts Company, LLC, Marysville, OH. Fertilizer composition given as N–P–K–Mg. Nitrogen (N): 6.87 ammoniacal-N, 5.87 nitrate-N, and 6.29% urea-N. Micronutrients: Cu, Fe, Mn, and Zn.

Harrells, Lakeland, FL. Micronutrient elements or concentration in “Minors,” undefined.

Iron sulfate (FeSO₄) source was undefined on substrate invoice.

Dolomite [CaMg(CO₃)₂] source was undefined on substrate invoice.

Calcium hydrate [Ca(OH)₂] source was undefined on substrate invoice.

Talstar, FMC, Corp., Philadelphia, PA.

**pH:** Indicated on substrate invoice.

![Fig. 2. Greenhouse temperature over the 52-week study with week-1 starting in March.](image-url)
Table 2. Inherent nutrient levels (± SE) for well-water collected at the nursery over the course of the 52-week study. Treatment is High-Alkalinity (H-A).

| Alkalinity level | Ca (mg·L⁻¹) | K (mg·L⁻¹) | Mg (mg·L⁻¹) | S (mg·L⁻¹) | P (mg·L⁻¹) | Cu (µg·L⁻¹) | Fe (µg·L⁻¹) | Mn (µg·L⁻¹) | Zn (µg·L⁻¹) |
|------------------|-------------|------------|-------------|------------|------------|-------------|-------------|-------------|-------------|
| H-A (control)    | 97.4 ± 4.3  | 1.3 ± 0.2  | 10.5 ± 0.4  | 2.7 ± 0.1  | 145.5 ± 14.6 | 6.9 ± 0.6  | 27.2 ± 4.8  | 31.2 ± 4.0  | 17.1 ± 2.7  |

Fig. 3. (A) Representative picture of experimental layout of Thryallis plants in the study. For pictures B-D, treatments are from left to right: High-Alkalinity (H-A), Medium-Alkalinity (M-A), and Low-Alkalinity (L-A) at 51 (B) or 52 [(C and D) harvest/end of the study] weeks after the start of the study. Plants are the same for pictures B-D. (B) Representative view of plant tops/compan before plants received their final shearing. (C) Side view of root growth, and (D) bottom view of root growth.
of Agriculture and Consumer Services, 2014; Yeager et al., 1997). Neutralizing alkalinity with H\_2SO\_4 did not alter irrigation water nutrient levels or significantly affect EC between treatments (Table 3), but pH dropped 1.0 and 2.6 pH units for the M-A and L-A treatment, respectively, compared with the control (H-A) with the addition of acid (Table 3). Irrigation water pH (7.4), in addition to alkalinity, was also considered high (>7.0) for containerized nursery plant production [Table 3 (H-A) (Yeager et al., 1997)]. Irrigation water sulfur levels were affected with the addition of sulfuric acid to neutralize alkalinity (Table 3).

### Substrate solution chemistry

Treatment was significant for pH but not for EC. There was a 1.51 pH unit drop, i.e. more acidic, from the H-A to the L-A treatment (Table 4). Optimal substrate pH varies with crop, but a general range of 4.5–6.5 is considered good for most nursery crops (Yeager et al., 2013).

**Thyrallis is a crop that can tolerate a broad pH range for most nursery crops (Yeager et al., 2013).**

A general range of 4.5–6.5 is considered good for most nursery crops (Yeager et al., 2013).

The most sensitive plants to alkalinity in their study showed symptoms of nutrient deficiency, with leaf wilting and necrosis and degeneration of root systems. This was attributed to the inability of root systems to physiologically and structurally function normally under high alkalinity conditions. Other studies have found that plants vary in susceptibility to alkalinity and at alkalinity levels lower than generally considered safe, i.e., ≤214 mg L\(^{-1}\) bicarbonate.

The most sensitive plants to alkalinity in their study showed symptoms of nutrient deficiency, with leaf wilting and necrosis and degeneration of root systems. This was attributed to the inability of root systems to physiologically and structurally function normally under high alkalinity conditions. Other studies have found that plants vary in susceptibility to alkalinity and at alkalinity levels lower than generally considered safe, i.e., ≤214 mg L\(^{-1}\) bicarbonate.

Kuehny and Morales (1998) looked at the effects of salinity and alkalinity on pansy and impatiens grown in three different substrates (peat, peat and pine bark, or pine bark) under greenhouse conditions. They found that irrigation water with ≥200 mg L\(^{-1}\) HCO\(_3\) from sodium bicarbonate (NaHCO\(_3\)) was associated with reduced plant growth, decreased flower number, general leaf chlorosis, and some leaf deformation and necrosis.

Foliar mineral concentration was not different between treatments for Ca, Mg, and Cu (Table 6). Iron, Mn, and Zn foliar concentration increased by 39%, 120%, and 36%, respectively, in the L-A treatment compared with the control H-A (Table 6). Potassium decreased 5% in the L-A treatment compared with the control H-A. Although not practically significant, nutrient level-wise (i.e., not of consequence to plant production), P was the only foliar nutrient analyzed that was significantly greater at M-A than in either the H-A or L-A treatments, which were not different (Table 6).

### Table 3. Treatment solution (irrigation water chemistry) pH, EC, and volume of sulfuric acid to neutralize 0%, 40%, and 80% neutralization of alkalinity over the 52-week course of the study. 

| Alkalinity level | pH | EC (mS cm\(^{-1}\)) | Sulfur (mg L\(^{-1}\)) | H\_2SO\_4 (µL L\(^{-1}\))  
|-----------------|----|---------------------|------------------------|--------------------------|
| H-A             | 7.4 ± 0.0 | 0.8 ± 0.1 | 2.7 ± 0.1 | 0  
| M-A             | 6.4 ± 0.1 | 0.9 ± 0.1 | 44.6 ± 0.1 | 82 ± 8  
| L-A             | 4.8 ± 0.2 | 0.9 ± 0.1 | 92.0 ± 0.8 | 164 ± 16  

*Sulfuric acid, 36 N, Certified ACS Plus, A300-212, Fisher Scientific.*

### Table 4. Media analysis by the 2:1 method at harvest, 52 weeks after the start of the study, n = 6.

| Alkalinity level | Macronutrients (mg L\(^{-1}\)) | Micronutrients (µg L\(^{-1}\)) | Chemistry | pH | EC (mS cm\(^{-1}\)) |
|-----------------|--------------------------------|-------------------------------|-----------|----|-------------------|
|                 | Ca | K | Mg | P | Fe | Mn | Zn | pH | EC (mS cm\(^{-1}\)) |
| H-A             | 51.0 ± 0.8 | 7.9 a | 7.7 a | 2.8 a | 23.3 a | 29.7 a | 153.3 b | 81.7 b | 6.2 a | 0.8 a |
| M-A             | 61.4 ± 0.8 | 9.5 a | 12.8 a | 2.9 a | 20.0 a | 33.7 a | 448.3 ab | 236.7 ab | 5.2 b | 1.5 a |
| L-A             | 126.3 ± 2.3 | 6.3 a | 11.7 a | 2.8 a | 21.7 a | 29.5 a | 990.0 a | 433.3 a | 4.7 c | 1.2 a |

*Means followed by the same letter within a column are not significantly different at P < 0.05, mean separation by LSD.*

### Table 5. Average growth index [height + width 1 + width 2 (perpendicular to width 1)/3] per plant growth index was determined weekly starting with week 9 except for weeks 13, 15, 17, 31, 47, and 48, over the 52-week study, n = 276 ([52 weeks – 6 weeks]/6 reps per treatment)]. Average fresh weight [FW (g)] sheared/pruned per plant over the 52-week study. Plants were sheared/pruned to side of pots and to height from substrate surface to 25.4 cm (10 inches), 30.5 cm (12 inches), 40.6 cm (16 inches), 25.4 cm (10 inches), 35.6 cm (14 inches), and 45.7 cm (18 inches), on days 58, 120, 181, 241, 304, and 358 of the study, respectively, to control plant shape and form as would be done at the nursery for this crop to maintain a suitable plant form during the production cycle.

Table 6. Media analysis by the 2:1 method at harvest, 52 weeks after the start of the study, n = 6. Treatments: High-Alkalinity (H-A), Medium-Alkalinity (M-A), and Low-Alkalinity (L-A).

| Alkalinity level | Ca | K | Mg | P | Fe | Mn | Zn | pH | EC (mS cm\(^{-1}\)) |
|-----------------|----|----|----|---|----|----|----|----|-------------------|
| H-A             | 51.0 ± 0.8 | 7.9 a | 7.7 a | 2.8 a | 23.3 a | 29.7 a | 153.3 b | 81.7 b | 6.2 a | 0.8 a |
| M-A             | 61.4 ± 0.8 | 9.5 a | 12.8 a | 2.9 a | 20.0 a | 33.7 a | 448.3 ab | 236.7 ab | 5.2 b | 1.5 a |
| L-A             | 126.3 ± 2.3 | 6.3 a | 11.7 a | 2.8 a | 21.7 a | 29.5 a | 990.0 a | 433.3 a | 4.7 c | 1.2 a |

*Means followed by the same letter within a column are not significantly different at P < 0.05, mean separation by LSD.*
Table 6. Plant tissue analysis at harvest over the course of the experiment. Sampling, 150 g fresh weight, occurred on day 1 and before each shearing (6).
Treatments: High-Alkalinity (H-A), Medium-Alkalinity (M-A), and Low-Alkalinity (L-A). n = 7.

| Alkalinity level | Macronutrients (%) | Micronutrients (µg·g⁻¹) |
|------------------|-------------------|------------------------|
|                  | Ca    | K   | Mg    | N      | P       | Cu     | Fe    | Mn    | Zn     |
| H-A              | 1.3 a | 0.9 a<sup>b</sup> | 0.4 a | 2.0 a | 0.2 a | 6.0 a | 94.9 b | 109.8 c | 45.3 c |
| M-A              | 1.3 a<sup>c</sup> | 0.9 ab | 0.4 a | 2.0 a | 0.2 b | 6.6 a | 109.0 ab | 146.0 b | 51.9 b |
| L-A              | 1.3 a<sup>c</sup> | 0.9 b | 0.4 a | 1.9 a | 0.2 a | 5.6 a | 132.1 a | 241.9 a | 61.6 a |

<sup>a</sup>Means followed by the same letter within a column are not significantly different at P < 0.05, mean separation by LSD.
<sup>b</sup>Differences between means at the tenths place: H-A, 0.93%; M-A, 0.92%; and L-A, 0.88%.

nutrient levels, for all treatments, Mg, N, P, Cu, and Zn were sufficient. Calcium and Mn for all treatment levels were higher than what is generally considered sufficient. Iron for the H-A treatment was slightly lower than what is generally considered sufficient for normal plant growth with the M-A and L-A treatments being sufficient (Table 6) (Yeager et al., 2013).

In this long-term study, micronutrient disorders did not develop in the H-A treatment as was observed in the nursery (Fig. 1). This could be due to several factors including differences in substrate and fertilizers [three different substrate compositions and various fertilizer types and rates were used on the nursery, in addition to different times of fertilizer application during the production schedule (personal communication with the production manager)]. It is also likely that irrigation water application was greater on the nursery and climatic conditions more variable in the field. Greater irrigation volume could result in increased leaching of nutrients from the substrate where it would otherwise be available for plant uptake, reducing the availability of certain nutrients in the substrate solution because of the effects of high alkalinity, inability to take up nutrients due to possible reduced root growth due to high alkalinity, or a combination of these factors.

**Conclusion**

Regardless of the results of this study, in particular, the lack of nutrient disorder, irrigation water pH, and alkalinity on the nursery warranted treatment by acidification based on BMP recommendations. Under the conditions of the study, the M-A treatment was most favorable for plant production for thryallis with greater growth, producing more biomass as a mean of shearing, and greener leaves based on SPAD readings. The substrate analysis of the M-A treatment also had high levels of soluble nutrients and a favorable pH that fell between the recommended pH-range for most nursery crops. Therefore, based on data presented here, the M-A treatment was suitable for the long-term production of thryallis with the H-A and L-A treatments being the extremes with time.

**Literature Cited**

Baily, D.A. 1996. Alkalinity, pH, and acidification, p. 69–91. In: D.W. Reed (ed.). Water, media, and nutrition for greenhouse crops. Ball, Batavia, IL.
Bell, D.T., C.F. Wilkins, P.G. Moezel, and S.C. Ward. 1993. Alkalinity tolerance of woody species used in bauxite waste rehabilitation, western Australia. Restor. Ecol. 1:51–58.
Coulombe, B.A., R.L. Cjanev, and W.J. Wiebold. 1984. Bicarbonate directly induces iron chlorosis in susceptible soybean cultivars. Soil Sci. Soc. Amer. J. 48:1297–1300.
Crist, R.H., J.R. Martin, J. Chonko, and D.R. Crist. 1996. Uptake of metals on peat moss: An ion-exchange process. Environ. Sci. Technol. 30: 2456–2461.
De la Guardia, M.D. and E. Alcántara. 2002. Bicarbonate and low iron level increase root to total shoot plant weight ratio in olive and peach rootstock. J. Plant Nutr. 25:1021–1032.
Demirbas, A. 2008. Heavy metal adsorption onto agro-based waste materials: A review. J. Hazard. Mater. 157:220–229.
Department of Agriculture and Consumer Services. 2014. Water quality/quantity best management practices for Florida nurseries. 6 Mar. 2017. <http://www.forestry BMP.pdf>.
Fish, J.E. and M.T. Stewart. 1991. Hydrology of the surficial aquifer system, Dade, County, Florida. USGS. WRIR 904108.
Gilman, E.F. 1999. Galphimia glauca. Univ. of Fla. Coop. Ext. Ser. Fact Sheet, FPS-219.
Kidder, G. and E.A. Hanlon. Jr. 1997. Neutralizing excess bicarbonates from irrigation water. Univ. of Fla. Coop. Ext. Ser. Circ. SL-142.
Kuehny, J.S. and B. Morales. 1998. Effects of salinity and alkalinity on panay and impatians in three different growing media. J. Plant Nutr. 21:1011–1023.
Lang, H.J. 1996. Growing media testing and interpretation, p. 123–139. In: D.W. Reed (ed.). Water, media, and nutrition for greenhouse crops. Ball, Batavia, IL.
Li, Y. and M. Zhang. 2002. Effects of urea and nitric acid on water quality and on response of anthurium. HortTechnology 12:131–134.

Physical and aggregate properties, Alkalinity: Titration method, Method 2320B p. 2–26. 1998. In: A.D. Eaton, L.S. Clesceri, and A.E. Greenberg (eds.). Standard methods for the examination of water and waste water. 20th ed. Amer. Public Health Assn., Washington, DC.

Roosta, H.R. 2011. Interaction between water alkalinity and nutrient solution pH on the vegetative growth, chlorophyll fluorescence and leaf magnesium, iron, manganese, and zinc concentration in lettuce. J. Plant Nutr. 34:717–731.

Ruter, J.M. 2013. Importance of water quality in container plant production. USDA Forest Serv. Proc. RMRS-P 69:36–38.

U.S. Environmental Protection Agency. 1996. Method 3052: Microwave assisted acid digestion of siliceous and organically based matrices. <http://www.caslab.com/EPA-Methods/PDF/EPA-Method-3052.pdf>.

U.S. Environmental Protection Agency. 2000. Method 6010C: Inductively coupled plasma-atomic emission spectrometry. <http://www.caslab.com/EPA-Methods/PDF/EPA-Method-6010-C.pdf>.

USDA, NRCS. 2016. The PLANTS database. 13 Sept. 2016. <http://plants.usda.gov> (National Plant Data Team, Greensboro, NC 27401–4901 USA).

Valdez-Aguilar, L.A. and D.W. Reed. 2007. Response of selected greenhouse ornamental plants to alkalinity in irrigation water. J. Plant Nutr. 30:441–452.

Yeager, T., T. Bilderback, D. Fare, C. Gilliam, A. Niemiera, and K. Tilt. 1997. Best management practices: Guide for producing container-grown plants. Southern Nursery Assn., Atlanta, GA.

Yeager, T., T. Bilderback, D. Fare, C. Gilliam, J. Lea-Cox, A. Niemiera, J. Ruter, K. Tilt, S. Warren, T. Whitwell, and R. Wright. 2013. Best management practices: Guide for producing nursery crops. 3rd ed. Southern Nursery Assn., Aecworth, GA.