Effect of Plant Species, Fertilizer Acidity/Basicity, and Fertilizer Concentration on pH of Soilless Root Substrate

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Abstract. The objective of this study was to determine how plant species, fertilizer potential acidity/basicity rating (PABR), and fertilizer concentration affect root substrate pH. Three experiments were conducted. In the first experiment, 13 herbaceous species were grown in a root substrate of three sphagnum peatmoss: one perlite (v/v) with deionized water and a neutral fertilizer (NF) with a PABR of 0 for 78 days to determine species relationships to substrate pH. The decrease in substrate pH ranged from 0.14 to 2.45 units, depending on species. In the second experiment, four of the 13 species from the previous trial representing the range of pH suppression were grown under similar growth conditions as the first experiment for 70 days. Substrate pH was lowered in the range of 0.47 to 2.72 units. In the third experiment, three fertilizers with PABRs of 150 kg-t⁻¹ CaCO₃ equivalent alkalinity, 0 neutral, and 193 kg-t⁻¹ CaCO₃ equivalent acidity were applied in a factorial design at 100 and 200 mg-L⁻¹ N at each irrigation to kalanchoe (the species with the greatest pH suppression from the previous experiments) for 56 days. When applied at the lower fertilizer rate (100 mg-L⁻¹ N), the PABRs resulted in the final substrate pH levels of 4.68, 5.60, and 6.11 for the acidic fertilizer (AF), NF, and basic fertilizer (BF), respectively. At the high fertilizer rate (200 mg-L⁻¹ N), substrate pH declined continuously to 3.97, 4.03, and 4.92 for the AF, NF, and BF, respectively. Expression of PABR depended on the balance between the abiotic (chemical) effect of the fertilizers vs. the biotic (physiological) effects of the fertilizers on microbes and plants. The PABR was best expressed when the fertilizer supply was just adequate or lower indicating a closer connection to the biotic effect.

It is relatively easy to set the initial target pH of a root substrate by matching lime type and rate with the acidity of the substrate components. The challenge lies in maintaining this target pH throughout crop production. Factors that impact pH over time include irrigation water alkalinity (Bailey, 1996); residual content and properties of liming materials (Huang et al., 2010; Rippe

et al., 2007, 2016); acidification due to nitrification (Marschner, 1995); plant and microbe respiratory acidification (Marschner, 1995); acidic, neutral, or alkaline biotic effect of nutrient uptake (Pertusatti and Prado, 2007), which varies among plant species (Fisher et al., 2014a; Johnson et al., 2013); and the abiotic effect of fertilizer (Hignett, 1985).

There is interplay between fertilizer type and some of these pH controlling factors. Most fertilizer solutions have a low pH, thus they are abiotically (chemically) acidic, even when they are biotically (physiologically) neutral or basic. When fertilizers supply ammonium, rhizosphere biotic acidification can occur during microbial nitrification of ammonium to nitrate, where two protons are generated for each ammonium ion oxidized. Plant and microbe uptake of ions supplied by fertilizers have yet another

biotic effect on substrate pH. During uptake of cationic nutrients, protons are released to the rhizosphere in exchange for uptake of positive cation charges (Havlin et al., 2014; Kafkafi, 2008; Marschner, 1995; Nelson, 2011; Zhu et al., 2009). Alkalinization occurs when microbes or plants take up protons along with anionic nutrients or release OH⁻ or HCO₃⁻ to the rhizosphere in exchange for anionic nutrients (Pertusatti and Prado, 2007).

Plant species also interact with some of the factors controlling substrate pH, namely respiration and proportion of cationic to anionic nutrient ions taken up. Release of CO₂ by roots and rhizosphere microorganisms during respiration has an acidifying effect on the rhizosphere through the generation of carbonic acid (Marschner, 1995). Root respiration differs among plant species and with growth conditions (Taiz and Zeiger, 2010) and thus the potential for acidification of the substrate pH from the release of CO₂ also varies across plant species. Plant species also differ in the proportions of ions extracted from the soil solution. Since nitrogen (N) is the only nutrient that is plant available in both anion (nitrate) and cation (ammonium) forms and more N ions are typically taken up than other types combined (Taylor et al., 2010), the form of N taken up by plants has the largest effect on substrate pH. Although the form of N taken up by plants is influenced to a degree by availability, plant species do vary in their affinity for ammoniacal vs. nitrate forms of N (von Witrén et al., 1997). Plants adapted to acid soils generally favor ammonium uptake, whereas those found in calcareous soils favor nitrate uptake (Marschner, 1995). As an example, ammonium uptake often predominates in blueberries (Hanson, 2006). A large differential effect of species on substrate pH during germination and early seedling growth was reported by Huang et al. (2001). Johnson et al. (2013) found a strong species effect on substrate pH when growing three bedding plant species for 4 weeks.

A PABR is included on the labels or technical sheets of greenhouse fertilizers. Pierre (1933) established the early procedures for this rating, which were later refined by the AOAC (1970, 1999) and described by Johnson et al. (2010, 2013). The PABR encompasses both biotic and abiotic impacts of fertilizer on substrate pH. Although this rating system does not allow for effects of plant species, stage of maturity, or fertilizer concentration on substrate pH, it is universally used today. In many situations, it adequately forecasts pH shifts. But there are other situations where it fails. The aberrant pH shifts are usually more acidic than predicted by PABR, suggesting involvement of the abiotic fertilizer effect. In this study, it was hypothesized that the unpredicted acidification is due to application of fertilizer in excess of that used by the plant and microbes. Production scenarios leading to excess fertilizer accumulation in the substrate can include the following: 1) quantity of fertilizer applied is higher than that recommended for the crop; 2) a single fertilizer program applied to multiple species that is

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designed to meet requirements of the faster growing species will result in excess application to the slower species; and 3) failure to reduce fertilizer application later in crop production when a plant's specific rate of growth and nutrient demand typically declines.

To test our hypothesis we 1) measured the differential effects of 13 plant species on substrate pH and 2) assessed the interactive effect of fertilizer concentration and PABR on substrate pH during plant growth.

Materials and Methods

General procedures. Three experiments were conducted in a glass greenhouse in Raleigh, NC, at 35° north latitude. Greenhouse temperature set points for heating and cooling were 18 and 24 °C, respectively. In all three experiments, the root substrate for propagation and subsequent experimentation consisted of 75% sphagnum peatmoss and 25% perlite by volume (Sun Gro Horticulture, Bellevue, WA). In Expt. 1, the root substrate was formulated with calcium carbonate powder at the rate of 65 g·kg⁻¹ of peatmoss (dry weight basis). In Expts. 2 and 3, the rate of calcium carbonate powder added to the substrate was adjusted to 60.1 g·kg⁻¹ of peatmoss (dry weight basis) to avoid a high initial pH (>6.5) and gypsum (CaSO₄) was incorporated at 0.9 g·L⁻¹ to maintain acceptable calcium levels. The substrates also contained a wetting agent (AquaGro 2000 G; Aquatrols, Paulsboro, NJ) at the label rate of 0.6 g·L⁻¹. In the three experiments, all species were grown in 16.5-cm top diameter, 1.8-L green, standard, plastic pots. Fertilizer treatments were applied with each irrigation to the top of each pot using a drip system supplied by sump-pumps (model 1A; Little Giant Pump Co., Oklahoma City, OK) in the bottom of opaque, plastic, 90-L tanks containing each single-strength fertilizer solution. Acidification was determined as the difference in substrate pH between the first and final measurements for each crop. The acidification level associated with each species was later categorized as minimal (Δ pH < 0.5), small (Δ pH = 0.50–0.99), moderate (Δ pH = 1.00–1.49), and large (Δ pH ≥ 1.50).

Expt. 1: 13 species. Seeds of fibrous begonia (*Begonia ×semperflorens-cultorum* Hort. ‘Encore III Pink Bicolor’), impatiens (*Impatiens walleriana* Hook. F. ‘Taboo Mix’), pansy (*Viola ×wittrockiana* Gams. ‘Ultima Radiance Red’), petunia (*Petunia ×hybrida* Vilm. ‘Petunia Easy Wave Blue’), sunflower (*Helianthus annuus* L. ‘Ballad’), and vinca [*Catharanthus roseus* (L.) G. Don ‘Pacifica XP Really Red’] were sown in 288-cell plug trays on 5 Nov. 2008. Tomato (*Solanum esculentum* L. ‘Early Girl Hybrid’) seeds were sown in 288-cell plug trays on 19 Nov. Cuttings of New Guinea impatiens (*Impatiens hawkeri* W. Bull ‘Super Sonic White’) and geranium (*Pelargonium zonale* L. ‘Tango’) were taken from stock plants and inserted into 51-cell trays on 18 Nov. Rooted cuttings of pot chrysanthemum [*Dendranthema ×grandiflora*

(Ramat.) Kitam ‘Kory’] and 51-cell tray liners of osteospermum [*Osteospermum ecklonis* (DC.) Norl. ‘Astra White’], kalanchoe (*Kalanchoe blossfeldiana* Poelln. ‘Kerinci’), and Rieger begonia (*Begonia ×hiemalis* Fotsch ‘Amstel Blitz’) were obtained from commercial propagators. The following numbers of established plants were transplanted on 23 Dec. into each pot: one for geranium, New Guinea impatiens, Rieger begonia, sunflower, and tomato; two for impatiens, pansy, and petunia; three for begonia, kalanchoe, and vinca; four for osteospermum; and five for pot chrysanthemum. Incandescent light was applied to the chrysanthemum plants at an intensity of 2 μmol·m⁻²·s⁻¹ for the first 2 weeks from 10:00 PM until 2:00 AM nightly to retard floral initiation after which plants were exposed to ambient short daylengths to induce flowering. During the 2 weeks of nightly light interruption, the chrysanthemum plants were isolated from the other species.

Plants were watered by species with deionized water from transplanting through the first day of substrate solution extraction [4 d after transplanting (DAT)], and then fertilized at each irrigation with a neutral water-soluble fertilizer (17N–2.2P–14.1K; Greencare 17N–5P₂O₅–17K₂O, Kankakee, IL) dissolved in deionized water. In accordance with crop requirements, fertilizer solutions were applied at rates of 200 mg·L⁻¹ N for sunflower, pot chrysanthemum, and kalanchoe and 100 mg·L⁻¹ N for the other species.

Expt. 2: four species. On the basis of the results from Expt. 1, the same cultivars of fibrous begonia, New Guinea impatiens, Rieger begonia, and kalanchoe were selected to represent the minimal, small, moderate, and large acidification categories, respectively, as a validation of Expt. 1. Plants, propagated and handled in a similar manner to Expt. 1, were transplanted on 5 Apr. 2010. The fertilizer and number of plants were the same as Expt. 1. The fertilizer concentrations were also the same: 100 mg·L⁻¹ N for fibrous begonia, New Guinea impatiens, and Rieger begonia and 200 mg·L⁻¹ N for kalanchoe. All fertilization was started after the first measurement of substrate pH on 3 DAT.

Expt. 3: fertilizer type–concentration.

This experiment was conducted concurrently with Expt. 2. The three commercial water-soluble fertilizers (Greencare, Kankakee, IL) used were an AF, 20N–4.4P–16.6K, with a potential acidity of 193 kg·t⁻¹ CaCO₃ equivalent; the same NF used in Expts. 1 and 2, 17N–2.2P–14.1K, with 0 potential acidity/basicity; and a BF, 13N–0.88P–10.8K, with a potential basicity of 150 kg·t⁻¹ CaCO₃ equivalent. The percentages by weight of fertilizer in the ammoniacal nitrogen (NH₄⁺-N) form were 8.0%, 4.2%, and 0.6%, whereas nitrate nitrogen (NO₃⁻-N) percentages were 12.0%, 12.8%, and 12.4% for AF, NF, and BF, respectively. The AF, NF, and BF were dissolved in deionized water (18 MΩ) at concentrations of 100 and 200 mg·L⁻¹ N. Rooted cuttings of kalanchoe ‘Kerinci’, propagated and handled in a similar manner to Expts. 1 and 2, were transplanted on 5 Apr. 2010. Plants were irrigated with deionized water until 7 DAT when fertilizer treatments were initiated and applied at each irrigation thereafter.

Data collection. Substrate pH in all three experiments and electrical conductivity (EC) in Expt. 3 were measured periodically in substrate solutions extracted with a Rhizon soil–moisture sampler (Soilmoisture Equipment Corp., Santa Barbara, CA) consisting of a porous polymer tube (10 cm length × 2.5 mm diameter). One sampler was placed diagonally in each pot by inserting the sampler at a 45° angle from the top to the bottom of the root substrate. Substrate solution was extracted 1 h after each fertilizer application by connecting the sampler to a sample vial and applying a vacuum.

Substrate pH and EC were measured using a Model 695 pH/conductivity meter (Extech Instruments, Waltham, MA). The pH electrode was standardized with pH 4 and 7 buffer solution for every five sample measurements. The change (Δ) in pH (all three experiments) and EC (Expt. 3 only) were determined as the difference between initial and final substrate levels determined by subtracting levels on the first day of fertilizer application from corresponding values on the last day of application. These pairs of DAT

Table 1. Results of statistical analysis of slice effects of plant species × days after transplanting (DAT) for pH data in Expts. 1 and 2 and fertilizer type × concentration × DAT for electrical conductivity (EC) and pH data in Expt. 3.

Expt. 1			Expt. 2			Expt. 3				
Species × DAT			Species × DAT			Fertilizer type × concn × DAT				
pH			pH			EC		pH		
DAT	F value	Pr > F	DAT	F value	Pr > F	DAT	F value	Pr > F	F value	Pr > F
4	6.82	<0.0001	3	1.92	0.1306	7	8.39	<0.0001	4.95	0.0004
14	2.27	0.0091	7	2.64	0.0525	14	27.64	<0.0001	5.13	0.0003
25	2.16	0.0136	14	3.61	0.0153	21	51.24	<0.0001	9.83	<0.0001
39	11.49	<0.0001	21	5.64	0.0012	28	112.08	<0.0001	23.50	<0.0001
57	44.60	<0.0001	28	13.61	<0.0001	35	140.30	<0.0001	25.62	<0.0001
78	58.85	<0.0001	35	39.00	<0.0001	42	236.83	<0.0001	81.00	<0.0001
			42	57.94	<0.0001	49	272.74	<0.0001	114.12	<0.0001
			49	92.94	<0.0001	56	261.74	<0.0001	157.15	<0.0001
			56	113.11	<0.0001					
			63	50.00	<0.0001					
			70	35.26	<0.0001					

for Expts. 1, 2, and 3 were 4 and 78, 3 and 70, and 7 and 56, respectively.

Experimental designs and statistical analysis. Expt. 1 was arranged in a randomized complete block with 13 species and five blocks. The pH was measured as repeated samples on 6 dates for a total of 390 measurements on 65 experimental units. Expt. 2 was also a randomized complete block with four species and five blocks. The pH was measured as repeated samples on 11 dates for a total of 220 measurements on 20 experimental units. Expt. 3 was a two-way factorial design with three fertilizer acidity–basicity types (acid, neutral, basic) and two fertilizer concentrations (100 and 200 mg·L⁻¹ N) for a total of six treatment combinations arranged in five blocks sampled on eight repeated dates (240 measurements on 30 experimental units). Each experimental unit consisted of two pots in all three experiments.

Analyses were done in SAS using PROC ANOVA, PROC GLM, and PROC MIXED for inference. Treatments were the individual

species in Expts. 1 and 2 and fertilizer type–concentration combinations in Expt. 3. All three experiments included variance components for rep and rep × treatment and a repeated measures structure for the measurements within each experimental unit. Kenward Roger df were used for inference. Analyzing the experiments as a whole allowed testing for differences in lsmeans of treatments within each day using a slice option for the lsmeans. The slice option enabled detection of any trends in the strength of evidence (*F* value) for treatment separation over time. For the polynomial analyses, the data set was divided into subsets by treatment. Reported *R*² for the graphs and tests of significance were computed using a model with rep and polynomial effects on the treatment subsets. The curve coefficients were computed on those same subsets using simple polynomial regressions. The ΔpH data were analyzed using analysis of variance (ANOVA) by PROC ANOVA. Means and standard errors were

calculated for all of the sample dates by treatment combinations using PROC MEANS.

Results and Discussion

Species effects. There were significant differences in substrate pH due to the two-way interaction of species by sample date in both Expts. 1 and 2. The slice option of PROC MIXED in Expt. 1 showed that for each measurement date, from 25 DAT on, the species had strongly significantly different responses with monotonically stronger statistical significance on each subsequent measurement date (Table 1). This indicated a strong divergence between species (Fig. 1). The slice option of PROC MIXED in Expt. 2 showed that for each measurement date, from 3 until 56 DAT, the species had strongly significantly different responses with monotonically stronger statistical significance on each subsequent measurement date until the trend reversed and *F* values decreased on 63 and 70 DAT (Table 1). This

Fig. 1. Mean root substrate pH levels measured from 4 to 78 d after transplanting for 13 plant species fertilized at each irrigation with a neutral, water-soluble fertilizer (17N–2.2P–14.1K) in Expt. 1. Petunia (Pet), fibrous begonia (FBeg), osteospermum (Ost), impatiens (Imp), pansy (Pan), New Guinea impatiens (NGI), geranium (Ger), tomato (Tom), Rieger begonia (RBeg), and vinca (Vin) were fertigated at 100 mg·L⁻¹ N; whereas sunflower (Sun), chrysanthemum (Chr), and kalanchoe (Kal) were fertigated at 200 mg·L⁻¹ N. The 13 species were grouped in these graphs by mean change in pH (ΔpH) from initial to final measurement as (A) minimal (ΔpH < 0.50), (B) small (ΔpH = 0.50–0.99), (C) medium (ΔpH = 1.00–1.49), and (D) large (ΔpH = 1.5–2.49) acidifier species. The regression (Regr) equations generated for the best fit models were (A) $y_{\text{Pet}} = 6.64$, $y_{\text{FBeg}} = 6.91 - 0.0279x + 0.000323x^2$ ($r^2 = 0.67$), and $y_{\text{Ost}} = 6.34 - 0.00463x$ ($r^2 = 0.21$); (B) $y_{\text{Imp}} = 6.74 - 0.00858x$ ($r^2 = 0.64$), $y_{\text{Pan}} = 6.80 - 0.0248x + 0.000224x^2$ ($r^2 = 0.86$), $y_{\text{NGI}} = 6.91 - 0.0367x + 0.000302x^2$ ($r^2 = 0.91$), and $y_{\text{Ger}} = 6.46 - 0.00996x$ ($r^2 = 0.59$); (C) $y_{\text{Tom}} = 6.87 - 0.0109x$ ($r^2 = 0.49$), $y_{\text{RBeg}} = 7.14 - 0.0343x + 0.000218x^2$ ($r^2 = 0.87$), and $y_{\text{Vin}} = 6.90 - 0.0295x + 0.000248x^2$ ($r^2 = 0.56$); and (D) $y_{\text{Sun}} = 7.41 - 0.0616x + 0.000384x^2$ ($r^2 = 0.86$), $y_{\text{Chr}} = 6.71 - 0.0199x$ ($r^2 = 0.86$), and $y_{\text{Kal}} = 6.73 - 0.0137x - 0.000208x^2$ ($r^2 = 0.95$). Bars indicate ±SE (n = 5).

indicated a strong divergence between species during most of Expt. 2 (Fig. 2). However, the regression analysis of the petunia data in Expt. 1 was not significant indicating there were no differences among data points. The mean pH for petunia was 6.64. Regression analysis for linear, quadratic, or both models were significant for all other species with the best fit provided in Figs. 1 and 2 for Expts. 1 and 2, respectively.

Resulting Δ pH values for Expts. 1 and 2 were significant (Table 2). In Expt. 1, the 13 species were categorized into four groups according to their associated acidification level, as defined in the Materials and Methods. Petunia (Δ pH = -0.14), fibrous begonia (-0.19), and osteospermum (-0.43) were in the minimal acidification category (Δ pH < 0.50) (Fig. 1A). Pansy (Δ pH = -0.51), impatiens (-0.79), New Guinea impatiens (-0.89), and geranium (-0.97) were in the small acidification category (Δ pH = 0.50–0.99) (Fig. 1B). Vinca (Δ pH = -1.00), tomato (-1.17), and Rieger begonia (-1.46) were in the moderate acidification category (Δ pH = 1.00–1.49) (Fig. 1C). Pot chrysanthemum (Δ pH = -1.56), sunflower (-2.44), and kalanchoe (-2.45) were in the large acidification category (Δ pH $\geq$ 1.50) (Fig. 1D). In Expt. 2, the Δ pH values for fibrous begonia, New Guinea impatiens, Rieger begonia, and kalanchoe were -0.47, -0.69, -1.05, and -2.72, respectively (Table 2). The moderate shifts in Δ pH values in Expt. 2 compared with those from Expt. 1 may have been caused by the intentionally lower initial substrate pH (less lime in the substrate), shorter growth period (70 d compared with 78 d in Expt. 1), and winter growing season in Expt. 1 vs. spring season in Expt. 2 (Table 2). However, species fell into the same acidification categories in both experiments. Similarly, Argo (1996) found that the substrate pH levels of pansy and petunia were the highest, whereas geranium was the lowest among nine bedding plant species 4 weeks after planting when all plants were grown under the same system. Although different cultivars were tested in our study than Argo's study, species effects on pH were in the same order in both studies.

Although the PABR of the fertilizer applied in Expts. 1 and 2 was 0 (neutral), this neutral impact on root substrate would only apply during plant uptake. The fertilizer solutions alone had acid pH levels of 5.02 and 4.55 at 100 and 200 mg·L⁻¹ N, respectively. Therefore, the acidic abiotic effect of fertilizer on substrate pH was expected to predominate during a period of early growth, whereas the neutral biotic effect of fertilizer on substrate pH was anticipated during a later period of larger biomass. This transition was seen in Expt. 2 in the resulting substrate pH curves for the three species fertilized at the lower concentration (Fig. 2). The larger decline in pH for kalanchoe could have been partly due to slower growth occurring in the reproductive stage, but more likely to aboveadequate fertilizer application since the decline in pH was continuous during the entire

Fig. 2. Mean root substrate pH levels measured from 3 to 70 d after transplanting for four plant species fertilized at each irrigation with a neutral, water-soluble fertilizer (17N–2.2P–14.1K) in Expt. 2. Fibrous begonia (FBeg), New Guinea impatiens (NGI), and Rieger begonia (RBeg) were fertilized at 100 mg·L⁻¹ N; whereas kalanchoe (Kal) were fertilized at 200 mg·L⁻¹ N. The regression (Regr) equations generated for the best fit models were $y_{\text{FBeg}} = 6.38 - 0.00527x$ ($r^2 = 0.42$), $y_{\text{NGI}} = 6.63 - 0.0376x + 0.000430x^2$ ($r^2 = 0.81$), $y_{\text{RBeg}} = 6.50 - 0.0345x + 0.000340x^2$ ($r^2 = 0.68$), and $y_{\text{Kal}} = 6.56 - 0.0406x$ ($r^2 = 0.98$). Bars indicate $\pm$ SE (n = 5).

crop. Argo et al. (1997) found a decline in substrate pH due to increasing fertilizer concentration with nine pot plant species. Therefore, our low substrate pH levels of pot chrysanthemum, sunflower, and kalanchoe may be due to high fertilizer concentration as well as species effects. This prompted the third experiment with kalanchoe, the species with the greatest decline in pH.

Fertilizer-type-concentration effects. All fertilizer solutions applied in Expt. 3 had an acidic pH. At a concentration of 100 mg·L⁻¹ N, the average pH level of AF (AF100), NF (NF100), and BF (BF100) solutions were 6.07 ± 0.11 , 5.02 ± 0.06 , and 6.19 ± 0.08 , respectively, whereas at a concentration of 200 mg·L⁻¹ N the pH of AF (AF200), NF (NF200), and BF (BF200) solutions were 6.02 ± 0.08 , 4.55 ± 0.14 , and 5.82 ± 0.06 , respectively. The NF solution was the most acidic among the three types of fertilizers at both concentrations. The average EC of the AF100, NF100, and BF100 solutions were 0.79 ± 0.03 , 0.75 ± 0.02 , and 0.86 ± 0.01 dS·m⁻¹, respectively, and the average EC of the AF200, NF200, and BF200 solutions were 1.53 ± 0.05 , 1.39 ± 0.03 , and 1.65 ± 0.03 , respectively.

There were significant differences in both substrate EC and pH due to the three-way interaction of fertilizer type by concentration by sample date in Expt. 3 (Fig. 3). The slice option of PROC MIXED on the EC data in Expt. 3 demonstrated that for each measurement date from 7 DAT onwards, the species showed strongly significantly different responses with monotonically stronger statistical significance on each subsequent measurement date until the last date (56 DAT), which had an *F* value slightly lower than the previous date (49 DAT) (Table 1). This indicated a strong divergence between the fertilizer type–concentration treatments throughout most of the experiment (Fig. 3B). The slice option of PROC MIXED on the

Table 2. Change (Δ) in mean root substrate pH of 13 plant species from 4 to 78 d after transplanting (DAT) in Expt. 1 and four plant species from 3 to 70 DAT in Expt. 2.^z

Species	Expt. 1	Expt. 2
	Δ pH	
Petunia	-0.14	—
Fibrous begonia	-0.19	-0.47
Osteospermum	-0.44	—
Pansy	-0.51	—
Impatiens	-0.79	—
New Guinea impatiens	-0.89	-0.69
Geranium	-0.97	—
Vinca	-1.01	—
Tomato	-1.18	—
Rieger begonia	-1.46	-1.05
Chrysanthemum	-1.56	—
Sunflower	-2.06	—
Kalanchoe	-2.45	-2.72
LSD _{0.05}	0.39	0.30

LSD = least significant difference.

^zPetunia, fibrous begonia, osteospermum, pansy, impatiens, New Guinea impatiens, geranium, vinca, tomato, and Rieger begonia were fertilized at 100 mg·L⁻¹ N; whereas chrysanthemum, sunflower, and kalanchoe were fertilized at 200 mg·L⁻¹ N.

pH data in Expt. 3 indicated that for each measurement date from 7 DAT on, the species showed strongly significantly different responses with monotonically stronger statistical significance on each subsequent measurement date indicating a strong divergence among fertilizer type–concentration treatments (Fig. 3B; Table 1).

There were significant differences in the Δ EC over time due to fertilizer type and concentration in Expt. 3. However, the fertilizer type by concentration interaction was not significant (data not shown). The AF had a greater overall mean Δ EC than the NF or BF (Table 3). The mean Δ EC values for 100 and 200 mg·L⁻¹ N were -0.75 and 1.03 dS·m⁻¹, respectively least significant

Fig. 3. Mean root substrate (A) electrical conductivity (EC) and (B) pH levels measured from 7 to 56 d after transplanting for kalanchoe fertilized at each irrigation with acidic (AF), neutral (NF), and basic (BF), water-soluble fertilizers (20N–4.4P–16.6K, 17N–2.2P–14.1K, and 13N–0.88P–10.8K, respectively). Each fertilizer was applied at two concentrations (100 and 200 mg·L⁻¹ N). The regression (Regr) equations generated for the best fit models were (A) $y_{AF100} = 0.924 + 0.0205x - 0.000496x^2$ ($r^2 = 0.83$), $y_{AF200} = 1.12 + 0.0576x - 0.000510x^2$ ($r^2 = 0.89$), $y_{NF100} = 1.47 - 0.0282x + 0.000136x^2$ ($r^2 = 0.94$), $y_{NF200} = 0.920 + 0.0568x - 0.000459x^2$ ($r^2 = 0.81$), $y_{BF100} = 1.43 - 0.0173x$ ($r^2 = 0.93$), and $y_{BF200} = 1.27 + 0.0567x - 0.000605x^2$ ($r^2 = 0.80$) and (B) $y_{AF100} = 6.37 - 0.0314x$ ($r^2 = 0.94$), $y_{AF200} = 6.33 - 0.0272x - 0.000290x^2$ ($r^2 = 0.95$), $y_{NF100} = 6.47 - 0.0366x + 0.000367x^2$ ($r^2 = 0.72$), $y_{NF200} = 6.42 - 0.0288x - 0.000292x^2$ ($r^2 = 0.95$), $y_{BF100} = 6.59 - 0.0212x + 0.000211x^2$ ($r^2 = 0.61$), and $y_{BF200} = 6.35 - 0.252x$ ($r^2 = 0.95$). Bars indicate $\pm$ SE (n = 5).

Table 3. Effects of fertilizer type on the change (Δ) in mean root substrate electrical conductivity (EC) and fertilizer type and concentration on the change (Δ) in mean root substrate pH of kalanchoe from 7 to 56 d after transplanting in Expt. 3.

Fertilizer type	Δ EC (dS·m ⁻¹)	Δ pH	
		100 mg·L ⁻¹ N	200 mg·L ⁻¹ N
Acidic (20N–4.4P–16.6K)	0.30	-1.41	-2.14
Neutral (17N–2.2P–14.1K)	0.10	-0.50	-2.14
Basic (13N–0.88P–10.8K)	0.01	-0.38	-1.29
LSD _{0.05} ²	0.16	0.25	

LSD = least significant difference.

²LSD values for Δ EC are for comparing between fertilizer types. LSD values for Δ pH are for fertilizer concentrations for a given fertilizer type or fertilizer types for a given fertilizer concentration.

difference (LSD_{0.05} = 0.13). This indicated insufficient fertilizer supply at the lower concentration. This was further supported by Fig. 3A, which shows substrate EC levels for the three 100 mg·L⁻¹ N treatments were characterized by a slow, steady decline reaching low levels of 0.38 to 0.52 dS·m⁻¹ at 56 DAT. Whipker et al. (2001) reported that the recommended pour-through extract EC range for kalanchoe is 2.0 to 3.5 dS·m⁻¹. All three fertilizers at 200 mg·L⁻¹ N in Expt. 3 rose into this range by 28 DAT.

There was a significant fertilizer type by concentration interaction for pH in Expt. 3. The overall effect showed the AF lowered the pH more than NF and BF at 100 mg·L⁻¹ N and the AF and NF lowered the pH more than the BF at 200 mg·L⁻¹ N (Table 3). Patterns of substrate pH decreases associated with the three fertilizers at the lower concentrations treatments are illustrated in Fig. 3B. Treatment AF100 resulted in a linear pH decline from 6.09 to 4.68 at 56 DAT. The potentially

neutral, NF100 solution was associated with a smaller pH decline from 6.10 to 5.60. Substrate pH in the potentially basic, BF100 treatment began at 6.49, declined to a minimum level around 42 DAT, and then increased ending at 6.11 at 56 DAT. The PABRs for these AF, NF, and BF were expressed in the final substrate pH levels of 4.68, 5.60, and 6.11, respectively.

Substrate EC and pH responses to the 200 mg·L⁻¹ N fertilizer treatments were very different. EC increased to levels of 2.72 to 2.82 dS·m⁻¹ at 42 DAT (Fig. 3A). After that time, the EC remained relatively constant. This suggested above-adequate fertilizer application to 42 DAT followed by application in balance with demand. Substrate pH declined continuously throughout the experiment in the three treatments (Fig. 3B). Responses to the potentially AF and NF were similar, with the final pH of $\approx$ 4.0. The BF resulted in a linear pH decline to a low value of 4.92.

The PABRs of the fertilizers were most closely correlated with change in substrate pH when the 100 mg·L⁻¹ N concentration was applied. Substrate EC levels in these treatments indicated inadequate nutrition, thus a high proportion of fertilizer provided was taken up by plants. Under this condition, the biotic fertilizer effect (the PABR) was strong relative to the abiotic effect. The biotic effect with fertilizer treatment BF100 counteracted the abiotic acidity effect of the fertilizer to a stronger degree than with NF100, as was expected. The acidic biotic effect of fertilizer treatment AF100 enhanced the abiotic effect as seen in the rapid decline in substrate pH throughout the 56 d. Accumulation of fertilizer salts in substrate of the 200 mg·L⁻¹ N series of fertilizer treatments, as seen in rising substrate EC levels, resulted in the biotic fertilizer effect being proportionately smaller than the abiotic effect on substrate pH. This relationship of declining substrate pH with rising fertilizer concentration has been reported by Fisher et al. (2014b). Consequently, all substrate pH values were lower in this fertilizer series than in the 100 mg·L⁻¹ N series. The basic BF200 fertilizer treatment had the highest pH values in the 200 mg·L⁻¹ N series. Substrate pH in this treatment did not plateau as in BF100, but continued to decline to a value of 4.92 compared with 6.11 in the BF100 treatment. The biotically neutral effect of NF200 fertilizer treatment was insufficient to counteract the abiotic fertilizer acidity effect, thus pH declined continuously.

The acidic abiotic effect of fertilizers is due in part to the acidity of the compounds making up the fertilizer solution. However, this does not explain all of the acidic effect since the solution pH of the high concentration acidic PABR fertilizer in this study (6.02) was higher than that of the NF (4.55) and BF (5.82). Influence of fertilizer cations on substrate cation exchange sites plays a major role (Fisher et al., 2014b). Alkaline PABR fertilizers typically have a higher Ca²⁺, and possibly Mg²⁺, but lower NH₄⁺ content than acidic PABR fertilizers. Due to a higher affinity of divalent than monovalent ions for

exchange sites, alkaline PABR fertilizer displaces more protons into the bulk solution than acidic PABR fertilizer. An initial decrease in pH can occur. But, this is rapidly replaced with a pH increase when displaced protons are leached by watering and fertilization, giving way to a lower bulk solution proton concentration in equilibrium with the lower proportion of protons on exchange sites.

In Table 3, it is apparent that the Δ pH value for kalanchoe declined from -2.14 to -0.50 , a shift from the large to small acidification categories, when NF concentration was reduced. This indicates the large role that fertilizer concentration played in acidification. It further suggests that fertilizer concentration could have played a role in the species differences measured in Expts. 1 and 2. Highly efficient fertilization and nutritional monitoring practices have not been developed for every crop. It is conceivable that across the species in this study, nutritional availability levels ranged from just sufficient to various levels moderately above sufficiency. This would have altered the balance between abiotic and biotic fertilizer influences confounding the species effect with the fertilizer concentration effect. This factor is present in commercial production as well, since multiple crops must be grouped into each of a limited number of fertilization programs to comply with physical equipment and economic constraints.

Conclusions

Commercially important differences in substrate pH occurred across the 13 plant species. This suggests the need to categorize greenhouse crops according to their association with substrate pH when developing fertilization programs. It further indicates a need in commercial production to analyze the substrate separately for these categories of crops for better management of pH. Expression of the current predicted PABRs assigned to fertilizers depends on the proportion of applied fertilizer taken up by the crop. Basic and neutral reaction fertilizers can have an acidic effect on substrate when applied to crops in high quantity. This calls attention to the importance of

monitoring substrate EC as a tool for regulating fertilizer application in accordance with crop demand. Furthermore, this justifies the value of understanding fertilizer use efficiency for implementation of best management practices.

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