The pH-Response of a Peat-based Medium to Application of Acid-reaction Chemicals

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Abstract. Medium-pH above 6.4 is a common cause of micronutrient deficiency for container-grown plants, and technologies are required to correct an excessively high medium-pH. The objective was to quantify the dose response from application of several acidic materials that have been recommended for lowering medium-pH in soilless media. A 70% peat/30% perlite (by volume) medium was mixed with a preplant nutrient charge, a wetting agent and 1.5, 1.8, 2.1, or 2.4 kg·m⁻³ of a dolomitic hydrated lime resulting in four starting pH levels ranging from 6.4 to 7.6. Aluminum sulfate (17% Al) at 1.8–28.8 g·L⁻¹, flowable elemental sulfur (52% S) at 3.55–56.8 mL·L⁻¹, ferrous sulfate (20.8% Fe) at 1.8–28.8 g·L⁻¹, Seplex-L organic acid at 0.32–5.12 mL·L⁻¹, sulfuric acid (93%) at 0.08–2.56 mL·L⁻¹, 21.1N–3.1P–5.8K water-soluble fertilizer at 50–400 mg·L⁻¹ N (potential acidity 780 g CaCO₃ equivalents/kg), and a deionized water control were applied at 60 mL per 126-cm³ container with minimal leaching as a single drench (except repeat sulfuric acid applications at 0.08 or 0.16 mL·L⁻¹ and 21.1N–3.1P–5.8K treatments that were applied about every 3 days). Medium-pH and electrical conductivity (EC) were tested over 28 days using the saturated medium extract method using deionized water as the extractant. One day after application, aluminum sulfate, ferrous sulfate, and sulfuric acid lowered pH by up to 3 pH units at the highest concentrations and medium-pH remained fairly stable for the following 27 days. Flowable sulfur lowered pH gradually over the course of the experiment by up to 3.3 pH units, with no difference across the wide range in concentrations. Organic acid had minimal impact on medium-pH, and 21.1N–3.1P–5.8K did not lower medium-pH despite the fact that all nitrogen was supplied in the ammonium and urea form. At recommended concentrations, chemicals tested raised medium-EC, but not above acceptable levels for plant growth. The highest rates of aluminum and ferrous sulfates, and sulfuric acid, however, increased medium-EC by 2.0 dS·m⁻¹ on day 1. Medium-pH-responses to acid-reaction chemicals would be expected to vary in commercial practices depending on additional factors such as lime type and incorporation rate, water alkalinity, media components, and plant interactions.

In container plant production, medium-pH affects micronutrient solubility and availability for plant uptake (Peterson, 1981). If medium-pH is too high (above 6.4 for most crops) the availability of some nutrients (mainly Fe, Mn, and P) may be insufficient for plant growth resulting in tissue damage and crop loss (Koranski et al., 1996; Nelson, 1998). More than half of all greenhouse nutritional problems have been attributed to excessively high or

low medium-pH (Nelson, 1994), and severe iron deficiency at medium-pH 6.5 or above is particularly common in species such as *Petunia* and *Calibrachoa* hybrids that are inefficient at taking up iron (Smith et al., 2001).

When medium-pH is above the optimum range, rapid amelioration can be necessary to prevent crop damage. Chemicals suggested for lowering pH in media include ammoniacal-based fertilizers (Lang and Elliott, 1991; Nelson, 1998), elemental sulfur (Beverly and Anderson, 1987; Hipp and Simpson, 1986; Lindemann et al., 1991), strong mineral acids and organic acids (Bailey, 1996; Kramer and Peterson, 1990), and ferrous sulfate or aluminum sulfate (Bailey, 1996; Beverly and Anderson, 1987; Peterson et al., 1987). Although these materials have been recommended to greenhouse growers for correcting low medium-pH, recommended rates often include a broad range with little information on dose-response effects (Bailey, 1996). A comparison between acidic materials applied under standard conditions is lacking for a peat-based medium.

The objectives of this experiment were to quantify and compare the pH-response for a 70% peat/30% perlite medium following application of several acid-reaction chemicals, and to determine how pH changed over time following application. In addition, the effect of initial medium-pH on dose response, the equivalency of pH-response for various chemicals, and effects on growing-medium electrical conductivity (EC) were determined. No plants were included in this experiment to eliminate the variable of plant interaction with medium and chemical application.

Materials and Methods

Root medium. The root medium used was (by volume) 70% Canadian sphagnum peat (Fisons professional black bale peat; SunGro Horticulture, Bellevue, Wash.) with long fibers and little dust (Von Post scale 1–2; Puustjarvi and Robertson, 1975), and 30% coarse perlite.

Six 126-cm³ containers (5.5 cm width × 6.1 cm length × 7.4 cm depth) were filled with the peat/perlite medium. Medium in containers was irrigated twice with excess water at 30-min intervals, allowed to drain for 60 min, and then weighed. The containers were then placed in a drying oven at 105 °C for 72 h and weighed again. Container water-holding capacity was estimated to be the difference between the drained weight and the oven dried weight. At container capacity, the medium held 79 mL of water per container.

At mixing, 0.6 kg·m⁻³ of a commercial 6N–3P–7K–10Ca–1Mg preplant nutrient charge [composed of commercial-fertilizer grade KNO₃, Ca(NO₃)₂, gypsum, triple superphosphate, and MgSO₄ (GreenCare, Chicago)] and a wetting agent (AquaGro 2000 L; Aquatrols, Pennsauken, N.J.) at 0.2 L·m⁻³ were added. A range of initial medium-pH levels were achieved by incorporating 1.5, 1.8, 2.1, and 2.4 kg·m⁻³ of a dolomitic hydrated lime [97% Ca(OH)₂·MgO; National Lime and Stone, Findlay, Ohio] in which 92% of the lime passed through a 45-μm screen. After mixing, the medium was moistened with deionized water and remained in plastic bags with the tops open to the air for gas exchange for 7 d at 17.7 °C (root-medium temperature) before filling the containers. The initial pH levels from the four lime treatments were 6.4, 6.5, 7.3, and 7.6, respectively.

Chemical treatments. Flowable elemental sulfur (W.A. Cleary Corp., Dayton, N.J.), formulated as a slurry, was thoroughly mixed and added to deionized water at 3.5, 7.1, 14.2, 28.4, and 56.8 mL·L⁻¹. Other chemical treatments (Table 1) were dissolved in deionized water before application to the medium, and included technical grade FeSO₄ (Crown Technology, Indianapolis, Ind.), technical grade Al₂(SO₄)₃ (EM Science, Gibbstown, N.J.), reagent-grade 96.5% H₂SO₄ (EM Science), Seplex organic acid (GreenCare Fertilizers, Chicago) and a commercial water-soluble fertilizer 21.1N–3.1P–5.8K, composed of commercial-fertilizer grade KCl, (NH₄)₂SO₄, NH₄H₂PO₄, and urea with 100% of N in the ammoniacal or urea form

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Table 1. Solution molarity, pH and electrical conductivity (EC) for chemical treatments (means of 10 replicate samples).

Chemical	Application rate	Molarity	Solution pH	Solution EC (dS·m ⁻¹)
Deionized water	NA	NA	6.14	0.0024
Aluminum sulfate (52.8%) ^z	1.8 g·L ⁻¹	0.0028	3.62	1.02
	3.6 g·L ⁻¹	0.0056	3.57	1.65
	7.2 g·L ⁻¹	0.0111	3.44	2.81
	14.4 g·L ⁻¹	0.0222	3.33	4.72
	28.8 g·L ⁻¹	0.0443	3.25	7.95
Ferrous sulfate (56.6%) ^y	1.8 g·L ⁻¹	0.0067	3.55	1.21
	3.6 g·L ⁻¹	0.0134	3.36	2.01
	7.2 g·L ⁻¹	0.0268	3.18	3.49
	14.4 g·L ⁻¹	0.0536	3.00	6.00
	28.8 g·L ⁻¹	0.1073	2.87	9.06
Flowable elemental sulfur (52%)	3.55 mL·L ⁻¹	0.0576	6.87	0.0847
	7.1 mL·L ⁻¹	0.1151	6.99	0.14
	14.2 mL·L ⁻¹	0.2302	6.91	0.28
	28.4 mL·L ⁻¹	0.4605	7.01	0.58
	56.8 mL·L ⁻¹	0.9210	6.99	1.05
Seplex-L organic acid	0.32 mL·L ⁻¹	not available	3.02	0.50
	0.64 mL·L ⁻¹		2.81	0.39
	1.28 mL·L ⁻¹		2.67	0.59
	2.56 mL·L ⁻¹		2.43	0.91
	5.12 mL·L ⁻¹		2.22	1.35
Sulfuric acid (96.5%)	0.16 mL·L ⁻¹	0.0016	2.15	2.17
	0.32 mL·L ⁻¹	0.0032	1.93	3.54
	0.64 mL·L ⁻¹	0.0063	1.66	6.31
	1.28 mL·L ⁻¹	0.0127	1.37	11.83
	2.56 mL·L ⁻¹	0.0253	1.09	22.7
21.1N–3.1P–5.8K fertilizer	0.08 mL·L ⁻¹ R ^x	0.0008	2.50	1.20
	0.16 mL·L ⁻¹ R	0.0016	2.15	2.17
	50 mg N·L ⁻¹ R	0.0036 N	6.68	0.29
	100 mg N·L ⁻¹ R	0.0071 N	6.21	0.63
	200 mg N·L ⁻¹ R	0.0143 N	5.95	1.23
	400 mg N·L ⁻¹ R	0.0286 N	5.69	2.27

^z7.2 g·L⁻¹ of hydrated (52.8%) aluminum sulfate corresponds to 433 mg·L⁻¹ Al³⁺.

^y7.2 g·L⁻¹ of hydrated (56.6%) ferrous sulfate corresponds to 1498 mg·L⁻¹ Fe²⁺.

^xTreatments followed by the symbol R were reapplied every 3 d (other treatments were applied only once).

^{na}Not applicable.

and 780 g CaCO₃ equivalents/kg of potential acidity (GreenCare).

Solution pH, EC, and solution molarity of each treatment are presented in Table 1. Bailey (1996) recommended corrective drenches of aluminum or ferrous sulfate at 7.2 g·L⁻¹ (the third-highest experimental concentration). Label recommendations and suggestions by Bailey (1996) for flowable sulfur (Sulfur-F) were in units of volume per area, rather than as mL·L⁻¹ concentrations for container media, but the recommended range from 29 to 387 mL·m⁻² corresponds to ≈1.7 to 23.1 mL·L⁻¹ when applied using the protocol for this experiment. No specific recommendations were found for sulfuric or organic acid drenches. Molarity of Seplex-L could not be calculated based on label information. For comparative purposes, however, sulfuric acid at 0.16 mL·L⁻¹ neutralizes 4 meq·L⁻¹ of CaCO₃ alkalinity, and at a given acid strength in mL·L⁻¹ strength, Seplex-L neutralizes 0.5 times the alkalinity compared with 96.5% sulfuric acid.

On 3 Mar. 1998, containers were arranged randomly on mesh benches in a well-ventilated glass greenhouse. During the experiment, medium temperature (using a copper-constantan thermocouple) and air temperature (using an aspirated, shielded thermistor) averaged 18.6 °C and 19.4 °C, respectively. Chemical treatments were applied by overhead irrigation at a rate of 60 mL per container (sufficient to bring contain-

ers to saturation with minimal leaching). After application, containers were irrigated overhead to container capacity (with minimal leaching) using 40 mL per container when they reached between 40% and 50% container capacity as determined gravimetrically (about every 3 d). Deionized water was used to irrigate all treatments except the 21.1N–3.1P–5.8K and repeat sulfuric acid treatments, which were reapplied at each watering.

Medium-pH and EC were measured using the saturated-medium extract method with deionized water as the extractant (Warncke, 1986), on media samples that did not include the top 2.5 cm from the container. Medium-pH was measured for 10 containers before the chemical application (day 0) and on four containers per treatment 1, 7, 14, 21, and 28 d after the application. Medium-pH was measured directly in the saturated medium using an Orion 620 pH-meter (Orion Technologies, Beverly, Mass.). Medium-EC was tested before the chemical application and 1 and 28 d after the application. Medium-EC was measured in the filtered extract using an Orion 130 EC-meter (Orion Technologies).

The experiment was a completely randomized factorial in which acidifying chemical treatments were applied at several rates, along with a deionized water control, to the peat/perlite medium at four starting-pH levels. Each chemical treatment was applied to 20 containers

per starting-pH, and 40 containers per starting-pH for the control. Analysis of covariance (ANCOVA) was run for each chemical to test how EC and pH were affected by starting-pH, days after application (1–28, analyzed as a continuous variable), the chemical concentration, and their interactions. ANCOVA was initially used to test whether the absolute pH effect of each chemical was significantly different from the control. We were also interested in change in pH (ΔpH) compared with that of the deionized water control at different starting pH levels. The ΔpH was calculated by subtracting each individual pH-measurement from the average pH for the deionized water control on the corresponding measurement day. The ΔpH data were reanalyzed using ANCOVA. SAS software (SAS Institute, Cary, N.C.) was used for all statistical analyses. Type III sums of squares were used to test hypotheses, and Tukey's honestly significant difference (HSD) multiple comparison test was used to compare treatment means. Mean ΔpH was graphed for combinations of starting-pH and chemical concentration.

Results

The four hydrated lime rates resulted in medium-pH levels of 6.4, 6.5, 7.3, and 7.6 on day zero, before chemical drench application. Each of the lime rates resulted in medium-pH levels that were statistically different from each other. For the deionized water controls, there was no statistically-significant change in pH over time. Medium-EC decreased from 0.666 to 0.288 dS·m⁻¹ between days 1 and 28 (Table 2).

Aluminum sulfate. All concentrations of aluminum sulfate resulted in a significantly lower pH than the control, and the response increased with concentration (Table 3, Fig. 1A). Effect on medium-pH ranged from –0.45 pH units at 1.8 g·L⁻¹ to –2.7 at 28.8 g·L⁻¹. The ΔpH increased as starting-pH increased. There was a slight effect of days after application, with the greatest drop in medium-pH occurring on day 1. Medium-pH of treated pots increased by an average 0.21 between days 1 and 28. At the two highest aluminum sulfate concentrations, medium-EC on day 1 (Table 2) was above the recommended level of 2.0 for seedlings and plugs (Lang, 1996) and was ≈1 dS·m⁻¹ above the control on day 28.

Ferrous sulfate. Ferrous sulfate also caused a rapid drop in medium-pH on day 1. From day 1 to day 28, pH dropped slightly compared with the control (by 0.19 pH units). There was no effect of starting-pH on dose response (Table 3, Fig. 1B), but pH-response increased with chemical concentration (ΔpH was up to –3.3 at 28.8 g·L⁻¹). Medium-EC after application of the two highest ferrous sulfate concentrations was >2.0 on day 1 (Table 2) and remained 1 dS·m⁻¹ above the control on day 28.

Flowable elemental sulfur. The pattern of decline in medium-pH following application of flowable sulfur was very different compared with aluminum sulfate or ferrous sulfate (Fig. 2, Table 3). There was no effect of chemical concentration, despite a wide range in chemical

Table 2. Effect of chemical concentration on medium-EC (least-square mean across four starting pH levels, with 20 replicates per mean).

Chemical	Application rate	Medium-EC after application (dS·cm ⁻¹)	
		Day 1	Day 28
Distilled water	NA	0.666	0.288
Aluminum sulfate (52.8%)	1.8 g·L ⁻¹	1.526*	0.411
	3.6 g·L ⁻¹	1.284	0.635
	7.2 g·L ⁻¹	1.769*	0.563
	14.4 g·L ⁻¹	2.307*	1.098*
	28.8 g·L ⁻¹	3.558*	1.344*
Ferrous sulfate (56.6%)	1.8 g·L ⁻¹	1.699*	0.436
	3.6 g·L ⁻¹	1.150	0.477
	7.2 g·L ⁻¹	1.471*	0.680
	14.4 g·L ⁻¹	2.273*	1.185*
	28.8 g·L ⁻¹	3.526*	1.577*
Flowable elemental sulfur (52%)	3.55 mL·L ⁻¹	0.691	1.430*
	7.1 mL·L ⁻¹	0.635	1.638*
	14.2 mL·L ⁻¹	0.637	1.595*
	28.4 mL·L ⁻¹	0.707	1.859*
	56.8 mL·L ⁻¹	0.771	1.303*
Seplex-L organic acid	0.32 mL·L ⁻¹	0.620	0.275
	0.64 mL·L ⁻¹	0.697	0.276
	1.28 mL·L ⁻¹	0.638	0.225
	2.56 mL·L ⁻¹	0.572	0.294
	5.12 mL·L ⁻¹	0.652	0.342
Sulfuric acid (96.5%)	0.16 mL·L ⁻¹	0.740	0.368
	0.32 mL·L ⁻¹	0.875	0.409
	0.64 mL·L ⁻¹	1.075*	0.449
	1.28 mL·L ⁻¹	1.554*	0.608
	2.56 mL·L ⁻¹	2.548*	1.037*
21.1N-3.1P-5.8K fertilizer	0.08 mL·L ⁻¹ R ²	0.664	0.337
	0.16 mL·L ⁻¹ R	0.792	0.491
	50 mg N·L ⁻¹ R	0.713	0.492
	100 mg N·L ⁻¹ R	0.739	0.675*
	200 mg N·L ⁻¹ R	0.883*	1.117*
	400 mg N·L ⁻¹ R	1.297*	1.704*

²Treatments followed by the symbol R were reapplied every 3 d (other treatments were applied only once).

*Indicates a significantly higher EC than the control ($P \leq 0.05$). NA = Not applicable.

Table 3. ANOVA summary of the response to drench applications of six chemicals on the Δ pH (mean treatment pH minus mean control pH) for a peat/perlite growing-medium with four starting-pH levels between 6.4 and 7.6.

Factor	Al ₂ (SO ₄) ₃	FeSO ₄	Flowable sulfur	Seplex-L organic acid	H ₂ SO ₄	21.1N-3.1P-5.8K
Starting-pH	**	NS	***	**	**	***
Concentration	***	***	NS	***	***	***
Starting-pH * concentration	**	***	NS	NS	*	NS
Days after application (covariate)	**	**	***	***	NS	NS

NS, *, **, *** Nonsignificant or significant at represent $P \leq 0.05$, 0.01, and 0.001, respectively.

treatments (3.55 to 56.8 mL·L⁻¹). A gradual decline in pH by up to -3.34 units was observed by day 28 (Fig. 2). As starting-pH increased, the acidifying effect of sulfur also increased (Fig. 2). EC increased over time, and medium-EC's were 1 dS·m⁻¹ or more above the control on day 28 (Table 2).

Seplex-L organic acid. Although there were statistically significant effects of concentration and starting-pH, the organic acid had only a slight effect on medium-pH (Fig. 3A, Table 3). Only the highest rate (5.12 mL·L⁻¹) caused a Δ pH that was significantly below zero, and the most negative Δ pH occurred with the lowest starting-pH. The EC of the medium was not affected by the organic acid.

Sulfuric acid. Sulfuric acid caused a rapid drop in medium-pH, with no difference in Δ pH between days 1 and 28 (Table 3). Increasing concentration of sulfuric acid caused a greater decline in medium-pH (Fig. 3B, Table 3). All

single-drench applications except the lowest concentration (0.16 mL·L⁻¹) caused a Δ pH that was significantly less than zero. The repeat application of 0.08 mL·L⁻¹ did not decrease medium-pH compared with the control, but the 0.16 mL·L⁻¹ repeat application caused a significant decline, averaging -0.40 pH units across starting-pH (data not shown). The highest three single-drench concentrations resulted in a medium-EC above the control on day 1, but by day 28 this increase was only significant for the highest (2.56 mL·L⁻¹) concentration (Table 2).

21.1N-3.1P-5.8K All concentrations of 21.1N-3.1P-5.8K caused a significant increase in pH, averaged across starting-pH levels (Table 3, Fig. 3C). The rise in medium-pH increased with concentration (Fig. 3C) and was more pronounced at lower starting-pH levels. The EC increased over time (Table 2) following repeat applications at high concentration.

Discussion

Increasing concentrations of aluminum sulfate, ferrous sulfate, and sulfuric acid achieved a rapid drop in pH 1 d after application, with a change in pH of <0.25 pH units between days 1 to 28. pH-response to these three chemicals increased as concentration increased, and each chemical decreased pH by ≈ 3 pH units at the highest concentrations tested.

We noted discoloration (darkening) of media by both aluminum sulfate and ferrous sulfate, which could decrease their desirability for application to floricultural crops grown for retail. High rates of aluminum sulfate might also cause plant nutrition problems due to high levels of aluminum that can adsorb phosphate and disrupt root uptake of other cations, as well as cause phytotoxicity (Marschner, 1995). Both aluminum and ferrous sulfate were highly soluble, safe, and easy to apply. Ferrous sulfate oxidizes to brown ferric sulfate (Ferrous sulfate MSDS from Mallinkrodt Baker, Philipsburg, N.J.) or other oxides, and should only be used to reduce medium-pH if the material has a greenish-blue color as a solid and the solution made from ferrous sulfate has a clear yellow color. Following oxidation, ferrous sulfate should not be used to lower medium-pH because it cannot be determined how much of the material has already oxidized and is therefore unreactive.

The organic acid caused only a slight decrease in pH (Fig. 3), despite application of a very high concentration (64 meq·L⁻¹ CaCO₃) of the Seplex-L in terms of label rates. At a given concentration (in mL·L⁻¹) of solution, Seplex-L had half the neutralizing ability (meq·L⁻¹ CaCO₃) of sulfuric acid, according to chemical label information. Solution-pH remained much higher than sulfuric acid (Table 1) at the same meq·L⁻¹, and effect on medium-pH was also less (Fig. 3), indicating that proton dissociation was limited. Seplex-L may therefore be more suited to reducing alkalinity, an important aspect of managing medium-pH (Bailey, 1996), rather than as a corrective drench.

Ammonium and urea-based fertilizers acidify the medium through nitrification (oxidation by chemoautotrophic bacteria), in a process that is favored by high microbial populations, warm temperature, and basic medium-pH (Lang and Elliott, 1991). Further acidification with ammonium or urea can occur because plant roots excrete protons when taking up ammonium (Marschner, 1995). Lang and Elliott (1991) found that nitrification (ammonium oxidation) activity was greater in root media that contained plants compared with unplanted media. Medium-pH in their study declined in both planted and unplanted media (not as a result of H⁺ extrusion and presumably from nitrification), and nitrification was minimal below pH 6.8. Lang and Elliott (1991, 1997) found that nitrification rates can differ between container media types, nitrification rate can increase with inoculation with *Nitrosomonas* or *Nitrobacter* bacteria, and that nitrifying activity increased over a 4-6 week experimental period. In our trial, 21.1N-3.1P-5.8K initially raised pH, especially at the lower starting-pH levels, probably because there was insufficient nitrifi-

Fig. 1. The ΔpH following an application of (A) aluminum sulfate or (B) ferrous sulfate at five concentrations ranging from 1.8 to 28 $\text{g}\cdot\text{L}^{-1}$ to a medium at four starting-pH levels. The ΔpH was quantified as the mean pH from treated media minus the mean pH of media that received the deionized water control. Symbols represent the least-square mean ΔpH over time for 20 containers destructively sampled on five dates between 1 and 28 d after application, and error bars represent 95% confidence intervals. Solid lines represent the least-square mean for each concentration across all starting-pH levels.

Fig. 2. The ΔpH over a 28-d period following an application on day zero of flowable elemental sulfur at five concentrations ranging from 3.55 and 56.8 $\text{mL}\cdot\text{L}^{-1}$. The ΔpH was quantified as the mean pH from treated media minus the mean pH of media that received the deionized water control. Symbols represent averages of 20 replicate media samples ($\pm$ 95% confidence intervals).

cation to reduce medium-pH. Lower starting-pH treatments were below the pH 6.8 threshold indicated by Lang and Elliott (1991), and the duration of our trial was only 4 weeks.

Sulfur acidifies the medium through oxidation to sulfuric acid, driven by microbial activity (Bloom, 2000), and Lindemann et al. (1991) noted that the reaction rate can be unpredictable in soils. Factors that increase sulfur oxidation include high population levels of *Thiobacillus* and other S-oxidizing bacteria, environmental conditions that favor microbial activity (sufficient aeration, moisture, and warm temperatures [S-oxidation rate at 24 °C was reported to be $\approx$ 15% of the rate at 29 °C (Camberato, 1999)], fine S-particle size (Janzen and Bettany, 1987), and lack of certain wetting agents (Lindemann et al., 1991). Medium-pH following application of flowable sulfur in this experiment continued to decline until the end of the experiment. The similarity in response across different concentrations may have been caused by a saturation of the medium ecosystem with sulfur, whereby microbial activity rather than sulfur supply was rate limiting. Further research would be needed to quantify the ideal application rate for container media. Elemental-S may not be the best technology for rapid pH-correction in containers because of the gradual pH-response combined with the likelihood that dose response will depend on factors influencing S-oxidation rate. With pH of chemical solutions between 6.87–7.01, flowable sulfur was safe to handle, but required constant agitation to avoid settling and the material could clog application equipment.

Sulfuric acid rapidly lowered medium-pH, but was also the most dangerous material tested with respect to worker safety. Repeat applications at a low concentration are less likely to cause a phytotoxic response compared with a single high-dose drench, for crops that do not require an immediate change in pH. In our trial, repeat applications of sulfuric acid at 0.16 $\text{mL}\cdot\text{L}^{-1}$ (1.6 mM) lowered medium-pH more effectively than a single drench at that concentration. In comparison, Elliott (1996) grew floricultural crops in containers and with each drip-irrigation of deionized water he supplied 2.5 mM sulfuric acid and a complete fertilizer. Elliott (1996) reported no detrimental effect of acid on poinsettia (*Euphorbia pulcherrima*) growth, and the acid caused an increase in growth of New Guinea Impatiens (*Impatiens xhybrida*) compared with plants fertilized without acid addition. Final pH of media irrigated with fertilizer and sulfuric acid averaged 0.6 units lower than media receiving fertilizer only in Elliott's (1996) study.

The acceptable medium-EC from a saturated media extract is between 1.0 and 2.0 $\text{dS}\cdot\text{m}^{-1}$ for seedlings and plugs, and for established plants is between 2.0 and 3.0 $\text{dS}\cdot\text{m}^{-1}$ (Lang, 1996). Decline in medium-EC over time for control media probably occurred because of salt stratification because no leaching occurred. Movement of nutrient salts into the upper 1 cm of the medium (which was discarded from the medium-test samples), can occur through evaporation from the medium surface (Argo and Biernbaum, 1994, 1995).

Fig. 3. The Δ pH following an application of (A) Seplex-L organic acid, (B) 96.5% sulfuric acid, and (C) 21.1N-3.1P-5.8K water-soluble fertilizer at different concentrations to a medium at four starting-pH levels (6.4, 6.5, 7.3, and 7.6). The Δ pH was quantified as the mean pH from treated media minus the mean pH of media that received the deionized water control. Bars represent the least-square mean Δ pH over time for 20 containers destructively sampled on five dates between 1 and 28 d after application, and error bars represent 95% confidence intervals. Solid lines represent the least-square mean for each concentration across all starting-pH levels.

The highest experimental rates of aluminum sulfate, ferrous sulfate, sulfuric acid increased medium-EC by 2–3 $\text{dS}\cdot\text{m}^{-1}$ compared with the control, however these chemical rates exceeded levels normally used in horticultural practice. At recommended concentrations of aluminum and ferrous sulfate, and all but the highest sulfuric acid concentration, medium-EC increased by up to 1 $\text{dS}\cdot\text{m}^{-1}$ above the control. Should a combination of high medium-EC and high pH in a container crop arise, where a drop in pH was also necessary, leaching may be necessary before applying any corrective acid at high rates.

This experiment was useful to compare the relative response of each chemical applied to one medium/water source/application volume combination, but further research is needed to quantify how different factors affect the dose response. The medium used in this experiment contained hydrated lime, which had little if any residual buffering capacity. Most container media use dolomitic carbonate lime which generally has greater residual buffering capacity than hydrated lime (Argo and Biernbaum, 1996), and different carbonate lime types vary in their tendency to resist drop in media pH (Elliott, 1996). Commercial con-

tainer media include components other than the peat and perlite evaluated in this study, for example bark, vermiculite, coconut coir, and rockwool (Nelson, 1998), which can differ in their buffering to pH change (Elliott, 1996). Absolute effects on medium-pH from these chemical applications will vary in practice because multiple factors influence medium-pH, including residual lime concentration and activity, plant uptake of nutrients, plant species, water alkalinity, and root medium components (Argo and Biernbaum, 1994, 1995, 1996; Elliott, 1996). Further research is also required to quantify how plant species respond to the chemicals, particularly with respect to phytotoxicity.

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