Validation of a Fertilizer Potential Acidity Model to Predict the Effects of Water-soluble Fertilizer on Substrate pH

Paul R. Fisher1,4
Environmental Horticulture Department, University of Florida, 2549 Fifield Hall, Gainesville, FL 32611-0670

William R. Argo2
Blackmore Company, Belleville, MI 48111

John A. Biernbaum3
Department of Horticulture, Michigan State University, East Lansing, MI 48824-1325

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Abstract. Two experiments were run to validate a “Nitrogen Calcium Carbonate Equivalence (CCE)” model that predicts potential fertilizer basicity or acidity based on nitrogen (N) form and concentration for floriculture crops grown with water-soluble fertilizer in containers with minimal leaching. In one experiment, nine bedding plant species were grown for 28 days in a peat-based substrate using one of three nutrient solutions (FS) composed of three commercially available water-soluble fertilizers that varied in ammonium to nitrate (NH4+ : NO3–) ratio (40:60, 25:75, or 4:96) mixed with well water with 130 mg L–1 calcium carbonate (CaCO3) alkalinity. Both the ammonium-nitrogen (NH4–N) content of the FS and plant species affected substrate pH. Predicted acidity or basicity of the FS for Impatiens walleriana Hook.f., petunia ×hybrida E. Vilm. (petunia), and Pelargonium hortorum L.H. Bailey (pelargonium) from the Nitrogen CCE model was similar to observed pH change with an adjusted R2 of 0.849. In a second experiment, water alkalinity (0 or 135.5 mg L–1 CaCO3), NH4+ : NO3– ratio (75:25 or 3:97), and N concentration (50, 100, or 200 mg L–1 N) in the FS were varied with impatiens. As predicted by the N CCE model, substrate pH decreased as NH4+ concentration increased and alkalinity decreased with an adjusted R2 of 0.763. Results provide confidence in the N CCE model as a tool for fertilizer selection to maintain stable substrate pH over time. The limited scope of these experiments emphasizes the need for more research on plant species effects on substrate pH and interactions with other factors such as residual limestone and substrate components to predict pH dynamics of containerized plants over time.

Substrate pH must be carefully managed to control nutrient availability in container substrates (Peterson, 1981). A number of factors that include substrate components, limestone type and rate, the irrigation water source may be considerable differences in the susceptibility of high pH-induced iron chlorosis because of differences in their ability to lower the rhizosphere pH (Froehlich and Fehr, 1981; Saxena and Sheldrake, 1980).

In floriculture crops, much less is known of species or cultivar effects on substrate pH and the resulting differences in nutrient uptake. In laboratory experiments on germinating seedlings, Bailey et al. (1996) found that substrate pH varied from 4.5 with Lycopersicon esculentum Mill. (tomato) to 7.5 with Zinnia hybrida Roem. & Usteri (zinnia) under the same conditions. In greenhouse experiments, Argo and Biernbaum (1997) found that the average substrate pH of 10 potted plant species given the same WSF [20N–4.3P–16.6K Peatlite Special (Scotts, Marysville, OH)] ranged from 5.1 with Saintpaulia ionantha Wendl. (African violets) to 6.5 with Gerbera jamesonii Bolus ex Hook. (gerbera). In addition, WSF concentration also influenced substrate pH. For example, the substrate pH of gerbera decreased from 7.1 to 5.8 as the N concentration of the WSF increased from 50 to 200 mg L–1, whereas the substrate pH decreased from 5.2 to 4.8 with African violets over the same range of WSF concentrations.

Johnson et al. (2013) showed that the majority of the WSF effect on substrate pH could be modeled based on the concentration of different N forms (NH4+, NO3–, or urea) despite a wide range in concentration of other ions. By analyzing the observed pH change for impatiens, petunia, and pelargonium, with a number of WSF formulations, parameters were developed for each N form and plant species. Estimated milliequivalents (meq) of acid (negative values) or base (positive values) per mmol of each N form applied were NH4–N –0.6678, –0.6143, and –0.8123; NO3–N 0.0713, 0.2746, and –0.1296; and urea-N –0.2038, –0.1445, and 0.2711 for impatiens, petunia, and pelargonium, respectively. The parameters for meq of acidity or basicity per mmol showed that NH4–N tended to be strongly acidic, urea-N somewhat acidic, and NO3–N weakly basic to slightly acidic. Parameter values were generally in line with expected effects of N forms on substrate pH. However, the pelargonium parameter for NO3–N was slightly negative, indicating acidity even with NO3–N as the sole N source, presumably because of the acidic effect of other cations such as calcium, magnesium, and potassium or from a greater overall tendency for pelargonium to acidify the root zone. Strong acidification of NH4–N could occur from both the charge balance effects of cation uptake by plant roots and nitrification by soil microbes with uptake of NH4–N favored over other N forms (Engels and Marschner, 1995; Lang and Elliott, 1991; von Wieren et al., 2001). Acidification from urea-N occurs through the net effect of hydrolysis (basic), nitrification (acidic), and nitrate uptake (basic) processes (Verburg et al., 2003). Basic effects of NO3–N occur through the charge balance effect (exudation of a base) from anion uptake by plant roots (Argo and Biernbaum, 1997; Marschner, 1995).
The need for species-specific parameters for NO₃-N and urea-N only, whereas in the alkalinity and N concentration experiment, the solution was applied at 100 mg L⁻¹ N. A second experiment focused on the effect of N concentration and water alkalinity with impatiens only with 50 to 200 mg L⁻¹ N concentrations, NH₄NO₃ ratios of 75:25 or 3:97, and water alkalinity at 0 to 136 mg L⁻¹ CaCO₃.

Materials and Methods

Plant species experiment. This experiment included 27 treatments composed of three nutrient solutions and nine species in a factorial design with three replicate cell trays per treatment combination completely randomized on a greenhouse bench and six destructive samples per replicate tray over time. The substrate used was (by volume) 70% Canadian sphagnum peat (Fisons professional black bale peat; Sun Gro Horticulture, Bellevue, WA) with long fibers and little dust (von Post scale 1 to 2; Puustjarvi and Robertson, 1975) and 30% perlite. A dolomite hydrated lime [97% Ca(OH)₂-MgO], 92% of which passed through a 45-μm screen, with reported acid neutralizing value of 161% CCE; National Lime and Stone, Findlay, OH) was added at 1.5 kg m⁻³. The lime type is an important aspect of the methodology, because the hydrated lime used is highly reactive and would not provide residual buffering to pH change during plant growth (Huang et al., 2010). In addition, 0.4 kg each of KNO₃ and gypsum, 0.1 kg triple superphosphate (0N-19P-0 K) and 0.07 kg fritted trace elements (FTE 555; Scotts, Marysville, OH) per m³ of substrate were added at mixing. Sufficient reverse osmosis (RO) purified water was added at mixing to bring the moisture content of the substrate to 40 to 50% of container capacity, and the substrate was allowed to equilibrate for 3 d before planting. At planting, the substrate had a pH of 5.9, an electrical conductivity (EC) of 1.3 dS m⁻¹, and (in mg L⁻¹) 75 NO₃-N, 20 phosphorus (P), 110 potassium (K), 105 calcium (Ca), 55 magnesium (Mg), and 60 SO₄-S based on the saturated media extract (Warncke, 1986).

Table 1. Total macronutrient concentrations of the nutrient solutions used in the two experiments resulting from different water-soluble fertilizers (WSFs) and water sources.⁴

| Fertilizer type | Water alkalinity (mg L⁻¹ CaCO₃) | NH₄-N | NO₃-N | P | K | Ca | Mg | Na | CCEIFS calculated using the N CCE method (meq/L of solution) |
|----------------|---------------------------------|-------|-------|---|---|---|----|----|-------------------------------------------------|
| Plant species experiment | | | | | | | | | Pelargonium | Impatiens | Petunia |
| Acidic WSF⁵ | 130 | 40 | 60 | 23 | 83 | 50 | 15 | 22 | -0.3 |
| Neutral WSF⁶ | 130 | 20 | 80 | 13 | 83 | 68 | 21 | 22 | 0.7 |
| Basic WSF⁶ | 130 | 3 | 97 | 7 | 83 | 96 | 38 | 22 | 1.5 |
| Alkalinity and N concentration⁶ | | | | | | | | | 50 mg L⁻¹ N | 100 mg L⁻¹ N | 200 mg L⁻¹ N |
| Acidic WSF⁵ | 0 | 75 | 25 | 13 | 66 | 1 | 0 | 1 | -1.7 |
| Basic WSF⁵ | 0 | 3 | 97 | 13 | 87 | 62 | 23 | 1 | 0.2 |
| Acidic WSF⁵ | 136 | 75 | 28 | 13 | 73 | 52 | 11 | 25 | 1.0 |
| Basic WSF⁵ | 136 | 3 | 100 | 13 | 94 | 114 | 34 | 25 | 2.9 |

⁴In the experiment, the solution was applied at 100 mg L⁻¹ nitrogen (N) only, whereas in the alkalinity and Na concentration experiment, the solution was applied at 50, 100, and 200 mg L⁻¹ N. The expected potential fertilizer acidity or basicity (CCEIFS) was calculated using the N calcium carbonate equivalent (CCE) method (Johnson et al., 2013).
⁵20N-4.3P-16.4K-0Ca-0Mg Peatlite Special (macronutrients derived from KNO₃, NH₄H₂PO₄, and NH₄NO₃) mixed with a blend of reverse osmosis and well water.
⁶17N-2.2P-14.1K-3Ca-1Mg [macronutrients derived from 5Ca(NO₃)₂, NH₄NO₃,10H₂O, KNO₃, Mg(NO₃)₂·6H₂O, NH₄H₂PO₄, and NH₄NO₃] mixed with a blend of reverse osmosis and well water.
⁷13N-0.9P-10.8K-6Ca-3Mg [macronutrients derived from 5Ca(NO₃)₂, NH₄NO₃,10H₂O, KNO₃, Mg(NO₃)₂·6H₂O, and NH₄H₂PO₄] mixed with a blend of reverse osmosis and well water.
⁸17N-2.2P-10.9K-0Ca-0Mg [macronutrients derived from KCl, NH₄NO₃, NH₄H₂PO₄, and (NH₄)₂SO₄] mixed with either reverse deionized or well water.
⁹12.6N-1.3P-7.7K-2.8Ca-2.82Mg [macronutrients derived from 5Ca(NO₃)₂, NH₄NO₃,10H₂O, KNO₃, KH₂PO₄, and Mg(NO₃)₂·6H₂O] mixed with either reverse deionized or well water.

Total concentrations of nutrient solutions are shown at 100 mg L⁻¹ N, but treatments also included 50 and 200 mg L⁻¹ N.
The three nutrient solutions varied in the NH$_4$-$\text{NO}_3$ ratio, P, Ca, and Mg concentrations, but were applied at a constant 100 mg L$^{-1}$ N. The three commercially available WSF were 1) acidic WSF with (in percent of total mass) 20N-$4.3\text{P}-16.6\text{K}-0\text{Ca}-0\text{Mg}, which had an NH$_4$-$\text{NO}_3$ ratio of 40:60 and a potential acidity using the industry standard Pierre’s Method (Pierre, 1933) of 200 kg/1000 kg of fertilizer; 2) neutral WSF with Pierre's Method (Pierre, 1933) of 200 t of potential acidity using the industry standard of ZnSO$_4$, CuSO$_4$, boric acid, and sodium molybdate for the acidic WSF or from Fe-EDTA, MnSO$_4$, ZnSO$_4$, CuSO$_4$, boric acid, and sodium molybdate for the other two WSFs. The WSFs were mixed with a blend of well and RO water (1:1.5 by volume) that had a pH of 6.7, an EC of 0.3 dS m$^{-1}$, 50 Ca, 15 Mg$^{2+}$, 25 Na$^+$, and 10 SO$_4^{2-}$ (mg L$^{-1}$); and a titratable alkalinity to pH 4.5 of 130 mg L$^{-1}$ CaCO$_3$. The total macronutrient concentration of the three FS applied at every irrigation is found in Table 1.

The experiment was conducted starting on 6 Mar. 1996 at Michigan State University, East Lansing, MI, in a well-ventilated glasshouse with constant air circulation and cement floors. The bedding plant species tested were pelargonium ‘Orbit Hot Pink’, bedding plant impatiens ‘Super Elfin Violet’, Tagetes patula L. ‘Bonauna Yellow’ (marigold), Begonia tuberhybrida Voss ‘Nonstop Pink’ (tuberous begonia), Viola ×wittrockiana Gams ‘Orange Crown’ (pansy), petunia ‘Flash Rose’, Salvia splendens Sellow ex Chult. ‘Sizzler Lavender’ (salvia), Vinca rosea L. ‘Little Bright Eyes’ (vinca), and Begonia semperflorens Hook. ‘Vodka’ (wax begonia). Plugs from a 512 tray (288 tray for pelargonium) were planted into 1204 (0.07 L per cell) bedding plant flats containing the peat/perlite mixture (Table 2) with a pH range of only 6.13 to 6.29. During this time, plants were irrigated with deionized water, zero alkalinity with (in mg L$^{-1}$) 0.0-NO$_3$-N 0.0 P, 0.4 Ca, 0.4 Mg, 0.9 sulphur (S), 0.3 Fe, 0.01 Mn, 0.01 Zn, 0.07 Cu, 0.10 B, and 0.05 Mo) and well water [135.5 Ca$^{2+}$, or 0.27 meq alkalinity, with (in mg L$^{-1}$) 2.8-NO$_3$-N 0.0 P, 11.1 K, 52.4 Ca, 11.1 Mg, 34.7 S, 0.3 Fe, 0.01 Mn, 0.01 Zn, 0.07 Cu, 0.10 B, and 0.05 Mo]. Applied fertilizer N concentrations were 50, 100, and 200 mg L$^{-1}$ N. With all solutions, micronutrients were added (in mg L$^{-1}$) at 1.0 Fe, 0.5 Mn, 0.5 Zn, 0.25 Cu, 0.25 B, and 0.05 Mo from Fe-EDDHA, MnSO$_4$, ZnSO$_4$, CuSO$_4$ boric acid, and sodium molybdate. Each combination of fertilizer type, alkalinity, and fertilizer concentration had 27 replications (10-cm diameter, 385-mL pots) organized in three blocks with nine replicate pots per fertilizer type*alkalinity*N concentration treatment completely randomized within each block.

A 70 peat:30 perlite (by volume) substrate was mixed with dolomitic hydrated lime-stone [97% Ca(OH)$_2$, MgO, 92% of which passed through a 44-$\mu$m screen with reported acid neutralizing value of 161% CCE; National Lime and Stone, Findlay, OH] at 2.01 kg m$^{-3}$ to raise substrate pH to $\approx$6.0. No other pre-plant fertilizer charge was applied. The peat source used in the research substrates was Canadian Sphagnum peat (Sun Gro Horticulture, Vancouver, Canada) with long fibers and little dust (von Post scale 1 to 2; Puustjarvi and Robertson, 1975).

After transplanting, the plants were grown for 2 weeks before the treatments began. During this time, plants were irrigated with 50 mg L$^{-1}$ N with the neutral FS from the Plant Species Experiment. Because there was no pre-plant nutrient charge in this experiment, in contrast to the Plant Species Experiment, the 2-week transition period allowed the WSF to react with the substrate cation exchange capacity to provide a stable pH. After the 2-week pre-treatment, the substrate pH and EC of 5.60 $\pm$ 0.04 and 0.85 $\pm$ 0.09 dS m$^{-1}$ (mean $\pm$ SE), respectively, were determined using the saturated medium extract with six replicate samples (Warncke, 1986). Saucers were placed under each pot to allow reabsorption of any leachate. After 5 weeks of treatment, and application of 2 L per pot of irrigation solution, four replicates per block (total of 12 plants per fertilizer * N concentration * water source treatment combination) were sampled for substrate pH and EC using the saturated medium extract method. At this final stage, plants all appeared healthy and in full bloom.

Substrate pH and EC data at Week 5 were subjected to ANOVA using PROC GLIMMIX (SAS Institute, Cary, NC) as a 2 x 2 x 3 factorial. The predicted pH effect of each FS (CCE$_{FS}$) was calculated from the meq of acidity or basicity of the fertilizer for impatiens using the N CCE model plus the alkalinity of the water source. The mean change in substrate pH from the beginning to the end of the experiment (Day 35) for each FS was compared with CCE$_{FS}$ using simple linear regression. The model was also validated using analysis of covariance (ANCOVA) in PROC GLM, which treated N concentration and water alkalinity as class variables and CCE$_{FS}$ as a continuous variable, change in measured pH was the dependent variable, and the tested effects included CCE$_{FS}$, N concentration, water alkalinity, and their interactions.

Results and Discussion

Plant species experiment. Results for ANOVA from Days 3, 7, 14, 21, and 28, analyzed separately by day (Table 2), showed a significant main effect of plant species on each measurement day, the main effect of WSF from Day 14 onward, and no interaction between plant species and WSF on any measurement day. Between planting and Day 7, substrate pH was similar for all treatments (Table 2) with a pH range of only 6.13 to 6.29 on Day 3 and 6.13 to 6.43 by Day 7. Argo and Biernbaum (1996, 1997) similarly found that the FS had minimal effect on substrate pH up to 4 weeks after planting in larger size containers (0.75 L). Fisher et al. (2014) showed that ammonium and nitrate had weak impacts on substrate pH in a peat-perlite substrate in the absence of plants, which is similar to the situation when plant root systems are small relative to the substrate volume.

From Day 14 onward, both the WSF and plant species affected substrate pH (Table 2). There was a significant difference between the pH level of each FS at Day 28 with a least-square mean of 6.04, 6.42, or 6.86 with the acidic, neutral, or basic WSF, respectively. Least-square mean pH by Day 28 ranged between species from 5.69 to 6.72 with pelargonium having a lower pH than all other species, regardless of the WSF that was
applied. In comparison, the other species maintained their substrate pH up to 1 pH unit higher than pelargonium. Marigold is considered an Fe-efficient species (Albano and Miller, 1996) and along with wax begonia had a lower pH than pansy, which is considered Fe-inefficient and susceptible to Fe deficiency at high pH (Argo and Fisher, 2002).

Bailey et al. (1996) suggested that the same WSF should not be used on all species, because plant species differ in their target substrate pH ranges and tendency to raise or lower pH. However, it may be impractical to use different WSF on bedding plant species being grown in the same greenhouse. An alternative method for optimizing pH management using the same WSF may be to use two or more substrates with different lime-stone rates and starting pH values. For example, species that tend to decrease substrate pH (such as pelargonium) can be planted into a substrate with a starting pH greater than 6.0. In contrast, species that tend to increase pH (such as pansy or petunia) could be planted into a substrate with a starting pH less than 5.8.

The change in substrate pH from Day 0 to Day 28 was compared with the acidity or basicity of each WSF as predicted by both the CCE$_{FS}$ (continuous variable) and plant species (class variable) using ANCOVA. The change in pH was affected by the CCE$_{FS}$ ($P < 0.0001$) but not by species or the interaction between CCE$_{FS}$ and species. The linear relationship between CCE$_{FS}$ and change in substrate pH is shown in Figure 1, whereby the more basic the CCE$_{FS}$, the higher substrate pH after 28 d. The only WSF predicted to have a negative (acidic) CCE$_{FS}$ was the acidic WSF in combination with pelargonium (Table 1), and this was the only treatment combination in which substrate pH decreased over time. The observed trend lends confidence to the N CCE method when selecting a WSF for a given species to achieve a stable substrate pH using an alkaline water source, whereas the model was developed using DI water (Johnson et al., 2013). However, although the model had a high adjusted $R^2$ of 0.849 and high level of statistical significance, the N CCE slightly underpredicted the observed acidity of FS overall for this experiment. The regression line in Figure 1 shows this bias, whereby an estimated N CCE of 0.94 meq (= 0.411 intercept/0.438 gradient) would be expected to have a neutral pH effect in this trial.

**Alkalinity and N concentration experiment.** Results from the ANOVA of effects of WSF, N concentration, and water alkalinity on substrate pH (Table 3) found main effects were significant for each factor, but there were no significant interactions. Basic WSF resulted in a higher pH (6.01) than acidic WSF (5.22). Water alkalinity increased substrate pH from 5.28 with DI water to 5.95 with alkaline water. Increasing N concentration decreased pH with a trend in pH of 5.74, 5.68, or 5.43 with 50, 100, or 200 mg·L$^{-1}$ N, respectively. The pH trends with WSF and water alkalinity were expected. However, ANOVA results indicate that increasing the concentration of not only the acidic WSF, but also the basic WSF, decreased substrate pH. A decreasing pH with increased concentration of a basic WSF is contrary to the trend expected using the N CCE model (and also Pierre’s method (Pierre, 1933). Our hypothesis for why pH was slightly lower pH as the N concentration of the basic WSF increased is that Ca and Mg in the basic WSF, which were higher than in the acidic WSF (Table 1), may have decreased substrate pH because of an interaction with exchange sites on the peat. Fisher et al. (2014) showed (in the absence of plants) that increasing concentration of Ca and Mg in a FS caused a decrease in pH of a peat-perlite substrate because of displacement of protons through cation exchange.

The relationship between final substrate EC and the nutrient solutions was complex, and substrate EC ranged widely between treatments (Table 3). The ANOVA of effects of WSF, N concentration, water alkalinity, and their interactions on substrate EC found all main and interaction effects were significant other than the interaction between WSF and water alkalinity (for which $P = 0.054$). In all treatment combinations, we observed healthy root and shoot tissue with heavy flower blooms despite the wide range in nutrient levels (data not shown). Substrate EC tended to increase with increasing N concentration with use of the acidic WSF and with alkaline water.

Fisher et al. (2014) showed a trend of decreased substrate pH as substrate EC increased with FS that contained Ca. Increasing the concentration of the basic fertilizer from 50 to 200 mg·L$^{-1}$ N would also increase the concentration of acidic NH$_4$-N ions, but the pH effect of NH$_4$-N would be expected to be minimal given that the concentration would only increase from 1.5 to 6 mg·L$^{-1}$ NH$_4$-N as N concentration increased from 50 to 200 mg·L$^{-1}$ N.

The predicted meq of acidity or basicity using the N CCE method (CCE$_{FS}$) shown in Table 1 was more affected by the N concentration for the acidic WSF than for the basic

| Plant Species | 3 | 7 | 14 | 21 | 28 |
|---------------|---|---|----|----|----|
| Impatiens     | 6.19 ab | 6.32 abc | 6.42 ab | 6.70 a | 6.66 ab |
| Marigold      | 6.14 b | 6.30 abc | 6.44 ab | 6.22 bc | 6.40 ab |
| Pansy         | 6.21 ab | 6.31 abc | 6.51 ab | 6.68 a | 6.72 a |
| Pelargonium   | 6.20 ab | 6.13 c | 5.92 c | 5.90 c | 5.69 c |
| Petunia       | 6.21 ab | 6.43 a | 6.54 a | 6.74 a | 6.70 ab |
| Salvia        | 6.18 ab | 6.38 ab | 6.51 ab | 6.55 ab | 6.70 ab |
| Tuberous begonia | 6.29 a | 6.29 abc | 6.27 ab | 6.41 ab | 6.36 ab |
| Vinca         | 6.18 ab | 6.23 abc | 6.28 ab | 6.22 bc | 6.42 ab |
| Wax begonia   | 6.13 b | 6.23 abc | 6.22 bc | 6.24 bc | 6.32 b |
| Acidic WSF    | 6.19 a | 6.29 a | 6.24 b | 6.26 b | 6.04 c |
| Neutral WSF   | 6.20 a | 6.30 a | 6.36 ab | 6.38 b | 6.42 b |
| Basic WSF     | 6.19 a | 6.28 a | 6.44 a | 6.58 a | 6.86 a |

| Plant species main effect$^a$ | $*$ | *** | *** | *** | *** |
| WSF main effect $^b$ | NS | NS | ** | *** | *** |

$^a$Data by species represent the least-square mean of three samples and by water-soluble fertilizer (WSF) for 27 samples with mean separation using Tukey’s honestly significant difference at the $P = 0.05$ level.

$^b$Statistical significance at the $P = 0.05$, **0.01, or ***0.001 levels or nonsignificant (ns).

Fig. 1. Plant species experiment: comparison of change in substrate pH from Day 0 to 28 (negative values indicate a drop in substrate pH over time) with predicted milliequivalents of acid (negative values) or base (positive) of each fertilizer solution (FS) using the nitrogen calcium carbonate equivalent (CCE) calculations for the three nutrient solutions, and petunia. The letters A, N, or B refer to the acidic, neutral, or basic reaction FS from Table 1. Symbols represent the mean of three replicates $± 1$ se calculated separately for each treatment mean.
Table 3. Alkalinity and nitrogen (N) concentration experiment: analysis of variance results for effects of fertilizer type, water alkalinity, and N concentration on substrate pH and substrate-electrical conductivity (EC) at Day 35.

| Fertilizer type | Water alkalinity mg L⁻¹ CaCO₃ | Substrate pH | Substrate EC |
|----------------|-------------------------------|-------------|-------------|
|                | 50 mg L⁻¹ N | 100 mg L⁻¹ N | 200 mg L⁻¹ N | 50 mg L⁻¹ N | 100 mg L⁻¹ N | 200 mg L⁻¹ N |
| Acidic WSF     | 0              | 5.03 bc       | 4.91 a       | 4.65 e       | 1.02 def      | 1.53 cd       | 4.29 b       |
| Basic WSF      | 0              | 5.72 bc       | 5.76 bc      | 5.64 bc      | 0.51 f         | 0.83 ef       | 3.67 b       |
| Acidic WSF     | 136             | 5.72 bc       | 5.56 bc      | 5.46 cd      | 1.28 cde       | 1.72 c        | 4.44 a       |
| Basic WSF      | 136             | 6.51 a        | 6.50 a       | 5.96 b       | 0.66 ef        | 1.08 cdef     | 4.80 a       |

WSF

| N concentration | Substrate pH | Substrate EC |
|-----------------|-------------|-------------|
| 50 mg L⁻¹ N     | 5.74 a      | 0.87 c       |
| 100 mg L⁻¹ N    | 5.68 a      | 1.93 b       |
| 200 mg L⁻¹ N    | 5.43 b      | 4.30 a       |

Water alkalinity

| Water alkalinity L⁻¹ CaCO₃ | Substrate pH | Substrate EC |
|---------------------------|-------------|-------------|
| 0                         | 5.28 b      | 1.96 b      |
| 135 mg L⁻¹ CaCO₃          | 5.95 a      | 2.33 a      |

WFS

| Water alkalinity | Substrate pH | Substrate EC |
|-----------------|-------------|-------------|
| NS              | ***         | ***         |

| N concentration | Substrate pH | Substrate EC |
|-----------------|-------------|-------------|
| NS              | ***         | ***         |

| WSF*N concentration | Substrate pH | Substrate EC |
|---------------------|-------------|-------------|
| NS                  | ***         | ***         |

| Water alkalinity*N concentration | Substrate pH | Substrate EC |
|----------------------------------|-------------|-------------|
| NS                               | ***         | ***         |

| WSF*water alkalinity*N concentration | Substrate pH | Substrate EC |
|-------------------------------------|-------------|-------------|
| NS                                  | ***         | ***         |

| Block | Substrate pH | Substrate EC |
|-------|-------------|-------------|
| NS    | ***         | ***         |

*Data by fertilizer type*water alkalinity*N concentration represent the least-square means of 12 samples. Mean separation for interaction and main effects was with Tukey’s honestly significant difference at the α = 0.05 level.

†Statistical significance at the *P = 0.05, **0.01, or ***0.001 levels or nonsignificant (NS).

WSF. For example, with the acidic fertilizer, predicted acidity ranged from −1.7 meq at 50 mg L⁻¹ N to −6.9 meq at 200 mg L⁻¹ N in DI water compared with a range of only 0.2 to 0.7 meq as the basic WSF increased from 50 to 200 mg L⁻¹ N in DI water. These predicted ranges in meq emphasize the stronger impact of NH₄-N compared with NO₃-N in the N CCE method. The water alkalinity of 135.5 mg L⁻¹ CaCO₃ (2.7 meq) increased the predicted meq of basicity of all FS by 2.7 meq compared with the same fertilizer type and concentration with the DI water source, because the meq of water alkalinity is simply added to the fertilizer meq in the N CCE method to calculate net meq of the combined water and fertilizer FS (from Eq. [2]).

The ANCOVA evaluated the effects of CCE₈⁹ (continuous variable), water alkalinity, and N concentration (class variables) on observed change in substrate pH. This analysis showed a significant effect of CCE₈⁹ (P < 0.0001), the interaction between CCE₈⁹ and N concentration (P < 0.0001), and the interaction of water alkalinity and N concentration. Least-square means for each treatment combination of water alkalinity and N concentration are presented in Figure 2, which shows an overall trend whereby an increasing complexity of fertilizer and water effects on substrate pH tends to result in a greater reduction in substrate pH over time. The significant interactions emphasize the underlying complexity of fertilizer and water effects on substrate pH. As indicated previously, increasing N concentration of the basic fertilizer did not cause the predicted increase in substrate pH, contrary to model predictions. For a complete model of substrate pH change, therefore, other nutrients such as Ca and Mg and factors such as substrate cation exchange capacity need to be accounted for.

Conclusion

In the production of container-grown crops, it is not environmentally or economically acceptable to manage pH and nutrient concentrations in the substrate and plant tissue with high WSF concentrations and high leaching rates (Biernbaum, 1992). Irrigation systems that minimize or eliminate water and fertilizer runoff into the environment are widely available. Optimizing pH management in low- or non-leaching irrigation systems requires an understanding of how a variety of factors, including the plant species, WSF, and water alkalinity, interact during production. The results provide confidence for the N CCE in a range of N concentrations and water alkalinites for impatiens, petunia, and pelargonium. Overall, the predicted pH effect of FS from the N CCE model were observed in the two experiments. However, the N CCE model is limited in scope (with just three species-specific N parameters) and predicted pH change would be improved with additional consideration of other ions such as Ca and Mg and substrate cation exchange capacity. Although the model predicted slightly higher pH as NO₃-N concentration increased, the opposite pH trend was observed with a slight drop in pH from 100 to 200 mg L⁻¹ N of the basic fertilizer in combination with the alkaline water source (Fig. 2), which may have resulted from increased Ca and Mg concentration and resulting acidification.

![Figure 2](image-url). Alkalinity and nitrogen (N) concentration experiment: comparison of the change in substrate pH from Day 0 to Day 35 (vertical axis) with predicted meq of acid (negative values) or base (positive) of the nutrient solution (FS). Predicted milliequivalents (meq) were calculated using the N calcium carbonate equivalent (CCE) model for the different FS with impatiens plus the alkalinity of the irrigation water (0 mg L⁻¹ CaCO₃ for deionized water and 136 mg L⁻¹ CaCO₃ for the alkaline well water). Labels next to symbols represent the mg L⁻¹ N. Symbols represent the least-square mean of 12 replicates ± 1 SE calculated from the residual mean square from the analysis of covariance.
from cation exchange. The model was calibrated and validated with low- or no-leaching irrigation regimes. Given that increased leaching will reduce the substrate nutrient concentration and may also increase the impact of water quality on the salt composition in the root zone, further research should be conducted on the pH response of fertilizers with higher leaching rates. In the validation experiments reported here, and in the original Johnson et al. (2013) study, a non-residual lime source was used, which would not provide pH buffering, only one peat/perlite substrate was used, which would have lower cation exchange capacity than degraded peat or topsoil, and fertilizer was provided through fertigation. The scope of the model could also be expanded to account for other factors that commonly vary in floriculture production such as lime type, substrate components, and use of controlled-release solid fertilizers. Further study is needed to determine how a broader range in plant species and observed differences in iron efficiency of cultivars within a given plant species (Albano and Miller, 1998) impact substrate pH and in turn respond to substrate pH and thereby parameterize the N CCE model for other species and cultivars. It would also be useful for plant breeders and horticulture producers to know which Fe-efficiency processes dominate in container production of floriculture species such as cation-anion uptake balance, acid exudation by proton pumps, and iron reductase activity (Albano and Miller, 1996; Marschner, 1995; Taylor et al., 2008).

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