Determining the Effect of Carrier Water pH and Bicarbonate Concentration on Final pH of Plant Growth Regulator Solutions

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Additional index words. alkalinity, buffer capacity, floriculture, greenhouse crops, PGRs, water quality

Abstract. Chemical plant growth regulators (PGRs) are important tools in greenhouse ornamental crop production because growers must increasingly meet specifications for plant shipping and marketability. However, the role of water quality parameters such as pH or alkalinity (bicarbonate in this study) on final PGR solution pH is not well documented and could impact efficacy. We assessed the interaction of PGR type and concentration on the final spray solution pH when combined with carrier water of varying pH and bicarbonate concentration. Eleven PGRs commonly used in floriculture (ancymidol, benzyladenine, chlormequat chloride, daminozide, dikegulac-sodium, ethephon, flurprimidol, gibberellic acid, gibberellic acid/benzyladenine, paclobutrazol, and uniconazole) at three concentrations (low, medium, and high recommended rates for each product) were added to reverse osmosis (RO) carrier water adjusted to four pH (5.3, 6.2, 7.2, 8.2) levels or added to tap carrier water adjusted to four bicarbonate concentrations (40, 86, 142, 293 mg·L⁻¹ of CaCO₃). Resultant solution pH levels were measured. Plant growth regulators were categorized as acidic, neutral, or basic in reaction based on the change of the carrier water pH on their addition. Benzyladenine, chlormequat chloride, gibberellic acid, and gibberellic acid/benzyladenine acted as weak acids when added to RO water, whereas daminozide, ethephon, and uniconazole reduced final solution pH from 1.25 to 5.75 pH units. Flurprimidol and paclobutrazol were neutral in reaction with final solution pH being similar to that of the RO carrier water before their addition. Ancymidol and dikegulac-sodium were basic in reaction, increasing final solution pH in RO carrier water up to 2.3 units. There was an interaction between chlormequat chloride concentration and RO carrier water pH on change in pH. When added to tap carrier water, final solution pH increased for all except the stronger acids, daminozide, ethephon, and uniconazole, where it decreased up to 3.5 units, and benzyladenine, where it decreased 0.35 units at 40 mg·L⁻¹ bicarbonate. There was an interaction between PGR concentration and bicarbonate concentration in tap carrier water for daminozide and ethephon. The magnitude of change in pH (final solution pH minus initial carrier water pH) with the addition of each PGR was greater for RO than for tap water containing 40 to 293 mg·L⁻¹ bicarbonate for all 11 PGRs tested.

Received for publication 16 Jan. 2014. Accepted for publication 10 July 2014.

We gratefully acknowledge Dana Williamson and Camille Mahan for laboratory assistance; funding from growers providing support for Purdue University floriculture research, Fine Americas, Inc., and OHP, Inc.; and support from the Purdue Agricultural Experiment Station and USDA-NIFA. Use of trade names in this publication does not imply endorsement by Purdue University of products named nor criticism of similar ones not mentioned.

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Chemical PGRs are commonplace in the horticulture industry, having been used commercially since the 1940s (Nickell, 1994). In high-value floriculture crops, PGRs are used in combination with cultural and environmental control methods to produce crops meeting increasingly specific market window and size specifications. The short production time of annual bedding plants in 10- to 15-cm diameter containers and the marketing advantage of compact plants (improved branching and structure) in flower (earlier and more uniform) and with improved shelf life have contributed to the necessity of using chemical

PGRs in the bedding plant industry (Barrett, 2006; Bell, 2001). There is also the possibility of additional benefits derived from PGR application: disease reduction, enhanced foliage color, and increased water use efficiency that contributes to their continued use (Whipker, 2013).

Much research has been conducted on efficient chemical PGR application: timing of application, application method and rates, target tissues, environmental conditions at application, and dosage (Whipker et al., 2003). Spray solution water quality, particularly pH and alkalinity [presence of bicarbonates (HCO₃⁻) and carbonates (CO₃⁻²)], may also play a role in PGR efficiency. Growth regulator solutions made with high pH (greater than 7.0) or highly buffered (greater than 100 mg·L⁻¹ CaCO₃) carrier water may reduce effectiveness, as suggested by Hammer (2001). A grower survey (Burns, 2004) indicated that 60% of respondents were aware of potential water quality effects on chemical PGRs and that 45% had a water treatment system in place, typically acid injection to lower pH and neutralize bicarbonates. Water used in U.S. greenhouse production facilities has traditionally come from groundwater wells (Biernbaum, 1999). Because many growers do not use a water treatment system, carrier water for PGR spray solutions can be variable in pH and buffering capacity. Research documents water quality effects on herbicides and insecticides, particularly in agronomic crops, but there is little research detailing how the pH or alkalinity aspects of water quality influence PGRs in horticultural crops. For example, phytotoxicity from glyphosate was reduced when mixed in carrier water with high concentrations of calcium and bicarbonate (Buhler and Burnside, 1983). Carrier water pH greater than 7.0 can cause weak acid herbicides such as glyphosate, 2,4-D, and dicamba to become negatively charged (OH⁻ from water accepts H⁺ from chemical) decreasing absorption by the leaf cuticle and cell membrane (Chahal et al., 2012). Insecticides and miticides are also sensitive to carrier water alkalinity, and alkaline hydrolysis can occur when spray solution pH is greater than 7.0 (Cloyd, 2007). Mudge and Swanson (1978) found that ethylene release from ethephon was dependent on solution pH and that the addition of buffers increased ethylene concentration to cuttings of *Phaseolus aureus* Roxb. (mung bean).

There is little information available on the reaction of the PGRs widely used in bedding plant production to carrier water pH and bicarbonate concentration. The objective of this study was to quantify the effects of carrier water pH, bicarbonate concentration, and PGR concentration on the final solution pH of 11 PGRs labeled for horticultural use. Final solution pH was compared with the recommended pH range for optimum PGR performance as indicated by manufacturer (Table 1) or Yates et al. (2011).

Table 1. Properties of the plant growth regulators used in the study as indicated on manufacturer label or material safety data sheet unless noted.

Chemical name	Chemical	Product name/ distributor ^z	Percent active ingredient	Class ^y	pH ^s	pKa ^w	Rec. final solution pH ^v	Rec. spray rates for bedding plants (mg L ⁻¹)	Effect
Ancymidol	a-cyclopropyl-a-(p-methoxyphenyl)-5-pyrimidinemethanol	Abide TM /a	0.0264	Pyrimidine	8.5	12.62 ^a	5.5–6.5 ^a Not critical	6–66	Reduces internode elongation
Benzyladenine	N-(phenylmethyl)-1H-purine-6-amine	Configure [®] /a	2.0	Purine	4–5 (1%)	9.4 ^b	5.0–6.5 ^b	50–500	Increases lateral branching and promotes flowering
Chlormequat chloride	(2-chloroethyl) trimethylammonium chloride	Cycocel [®] /b	11.8	Quaternary ammonium	4.8–5.2	NA ^b	3.0–7.0 ^a	800–1500	Reduces internode elongation
Daminozide	Butanedioic acid mono (2,2-dimethylhydrazide)	B-Nine [®] WSG/b	85	Hydrazide	3.9 (1%)	4.68 ^c	4.0–8.0 ^c	2500–5000	Reduces internode elongation
Dikegulac-sodium	2,3,4,6-Bis-O-(1-methylethylidene)-alpha-L-xylo-2-hexulofuranosonic acid, sodium salt	Augeo TM /b	18.5	Cyclohexa-ketone	9.5	2.71 ^d	6.0–9.0 ^e	400–1600	Cell wall lysis resulting in chemical pinch
Ethephon	(2-chloroethyl) phosphonic acid	Florol [®] /c	3.9	Phosphonic acid		2.5/7.2 ^c	< 5.0 (4.0) ^a	250–500	Increase lateral branching
Flurprimidol	α-(1-methylethyl)-α-[4-(trifluoromethoxy)phenyl]-5-pyrimidinemethanol	Topflor/d	0.38	Pyrimidine	8.0 (1%)	12.22 ^a	5.5–8.5 ^d Not critical	2.5–80	Reduces internode elongation
Gibberellic acid	Gibberellic acid (A ₃)	Florigib [®] /a	4.0	Gibberellin	3–4 (50% v/v sol.)	4.0 ^e	5.5–6.5 ^a	50–500	Influences flowering
Gibberellic acid/benzyladenine	Gibberellins A ₄ A ₇ N-(phenylmethyl)-1H-purine-6-amine	Fresco TM /a	1.8 GA 1.8 BA	Gibberellin/Purine	4.2 (1%)		5.5–6.5 ^a	3/3–10/10	Prevents lower leaf yellowing
Paclobutrazol	{(±)-(R*,R*)-β-[4-chlorophenyl]methyl}-α-(1,1-dimethylethyl)-1H-1,2,4-triazole-1-ethanol}	Piccolo TM /a	0.04	Triazole	7.7	NA ^e	4.0–9.0 ^a	2.5–60	Reduces internode elongation
Uniconazole-p	(E)-(+)-(S)-1-(4-chlorophenyl)-4,4-dimethyl-2-(1,2,4-triazol-1-yl)-pent-1-ene-3-ol	Concise TM /a	0.055	Triazole	6.26	NA ^b	5.5–7.0 ^b	1–50	Reduces internode elongation

^za = Fine Americas, Inc., Walnut Creek, CA; b = OHP, Inc., Mainland, PA; c = Southern Agricultural Insecticides, Inc., Palmetto, FL; d = SePRO, Carmel, IN.^yFrom Chemical Class Chart vol. XV, OHP, Inc., 2013, except benzyladenine, which was from product label.^xpH of product unless noted.^wa = <http://www.chemicaldictionary.org>; b = <http://www.sitem.herts.ac.uk>; c = <http://www.wuzhouchem.com>; d = <http://www.toxnet.nlm.nih.gov>; e = <http://www.efsa.europa.eu>.^va = Yates et al. (2011); b = Fine Americas, Inc.; c = OHP, Inc., Mainland, PA; d = SePRO, Carmel, IN.

Rec. = Recommended.

Materials and Methods

Initial carrier water characteristics. Because water is used as the carrier for the application of PGRs, the term carrier water will be used to distinguish initial water qualities before PGR addition from final solution water characteristics after PGR addition. Samples of well water from the Wabash River Valley aquifer (to be referred to as tap) were placed in 1-pint polypropylene containers filled completely to eliminate air, sealed tightly, and shipped the same day to a commercial laboratory (Sherry Laboratories, Fort Wayne, IN) in March of 2011 (Replication 1) and in June 2012 (Replication 2) for analysis. Results of Replications 1 and 2 were similar and thus data were pooled. Tap water alkalinity [determined by the amount of carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) present] were determined by the SM (20th)-2320B method (Clescerl et al., 1998). Because the amount of carbonate was negligible, alkalinity is represented by the amount of bicarbonate (293 mg CaCO_3/L) and thus the term bicarbonate will be used. Average pH was 7.34 as measured by the SM (20th)-4500- H^+ B method (Clescerl et al., 1998). Other tap water characteristics were (in $\text{mg}\cdot\text{L}^{-1}$) 0.3 nitrogen, 0.5 phosphorus, 65 $\text{SO}_4\text{-S}$, 96 calcium, 3 potassium, 34 magnesium, 0.1 iron, 0.2 manganese, 9 sodium, 33 chlorine, and less than 0.1 boron. ALKCALC (UNH, 2009) was used to determine the amount of 96% sulfuric acid (H_2SO_4) (Mallinckrodt Chemicals, Phillipsburg, NJ) to add to tap water to achieve target bicarbonate concentrations of ≈ 295 , 150, 75, and 35 $\text{mg}\cdot\text{CaCO}_3/\text{L}$. Actual bicarbonate concentrations were 293, 142, 86, and 40 $\text{mg}\cdot\text{CaCO}_3/\text{L}$ at pH 7.3, 6.2, 5.8, and 5.4, respectively (average of two replications; same laboratory and methods as for initial samples).

Reverse osmosis water was analyzed as reported previously. Results of Replications 1 and 2 were similar with an average pH of 6.3 and bicarbonate concentration of 11 $\text{mg}\cdot\text{CaCO}_3/\text{L}$; cations and anions were negligible, so values are not presented. Additions of 0.1 N potassium hydroxide (KOH) (Mallinckrodt Baker, Phillipsburg, NJ) or 0.1 N H_2SO_4 were made to RO water to achieve target solutions of pH 8.2, 7.2, 6.2, and 5.2. Actual solution pH averaged for the two replications was 8.2, 7.2, 6.2, and 5.3 (Table 3; Fig. 3).

Plant growth regulator treatments. The effect of ancymidol (AC), benzyladenine (BA), chlormequat chloride (CC), daminozide (DZ), dikegulac-sodium (DS), ethephon (EP), flurprimidol (FP), gibberellic acid (GA), gibberellic acid/benzyladenine (GA/BA), paclobutrazol (PB), and uniconazole (UC) (Table 1) on final solution pH was evaluated at three solution concentrations based on suggested low, medium, and high rates (Table 2) used for foliar spray application on bedding plants. Growth regulators were added using a pipette-lite (Rainin Instruments, LLC, Oakland, CA) to 100 mL of carrier tap or RO water at each bicarbonate

Table 2. Active ingredient concentration of final solutions for ancymidol, benzyladenine, chlormequat chloride, daminozide, dikegulac-sodium, ethephon, flurprimidol, gibberellic acid, gibberellic acid/benzyladenine, paclobutrazol, and uniconazole at listed chemical concentrations.

Percent active ingredient in product	Product concn ($\text{mL}\cdot\text{L}^{-1}$)	Active ingredient in final solution ($\text{mg}\cdot\text{L}^{-1}$)
0.026 ancymidol	57.72	15
	115.40	30
	173.12	45
2.0 benzyladenine (6-BA)	7.52	150
	15.00	300
	22.52	450
11.8 chlormequat chloride	6.78	800
	12.71	1500
	18.64	2200
85.0 daminozide	1.76 g	1500
	3.53 g	3000
	5.29 g	4500
18.5 dikegulac-sodium	2.16	400
	4.32	800
	6.48	1200
3.9 ethephon	6.41	250
	12.82	500
	19.23	750
0.38 flurprimidol	5.26	20
	10.53	40
	21.05	80
4.0 gibberellic acid (GA_3)	0.625	25
	1.25	50
	1.875	75
1.8/1.8 gibberellic acid/benzyladenine ($\text{GA}_{4+7}/6\text{-BA}$)	0.056	1/1
	0.278	5/5
	0.556	10/10
0.4 paclobutrazol	3.75	15
	7.50	30
	11.25	45
0.055 uniconazole	18.18	10
	45.46	25
	72.73	40

concentration or pH level, respectively, in a 250-mL erlenmeyer flask. Plant growth regulator solutions were stirred continuously while pH was measured with an Orion 5 Star pH meter and Ross Ultra[®] Combination pH electrode (Thermo Scientific, Beverly, MA). Final solution pH was measured twice per replication, ≈ 45 min apart, and the average value was used for statistical analysis.

Data collection and analysis. The 11 PGRs at three concentrations were added to RO water adjusted to four initial pH levels with four replications of each treatment (264 individual solutions). As a result of the abundance of treatments and the time required to mix each treatment, treatments and measurements were made over a 3-d period beginning late Apr. 2011 for Replication 1 and late June 2012 for Replication 2. Three to four PGRs were evaluated each day. The 11 PGRs at the same three concentrations were also added to tap water adjusted to four initial bicarbonate concentrations with four replications of each treatment (264 individual solutions). Treatments and measurements were

made over a 3-d period beginning early May 2011 for Replication 1 and early July 2012 for Replication 2 with three to four PGRs evaluated each day. Each PGR–water type combination was an experiment with PGR concentration and initial carrier water pH (RO water) or bicarbonate concentration (tap water) as treatment variables. Each treatment was replicated twice in a completely randomized design. Analysis of variance and means separations (least significant difference) were calculated with PROC GLM (SAS Institute, Cary, NC) and considered significant at $P \leq 0.05$.

Results and Discussion

The 11 PGRs studied were classified based on their acidity, basicity, or neutrality as determined by the effect (predominant direction of pH movement) of the PGR on final solution pH (Figs. 1 to 4) regardless of initial carrier water pH or PGR concentration.

Ancymidol was basic in reaction as final solution pH increased in RO water for all but

Fig. 1. Main effects of plant growth regulator (PGR) solution concentration and initial carrier water (reverse osmosis) pH on change in pH (final solution pH minus initial carrier water solution pH). Final pH values are shown above each column and PGR solution concentrations are shown below each column. PGRs were ancymidol, benzyladenine, daminozide, dikegulac-sodium, ethephon, flurprimidol, gibberellic acid, gibberellic acid/benzyladenine, paclobutrazol, and uniconazole. Columns within each treatment variable without letters or with the same letter indicate no significant treatment effects ($P > 0.05$). Columns within each treatment variable with different letters indicate significant treatment differences ($P \leq 0.05$).

Fig. 2. Change in pH (final solution pH minus initial carrier water pH) for interaction of chlormequat chloride at three concentrations and four initial pH values in reverse osmosis (RO) water. Final solution pH values are shown above each column.

the highest initial pH level of 8.2 (Fig. 1). The greatest pH change (+2.2 units) occurred at a carrier pH of 5.3 (Table 3; Fig. 1). The small range of final solution pH values (7.6 to 8.0) across a wide range of initial pH levels indicates a strong buffering of the solution. There was no significant pH change when PGR concentration was increased from 15 to 45 mg·L⁻¹ although the volume of AC added went from 58 to 173 mL·L⁻¹ (Table 2), another indication of a strongly buffered solution. When AC was added to tap water, the change in final solution pH diminished by one unit as bicarbonate concentration increased from 40 to 293 mg CaCO₃/L and final solution pH was less than values with RO water (Table 3; Fig. 3).

Benzyladenine was acidic in reaction. In RO water, the change in pH decreased 0.5 to 1.75 units as BA concentration and carrier water pH increased (Table 3; Fig. 1). With tap

Fig. 3. Main effects of plant growth regulator (PGR) solution concentration and initial carrier water (tap water) bicarbonate concentration on change in pH (final solution pH minus initial carrier water pH). Final pH values are shown above each column and PGR solution concentrations are shown below each column. PGRs were ancymidol, benzyladenine, chlormequat chloride, dikegulac-sodium, flurprimidol, gibberellic acid, gibberellic acid/benzyladenine, paclobutrazol, and uniconazole. Columns within each treatment variable without letters or with the same letter indicate no significant treatment effects ($P > 0.05$). Columns within each treatment variable with different letters indicate significant treatment differences ($P \leq 0.05$).

water containing bicarbonate, adding BA had little effect on final solution pH (Table 3; Fig. 3), suggesting it was as a weak acid.

Chlormequat chloride was acidic in RO water but weakly basic in tap water. The effect of PGR concentration on final solution pH was dependent on RO carrier water pH (Table 3; Fig. 2). Increasing PGR concentration resulted in a greater reduction in pH at a carrier water pH of 6.2, 7.2, and 8.2, but not at 5.3. The largest reduction in pH of 2.0 units occurred at a CC concentration of 2200 mg·L⁻¹ and a carrier water pH of 8.2. When CC was added to tap water containing bicarbonate, final solution pH increased as much as 0.3 pH units across all PGR and bicarbonate concentrations.

Daminozide was strongly acidic in reaction. In RO water, final solution pH was 4.0 to 4.1 regardless of initial carrier water pH or PGR concentration (Table 3; Fig. 1). In tap water there was a significant interaction between PGR and bicarbonate concentration

on change in pH (Table 3; Fig. 4). At the lowest bicarbonate concentration, 40 mg CaCO₃/L, the decrease in pH was similar across all DZ concentrations with final pH between 4.0 and 4.2. However, the reduction in final solution pH increased with increasing DZ concentration at bicarbonate concentrations greater than 40 mg CaCO₃/L.

Dikegulac-sodium was strongly basic in reaction. Final solution pH increased by as much 2.2 pH units in RO carrier water and final solution pH was 9.0 when DS was added to RO carrier water at pH 8.2 (Table 3; Fig. 1). In buffered tap water, DS increased solution pH (Table 3; Fig. 3), although the magnitude of pH change was reduced compared with RO water and the highest pH achieved was 7.8. RO water and tap carrier water both at initial pH 6.2 yielded different results for DS with a final solution pH of 7.8 (Fig. 1) and 6.8 (Fig. 3), respectively.

Ethephon was strongly acidic in reaction. In RO water, final solution pH decreased 2.5

units at carrier water pH 5.3 and almost six units at carrier water pH 8.2 (Table 3; Fig. 1). Final solution pH ranged from 2.2 to 2.7. In tap water there was an interaction between EP and bicarbonate concentration (Table 3; Fig. 4). At bicarbonate concentrations of 142 and 293 mg CaCO₃/L the lowest EP concentration of 250 mg·L⁻¹ decreased final solution pH much less than did EP concentrations of 500 and 750 mg·L⁻¹. Similarly at a bicarbonate concentration of 293 mg CaCO₃/L, an EP concentration of 500 mg·L⁻¹, compared with that of 750 mg·L⁻¹, had a diminished effect on final solution pH.

Flurprimidol was nearly neutral in reaction when added to RO water and slightly basic when added to tap water. Final solution pH was nearly identical to initial carrier water pH irrespective of FP concentration or initial pH (Table 3; Fig. 1). In tap water, FP increased pH ≈ 0.5 units with no difference resulting from FP concentration and little effect of bicarbonate concentration (Table 3; Fig. 3).

Gibberellic acid was acidic in RO water but weakly basic in tap water. In RO water there was a negligible pH decrease at initial carrier water pH 6.2 to almost one unit at carrier water pH 8.2 (Table 3; Fig. 1). Gibberellic acid concentration had no effect on the magnitude of pH change when added to RO water. When GA was added to tap water containing bicarbonate, final solution pH increased as much as 0.5 pH units, despite a product pH of 4.0 (Table 1). Gibberellic acid or bicarbonate concentration had no effect on the magnitude of pH change in tap water (Table 3; Fig. 3). The combination of GA/BA had similar effects as those seen with GA alone (Table 3; Figs. 1 and 3).

Paclobutrazol was nearly neutral in reaction when added to RO water and slightly basic when added to tap water. Final solution pH was nearly identical to initial carrier water pH irrespective of PB concentration or initial pH (Table 3; Fig. 1). In tap water, PB increased pH ≈ 0.5 units with no difference resulting from PB concentration and little effect of bicarbonate concentration (Table 3; Fig. 3).

Uniconazole was acidic in reaction. In RO water, the change in pH increased from 1.3 to 2.4 pH units as UC concentration increased from 10 to 40 mg·L⁻¹ and similarly as initial carrier water pH increased from 5.3 to 8.2 (Table 3; Fig. 1). In tap water, pH decreased 0.1 to 1.2 units with increasing UC concentration and decreased 1.1 to 0.4 units with increasing bicarbonate concentration up to 142 mg CaCO₃/L (Table 3; Fig. 3).

Yates et al. (2011) compiled a list of the manufacturer's recommended pH range for maximum effectiveness of final spray solutions for each PGR (Table 1). The GA product was the only one of the 11 PGRs studied to provide information regarding carrier water pH on the label. The GA product label indicated GA is most effective when combined with neutral or slightly acid pH water. Gibberellic acid (GA₃) undergoes alkaline hydrolysis when mixed with high pH water and spray solutions below pH 8.0 resulted in greater

Fig. 4. Change in pH (final solution pH minus initial carrier water pH) for the interaction of daminozide and ethephon at three solution concentrations and four initial bicarbonate concentrations in tap water. Final solution pH values are shown above each column.

Table 3. Analysis of variance for the effects of plant growth regulator (PGR) concentration (C), initial carrier water pH, and bicarbonate concentration in reverse osmosis or tap water on change in pH for 11 PGRs—ancymidol, benzyladenine, chlormequat chloride, daminozide, dikegulac-sodium, ethephon, flurprimidol, gibberellic acid, gibberellic acid/benzyladenine, paclobutrazol, and uniconazole.

PGR active ingredient	Reverse osmosis water			Tap water		
	Source of variation					
	PGR concn (C)	Initial carrier water pH	C × initial carrier water pH	PGR concn (C)	Initial carrier water bicarbonate concn	C × initial carrier water bicarbonate concn
	Level of significance					
Ancymidol	0.11	<0.0001	0.97	0.001	<0.0001	0.23
Benzyladenine	0.03	0.01	1.00	0.11	0.04	1.00
Chlormequat chloride	<0.0001	<0.0001	0.04	0.002	<0.0001	0.57
Daminozide	0.29	<0.0001	0.93	<0.0001	<0.0001	0.04
Dikegulac-sodium	0.002	<0.0001	0.49	0.003	0.003	1.00
Ethephon	<0.0001	<0.0001	1.00	<0.0001	<0.0001	<0.0001
Flurprimidol	0.66	<0.0001	0.61	0.71	0.02	0.95
GA	0.17	0.01	1.00	0.76	0.30	1.00
GA/BA	0.19	0.01	0.97	0.98	0.42	1.00
Paclobutrazol	0.80	0.0001	0.99	0.64	0.01	0.99
Uniconazole	<0.0001	<0.0001	0.75	<0.0001	<0.0001	0.07

plant absorption and more stable solutions (Coggins, 2008). This rate of hydrolysis can increase with increasing pH for susceptible materials (Smith, 2010). Dikegulac-sodium is also susceptible to hydrolysis, but at acidic pH levels below 6.0 (D. Barcel, personal communication). Unfortunately, there is little information for other PGRs related to performance at various solution pH and the mechanism by which pH affects their performance.

Our research found that for several PGRs, the final spray solution pH was outside of the recommended pH range. When added to high pH or high bicarbonate carrier water, the weak acid PGRs such as CC, GA, BA, and GA/BA resulted in a final solution pH above the

maximum recommended pH of 6.5. The relatively strong acid, EP, when added at a low concentration to high bicarbonate water had a final solution pH greater than 5, also exceeding the recommended range for this PGR. Uniconazole when added to carrier water with moderate to low pH and low bicarbonate resulted in final solution pH less than 5.5, the minimum recommended pH for this PGR. Recommended range should be verified for the basic AC (5.5 to 6.5). Although final solution pH value was higher than recommended in RO carrier water at all pH levels, the range is indicated as “not critical.”

Our work identified PGR and carrier water combinations that produce final solu-

tion pH that fall outside of recommended pH ranges for several acidic PGRs and two basic PGRs. Given the paucity of published data establishing the recommended pH ranges for these PGRs (except perhaps GA), the effectiveness of these spray solutions on bedding plant growth regulation should be examined in future research. It would also be useful to determine the effect on final solution pH of commonly tank-mixed products such as CC and DZ and their combined performance.

In summary, most of the 11 PGRs evaluated affected solution pH when mixed with carrier water varying widely in pH level and bicarbonate concentration. Bicarbonate reduced carrier water pH change for both acidic and basic PGRs compared with RO water. Increasing the concentration of several PGRs increased the change in final solution pH. Quantifying bicarbonate concentration as well as carrier water pH is important in anticipating final solution pH. Establishment of a range of recommended carrier water pH and bicarbonate levels for these PGRs through efficacy studies on bedding plants is necessary to provide applicators and consultants with accurate information on which to base recommendations for efficient and effective PGR use. It would also provide a basis for future research on water carrier pH and bicarbonate effects on solutions of new products and on other crops.

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