Evaluation of Antitranspirants for Enhancing Temporary Water Stress Tolerance in Bedding Plants

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ADDITIONAL INDEX WORDS. abscisic acid, β -pinene polymer, wilt status, shelf life extension, stomatal conductance, postproduction

SUMMARY. Water stress during shipping and retailing reduces the postproduction quality and marketability of bedding plants. Antitranspirants can temporarily prevent plants from wilting by either physically blocking stomata or physiologically inducing stomatal closure, limiting transpirational water loss from leaves. The goal of this research was to evaluate the efficacy of commercially available antitranspirants on enhancing temporary water stress tolerance in bedding plants. Two physical antitranspirants [β -pinene polymer (β P) and vinyl-acrylic polymer (VP)], and three physiological antitranspirants [two sugar alcohol-based compounds (SACs) and a biologically active form of abscisic acid (s-ABA)] were applied to begonia (*Begonia semperflorens-cultorum*), new guinea impatiens (*Impatiens hawkeri*), impatiens (*Impatiens walleriana*), petunia (*Petunia* $\times$ *hybrida*), african marigold (*Tagetes erecta*), and french marigold (*Tagetes patula*). Physical antitranspirants were sprayed on foliage and physiological antitranspirants were drenched to the media. All antitranspirants were applied at half (0.5 $\times$), equal to (1 $\times$), or twice (2 $\times$) the manufacturer's recommended rate. Extended shelf life was observed when β P or s-ABA was applied. Treatment with β P increased the shelf life of impatiens and african marigold by 1 and 1.3 days compared with control plants, respectively. The application of β P at 2 $\times$ was more effective at delaying visual wilting than at lower rates (0.5 $\times$ and 1 $\times$) in african marigold. Applications of s-ABA delayed wilting by 1.3 to 3.7 days in all tested cultivars. The shelf lives of impatiens and petunia treated with s-ABA at 2 $\times$ were extended the most by 3.7 and 3.0 days compared with control plants, respectively. A rapid reduction of stomatal conductance (g_s) was observed within 4 hours of β P or s-ABA application in plants showing delayed wilting symptoms. s-ABA treatment appeared to cause marginal leaf chlorosis in impatiens, whereas application of β P damaged the opened flowers in all tested cultivars. The application of VP or SACs did not extend shelf life in any treated plants. These results suggest that foliar application of β P on selected species and treatment with s-ABA on most of species would allow bedding plants to withstand water deficit during shipping and/or retailing.

Ornamental bedding plants represent the largest sector of the floriculture industry in the United States and have a wholesale

value of \$1.96 billion accounting for 45% of all floriculture crops (U.S. Department of Agriculture, 2014). In the last decade, there has been a shift in the retailing of ornamental crops. Customers tend to purchase bedding plants more in mass market retailers or superstores and general retail outlets (such as supermarkets) than in traditional garden centers and florists

because of convenience and lower prices (Yue and Behe, 2008). In addition, the major growers have moved their production into areas characterized by lower labor cost and more favorable climate conditions to reduce the cultivation cost (Ferrante et al., 2015). As a result, the location of crop production could be further away from markets, forcing plants to spend an extended period of time without proper irrigation during shipping and/or retailing (Waterland et al., 2010a; Weaver and van Iersel, 2014). Additionally, during postproduction periods, plants are often exposed to adverse environmental conditions, including high temperatures and inadequate irrigation, which accelerate substrate drying and plant wilting. Crop losses caused by these poor postproduction conditions are estimated to result in 5% to 20% of unsalable crops (Healy, 2009), and water stress is one of the major causes of diminished aesthetic quality and salability of plants. Therefore, it is highly desired to minimize crop damage caused by water deficit to maintain high quality and prolong longevity of bedding plants during postproduction.

Water stress causes plants to synthesize a phytohormone called abscisic acid (ABA) in the root system, and it is translocated to leaves through the transpiration stream (Taiz and Zeiger, 2010). When ABA reaches guard cells, it binds to ABA receptors that activate an ion efflux, which reduces turgor pressure in the guard cells. Due to loss of turgidity, the guard cells become flaccid and stomata are closed. Closing of stomata inhibits transpiration and allows the plant to withstand water stress by decreasing water loss. Using this principle, growers can utilize antitranspirants to reduce transpiration, thereby limiting water loss during shipping and retailing (Iriti et al., 2009; Odium and Colombo, 2007; Waterland et al., 2010b).

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
29.5735	fl oz	mL	0.0338
2.54	inch(es)	cm	0.3937
1	ppm	mg·L ⁻¹	1
0.001	ppm	mL·L ⁻¹	1,000
10.7639	W/ft ²	W·m ⁻²	0.0929
(°F - 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

Antitranspirants are chemical compounds that increase water stress tolerance by preventing transpirational water loss in plants. Based on their mode of action, antitranspirants can be classified into two major groups, physical and physiological antitranspirants (Anderson and Kreith, 1978; Shinohara and Leskovar, 2014; Waterland et al., 2010b). Physical antitranspirants contain waxes, resins, latexes, or polymers that coat the leaf surface and minimize water loss from the plant by blocking stomata (Goreta et al., 2007). Such physical antitranspirants have shown positive effects on water stress tolerance in pepper [*Capsicum annuum* (del Amor et al., 2010)], peach tree [*Prunus persica* (Steinberg et al., 1990)], and herbaceous plants (Anderson and Kreith, 1978). Physiological antitranspirants minimize transpiration by inducing plants to close stomata. These compounds may contain ABA or other chemicals that increase the ABA concentration in plants (Waterland et al., 2010b). Exogenous application of ABA has enhanced water stress tolerance in various horticultural crops (Agehara and Leskovar, 2012; Astacio and van Iersel, 2011; Goreta et al., 2007; Shinohara and Leskovar, 2014). Goreta et al. (2007) found that foliar application of ABA enhanced water deficit tolerance of pepper, which was attributed to decreased g_s and increased leaf water potential. Overall, antitranspirants have been shown to reduce wilting caused by water stress. However, some studies have demonstrated that plant responses to antitranspirants vary depending on species, concentrations of antitranspirants applied, developmental stages, and growing environmental conditions (Blanchard et al., 2007; Dunn et al., 2012; Shinohara and Leskovar, 2014; Waterland et al., 2010a).

Antitranspirants have been used to help plants withstand stress caused by water deficit, and many studies have focused on fruits, vegetables, turf, field crops, and woody plants. Little research has been conducted on the effect of antitranspirants on the postproduction quality of bedding plants. Furthermore, most research has evaluated individual antitranspirant and an efficacy comparison study

among different products of physical and physiological antitranspirants is lacking. The physical antitranspirants in this study contained either β -P or VP as a coating agent and the physiological antitranspirants were two sugar alcohol-based compounds (SAC1 and SAC2), which are supposed to increase the concentration of ABA in plants, and s-ABA. SAC1 contains xylitol, and SAC2 contains polyhydric alcohol and extracts from seaweed [e.g., red algae (*Gracilaria* sp.)], corn (*Zea mays*), and berries [e.g., brambles (*Rubus* sp.), blueberry (*Vaccinium* sp.), strawberry (*Fragaria xananassa*)]. The goal of this research was to evaluate the efficacy of these commercially available antitranspirants on enhancing water stress tolerance in bedding plants.

Materials and methods

EXPT. 1: SHELF LIFE OF ANTITRANSPIRANT-TREATED BEDDING PLANTS. Eight cultivars of six popular bedding plant species were selected in this experiment. Four-week-old seedlings of 'Bada Bing Rose' begonia, 'Harmony Spicy Peach' new guinea impatiens, 'Double Fiesta Ole Purple Stripe' impatiens, 'Madness Double Red' and 'Wave Pink' petunia, 'Antigua Yellow' and 'Taishan Orange' african marigold, and 'Bonanza Yellow' french marigold were obtained in 288-plug trays except for impatiens and new guinea impatiens (72-plug tray) from Green Circle Growers Inc. (Oberlin, OH). All plants were transplanted into 4-inch pots with soilless greenhouse media (Sunshine® Mix #1; Sun Gro Horticulture, Agawam, MA) in Apr. 2013. They were grown in the greenhouse (Morgantown, WV) under natural irradiance with supplemental lighting. High-pressure sodium lamps (600W HS200 deep reflector; Hortilux, Pijnacker, The Netherlands) were used for supplemental lighting when natural radiance fell below 50 W·m⁻². The average photosynthetic photon flux density (PPFD) was 412 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ from 0630 to 2030 hr daily [mean daily light integral (DLI) = 20.8 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$]. Mean greenhouse temperatures were 23.1/19.6 $\pm$ 2.9/2.3 °C day/night (mean $\pm$ SD) with daytime relative humidity of 76.3% $\pm$ 13.7%. Plants were fertilized with 15N-2.2P-12.5K (Peter® Excel Cal-Mag; Everris

NA, Marysville, OH) at 200 mg·L⁻¹ nitrogen (N). This was reduced to 100 mg·L⁻¹ N one week before treatment.

All bedding plants were treated with antitranspirants when they reached a marketable stage of at least one open flower per plant. Begonia, new guinea impatiens, and impatiens were treated in June 2013, and marigold and petunia were treated in July 2013. Plants were irrigated with deionized (DI) water to container capacity 12 h before treatment. Physical antitranspirants were sprayed on the top and the underside of the plant canopy (about 35 mL per plant) with a pressurized sprayer (Regulator Bak-Pak; H.D. Hudson, Chicago, IL), and physiological antitranspirants were drenched in substrates (60 mL per pot). Control treatments for physical and physiological antitranspirant applications were sprayed and drenched with DI water, respectively, and then they were irrigated daily with 100 mg·L⁻¹ N (irrigated control) or water was withheld (water-stressed control) during the period of the experiment. The physical antitranspirants used were β P (Wilt-Pruf®; Wilt-Pruf Products, Essex, CT) and VP (Moisturin; WellPlant, Sparks, NV). The physiological antitranspirants used were SAC1 (Stasis™; Natural Industries, Houston, TX), SAC2 (RootZone™; GSI Horticultural, Bend, OR), and s-ABA (ConTego™, VBC-30101, Valent BioSciences, Libertyville, IL). All antitranspirants were applied at either half (0.5×), equal to (1×), or twice (2×) the manufacturer's recommended application rate (Table 1). Plants were held in the greenhouse under the previously described environmental conditions for subsequent evaluations. Half of plants treated with each antitranspirant had water withheld (water-stressed) until all treated plants reached a visual wilt status rating of 3 or below (unmarketable) as described by Waterland et al. (2010c). Wilt status ratings were from 1 to 5 with 5 = completely turgid, 4 = soft to the touch but still upright, 3 = starting to wilt, 2 = severely wilted, and 1 = wilted to the point that leaves are dried and desiccated (Waterland et al., 2010a). The other half were irrigated daily with 100 mg·L⁻¹ N (irrigated daily) to

Table 1. Manufacturer's recommended application rate of antitranspirants.

Antitranspirant ^a	Rate (mL·L ⁻¹) ^y
βP	100.0
VP	100.0
SAC1	50.0
SAC2	7.8
s-ABA	0.5

^aβP = β-pinene polymer (Wilt-Pruf®; Wilt-Pruf Products, Essex, CT); VP = vinyl-acrylic polymer (Moisturin; WellPlant, Sparks, NV); SAC1 = sugar alcohol-based compound 1 (Stasis™; Natural Industries, Houston, TX); SAC2 = sugar alcohol-based compound 2 (Root-Zone™; GSI Horticultural, Bend, OR); s-ABA = biologically active form of abscisic acid (ConTego™, VBC-30101; Valent BioSciences, Libertyville, IL).

^y1 mL·L⁻¹ = 1000 ppm.

determine whether antitranspirants caused any side effect on plants.

Visual observations of wilt status were taken daily. Evaluation of wilt status was started just before the application of antitranspirants. Evaluation continued until all plants reached a visual wilt status rating of 3 or below. The shelf life of water-stressed plants was calculated as the number of days from the initiation of water being withheld until plants reached a wilt status rating of 3 (Waterland et al., 2010c).

EXPT. 2: WILT STATUS AND STOMATAL CONDUCTANCE OF ANTITRANSPIRANT-TREATED BEDDING PLANTS. Four-week-old seedlings of 'Harmony Spicy Peach' new guinea impatiens were obtained in 72-plug trays from Green Circle Growers Inc. in Apr. 2014. Seeds of 'Antigua Yellow' and 'Taishan Orange' african marigold, and 'Ultra Red' petunia were sowed in a 288-plug tray in Mar. 2014. 'Ultra Red' petunias were used in Expt. 2, because 'Madness Double Red' and 'Wave Pink' petunias used in Expt. 1 were unavailable. All seedlings were transplanted into 4-inch pots in Apr. 2014 and grown in the greenhouse as described previously. Average PPFD was 304 μmol·m⁻²·s⁻¹ from 0630 to 2030 HR daily (DLI = 15.3 mol·m⁻²·d⁻¹). Average greenhouse temperatures were 23.7/18.1 ± 3.0/2.5 °C day/night (mean ± SD) with daytime relative humidity of 72.6% ± 16.1%. Based on the observations from Expt. 1, one physical (βP) and a physiological (s-ABA) antitranspirant were selected for the additional experiment at the recommended rate (1×). An additional treatment of 'Antigua Yellow'

and 'Taishan Orange' african marigold with βP at 2× was performed. Antitranspirants were treated to new guinea impatiens and marigold in July 2014 and petunia in Aug. 2014. βP was sprayed (about 35 mL per plant), and s-ABA was drenched (60 mL per pot). Plants were watered to container capacity 12 h before application. Control plants and antitranspirant-treated plants were either irrigated or water-stressed as described above. After all water-stressed plants reached a wilt status rating of 3 or below, they were rewatered daily to determine if there was any damage by antitranspirant. Visual wilt status of stressed plants was evaluated as described previously.

Stomatal conductance was measured with a portable photosynthesis system (LI-6400XT; LI-COR, Lincoln, NE). Three fully expanded leaves per plant were tagged for measurements. Stomatal conductance measurements were taken 1 d before treatment, 4 h after the treatment, daily until all plants showed visual wilting, and 3 d after plants were rewatered. A leaf was placed into a light-emitting diode light source chamber (6400-02B, LI-COR). Environmental conditions in the chamber were set at 1000 μmol·m⁻²·s⁻¹ PPFD, 400 μmol·mol⁻¹ carbon dioxide, and 25 °C as the block temperature. Readings were conducted from 1000 to 1400 HR. Data are the means of measurements from three replications (or three plants), with three leaves measured per plant (n = 3).

STATISTICAL ANALYSIS. Experiments were conducted as a randomized complete block design with three replications (n = 3). Analysis of variance was performed by SAS (version 9.3; SAS Institute, Cary, NC). Bedding plants were blocked by replication based on plant position in the greenhouse and watering regimen (irrigated daily vs. water-stressed). Differences among the treatment means were assessed by Tukey's test at *P* ≤ 0.05.

Results

EXPT. 1: SHELF LIFE OF ANTITRANSPIRANT-TREATED BEDDING PLANTS. The application of βP at manufacturer's recommended rate (1×) delayed wilting symptoms in impatiens and two cultivars of african marigold increasing shelf life by 1 to

1.3 d as compared with stressed controls, whereas other species of plants did not show any extension of shelf life with βP (Table 2). All tested bedding plants showed delayed visible wilting by s-ABA treatment and extended shelf life by 1.3 to 3.7 d depending on the cultivar (Table 2). In contrast to βP or s-ABA treatment, shelf life extension was not observed in any species treated with VP or SACs. Among the three rates of application (0.5×, 1×, and 2×), longer shelf life extension was observed when a higher rate (2×) of antitranspirant was applied compared with lower rates (0.5× and 1×) in 'Taishan Orange' african marigold treated with βP and 'Wave Pink' petunia treated with s-ABA (Table 3). Impatiens treated with s-ABA had longer shelf life extension at 1× and 2× than that at 0.5× (Table 3). All other plant species treated with βP or s-ABA and any of the plants treated with VP or either SACs had no difference in extension of shelf life regardless of application rates (data not shown). Overall, the longest shelf life extension was observed in 'Taishan Orange' african marigold treated with βP at 2× by 2 d, and in impatiens and new guinea impatiens by almost 4 d when treated with s-ABA at 2× and 1×, respectively (Tables 2 and 3).

EXPT. 2: WILT STATUS AND STOMATAL CONDUCTANCE OF ANTITRANSPIRANT-TREATED BEDDING PLANTS. Applications of βP and s-ABA, which showed the extended shelf life in Expt. 1, were performed to examine if there was a relationship between wilt status and *g*_s. Two cultivars of african marigold, new guinea impatiens, and 'Ultra Red' petunia were treated with βP and s-ABA at the recommended rate (1×). Additionally, the application of βP at 2× was included in both cultivars of african marigold since the longest shelf life was observed at that rate in Expt. 1 (Table 3).

As in Expt. 1, the application of βP delayed wilting symptoms in african marigold, but not in new guinea impatiens and petunia (Fig. 1). 'Antigua Yellow' african marigold treated with βP at 1× and 2× did not show any visible wilting symptom 2 d after treatment, whereas stressed control plants had a lower wilt status rating on the same day (Fig. 1B). A different african marigold cultivar, Taishan Orange, treated with the

Table 2. The number of days until the appearance of wilting symptom in eight bedding plants treated with antitranspirants at manufacturer's recommended rate (1×) under water deficit stress.

Cultivar	Type of antitranspirant						
	Time before wilted (d) ^z						
	Physical ^y			Physiological ^x			
	Control	βP	VP	Control	SAC1	SAC2	s-ABA
Bada Bing Rose begonia	8.3 a ^w	8.3 a	9.0 a	8.7 b	8.0 b	8.7 b	10.0 a
Harmony Spicy Peach new guinea impatiens	2.0 a	2.0 a	2.3 a	2.0 b	2.3 b	2.0 b	5.7 a
Double Fiesta Ole Purple Stripe impatiens	2.0 b	3.0 a	2.3 ab	2.3 b	2.7 b	2.0 b	5.3 a
Madness Double Red petunia	3.0 a	3.7 a	2.7 a	2.7 b	3.3 b	3.3 b	6.0 a
Wave Pink petunia	2.7 a	3.0 a	2.7 a	3.0 b	3.0 b	3.3 ab	4.7 a
Antigua Yellow african marigold	2.0 b	3.3 a	2.0 b	2.3 b	2.0 b	2.3 b	5.3 a
Taishan Orange african marigold	2.0 b	3.0 a	2.3 ab	2.0 b	2.0 b	2.0 b	5.0 a
Bonanza Yellow french marigold	2.0 a	2.0 a	2.0 a	2.0 b	2.0 b	2.0 b	4.7 a

^zValues are the number of days from the time antitranspirants were applied until plants started showing visible symptoms of wilting. Values are means of three replications (n = 3).

^yControl = sprayed with deionized (DI) water once on Day 0 and then water was withheld; βP = β-pinene polymer; VP = vinyl-acrylic polymer.

^xControl = drenched with DI water once on Day 0 and then water was withheld; SAC1 = sugar alcohol-based compound 1; SAC2 = sugar alcohol-based compound 2; s-ABA = biologically active form of abscisic acid.

^wMean separation among either physical or physiological antitranspirants within cultivars by Tukey's significance test at $P \leq 0.05$.

Table 3. Shelf life extension of two cultivars of african marigold treated with β-pinene polymer (βP), and impatiens and petunia treated with a biologically active form of abscisic acid (s-ABA) at three rates under water deficit stress.

Antitranspirant	Cultivar	Rate ^z	Shelf life extension (d) ^y	
βP	Antigua Yellow african marigold	0.5×	0.7 b ^x	
		1×	1.3 ab	
		2×	1.7 a	
	Significance		*	
	Taishan Orange african marigold	0.5×	0.7 b	
		1×	1.0 b	
		2×	2.0 a	
	Significance		*	
	s-ABA	Double Fiesta Ole Purple Stripe impatiens	0.5×	1.7 b
			1×	3.0 a
			2×	3.7 a
		Significance		**
Wave Pink petunia		0.5×	2.0 b	
		1×	1.7 b	
		2×	3.0 a	
Significance		*		

^zHalf (0.5×), equal to (1×), or twice (2×) the manufacturer's recommended application rate.

^yValues are the number of additional days from the time when the control plants began to wilt until the time antitranspirant-treated plants started to show visible symptoms of wilting. Values are means of three replications (n = 3).

^xMean separation among three rates within a cultivar by Tukey's significance test at $P \leq 0.05$.

*, **Significant at $P \leq 0.05$ or 0.01, respectively.

higher rate of βP (2×) showed less visible wilting than stressed control or plants treated with 1× of βP on 2 and 3 d after treatment (Fig. 1C). Petunia did not show any difference in visual wilting symptoms between stressed control and βP-treated plants during the period of water deficit stress (Fig. 1D).

Stomatal conductance decreased 45% to 73% compared with that of control plants within 4 h after treatment with βP in both irrigated daily and water-stressed new guinea impatiens and two cultivars of african marigold

(Fig. 1A–C). As water stress progressed, g_s of stressed controls declined and their value became similar to that of βP-treated plants 4, 2, and 2 d after treatment in new guinea impatiens, 'Antigua Yellow' african marigold, and 'Taishan Orange' african marigold, respectively (Fig. 1A–C). The application of βP reduced g_s in water-stressed petunia 4 h after treatment, but it became similar to control 1 d after treatment (Fig. 1D). Comparing the application rates of βP in two cultivars of african marigolds, there was no g_s difference

between plants treated at 2× and 1× 4 h after treatment (Fig. 1B and C).

All plants treated with s-ABA had delayed visual wilting (Fig. 2) and exhibited a wilt status rating over 4 for 4 d (new guinea impatiens) and 3 d (african marigold and petunia) after the application (Fig. 2). Four hours after s-ABA application, reduced g_s was observed in all cultivars tested under irrigated daily and water-stressed conditions (Fig. 2). Stomatal conductance of water-stressed control plants reached nearly the same level as s-ABA-treated plants 2 to 4 d after treatment (Fig. 2).

Fig. 1. Stomatal conductance (g_s) and wilt status rating of β -pinene polymer (βP)-treated (A) 'Harmony Spicy Peach' new guinea impatiens, (B) 'Antigua Yellow' african marigold, (C) 'Taishan Orange' african marigold, and (D) 'Ultra Red' petunia. βP was applied at the manufacturer's recommended rate ($1\times$) in all tested cultivars. African marigolds were treated with βP at $1\times$ and $2\times$. Half of plants were irrigated daily (left), and the other half had water withheld until plants showed wilt status rating of 3 and irrigation was resumed for 3 d (right). Stomatal conductance was measured 1 d before the application, 4 h after the application, daily until all plants showed wilt symptom, and 3 d after plants were rewatered. Irrigated controls had wilt status of 5 for the duration of the experiment, and water-stressed plants had a rating of 5 after 3 d rewatering period. Wilt status ratings were from 5 to 1, where 5 = completely turgid, 4 = soft to touch but still upright, 3 = starting to wilt, 2 = severely wilted, and 1 = wilted to the point that leaves are desiccated. Vertical bars are standard errors of the means with three replications ($n = 3$). *, **, ***Significant at $P \leq 0.05$, 0.01 , or 0.001 , respectively.

Fig. 2. Stomatal conductance (g_s) and wilt status rating of a biologically active form of abscisic acid (s-ABA)-treated (A) 'Harmony Spicy Peach' new guinea impatiens, (B) 'Antigua Yellow' african marigold, (C) 'Taishan Orange' african marigold, and (D) 'Ultra Red' petunia. s-ABA was applied at the manufacturer's recommended rate (1 $\times$). Half of plants were irrigated daily (left), and the other half had water withheld until plants showed wilt status rating of 3 and irrigation was resumed for 3 d (right). Stomatal conductance was measured 1 d before the application, 4 h after the application, daily until all plants showed wilt symptom, and 3 d after plants were rewatered. Irrigated controls had wilt status of 5 for the duration of the experiment, and water-stressed plants had a rating of 5 after 3 d rewatering period. Wilt status ratings were from 5 to 1, where 5 = completely turgid, 4 = soft to touch but still upright, 3 = starting to wilt, 2 = severely wilted, and 1 = wilted to the point that leaves are desiccated. Vertical bars are standard errors of the means with three replications ($n = 3$). *, **, ***Significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Discussion

Two physical and three physiological antitranspirants were evaluated for enhancing temporary water stress tolerance in eight popular cultivars of bedding plants. Among the five antitranspirants examined, only β P in certain cultivars and s-ABA in all cultivars showed positive effects on enhancing water stress tolerance. Three other antitranspirants (VP and SACs) were not effective and consequently further evaluation of VP and SACs was not performed.

A sharp decline of g_s 4 h after application of β P and s-ABA compared with controls indicated that application of β P effectively blocked stomata or s-ABA induced stomatal closure at the early stage of application in those plants (Figs. 1 and 2). The delay in wilting was likely due to stomatal closure and the subsequent reduction in water loss, thus delaying the loss in leaf turgidity (Figs. 1 and 2). A rapid reduction of g_s resulting from application of antitranspirants helped to maintain a high water status under water stress and thus improved water stress tolerance (Astacio and van Iersel, 2011; Kim and van Iersel, 2011; Shinohara and Leskovar, 2014; Waterland et al., 2010b). Additionally, Anderson and Kreith (1978) reported that β P treatment resulted in initial reduction of transpiration rate by reducing g_s of sweetclover (*Melilotus officinalis*) leaves. The application of β P caused a reduction in water use of peach trees by 40% immediately after treatment, with a subsequent decrease in water use by 30% for the next 30 d (Steinberg et al., 1990). Although β P treatment reduced g_s within 4 h in petunia, transpiration resumed 1 d after treatment, as indicated by similar g_s to control, and it did not delay wilting (Fig. 1D). Therefore, the rapid and sustained reduction in g_s by antitranspirants before water stress seemed to

greatly reduce transpirational water loss during the beginning of water stress period, thus delaying wilting symptoms. As β P- and s-ABA-treated plants were irrigated daily, g_s gradually increased to the same level of irrigated controls (Figs. 1 and 2). Thus, the efficacy of antitranspirants was diminished as plants were irrigated or as time passed.

Our findings also support the idea that the effects of β P on enhancing water stress tolerance appeared to be species dependent. Application of β P did not extend shelf life universally, but only in impatiens and african marigold, among the six species tested when they were treated at the manufacturer's recommended rate (Table 2). Studies have reported that physical antitranspirants resulted in different responses depending on species (Davies and Kozłowski, 1974; Hummel, 1990). Species differences in response to physical antitranspirants might be associated with differences in shape, size, and density of trichomes (Goreta et al., 2007). Since physical antitranspirants are sprayed on the leaf surface to coat the stomata with a thin film of the chemicals, trichome patterns might affect the chemical's adhesion and retention on leaves differently (Pallioti et al., 2010; Pathan et al., 2009). In artichoke (*Cynara cardunculus*), physical antitranspirants were not effective to mitigate water stress, presumably due to the dense glandular trichomes (Shinohara and Leskovar, 2014). Indeed, the petunia cultivar evaluated in this research has hirsute leaves, whereas african marigold has rather glabrous leaves. New guinea impatiens tested also have fewer trichomes than petunia and reduced g_s was observed when β P was applied (Fig. 1A). The denser trichomes might have prevented β P from forming a thin film layer on the stomata. Species-dependent response to β P in

this experiment may have been due to the different characteristics of surface trichome patterns.

Application of s-ABA enhanced water stress tolerance in all plants tested, and the range of extended shelf life varied from 1.3 to 3.7 d depending on species and cultivars. Responses to ABA treatments have been shown to vary according to species (Blanchard et al., 2007; Waterland et al., 2010a). Blanchard et al. (2007) reported that s-ABA application of s-ABA at 125 or 250 mg·L⁻¹ delayed wilting by 1.1 to 5.8 d in 'Harmony Grape' new guinea impatiens, but no significant effect of s-ABA on shelf life was observed in 'Tempo Lavender' impatiens or 'Vabana' bacopa (*Sutera cordata*). In 'Double Fiesta Ole Purple Stripe' impatiens, application of s-ABA at 250, 500, and 1000 mg·L⁻¹ extended the shelf life by 1.7 to 3.7 d (Table 3). Longer shelf life of 'Xtreme Lavender' impatiens either drenched or sprayed with s-ABA was also observed by Waterland et al. (2010a). The differences between previously published reports and the result from our research may be due to different cultivar selection, s-ABA concentration, application method, and environmental conditions.

In contrast to β P and s-ABA, VP and SACs did not exhibit any positive or negative effect on shelf life extension in all eight cultivars at manufacturers' recommended rates (Table 2). VP had shown increased survival rate of green ash [*Fraxinus pennsylvanica* (Harris and Bassuk, 1995)] and reduced water use in nursery trees (Englert et al., 1993) after transplanting. However, those plants were subjected to water stress by transplanting and might not have experienced similar levels of water stress as in the present study, which withheld water from container-grown plants. Dunn et al. (2012) found that SACs delayed

Fig. 3. Floral damage of bedding plants treated with β -pinene polymer (β P) at 1 $\times$. (A) 'Bada Bing Rose' begonia, (B) 'Harmony Spice Peach' new guinea impatiens, (C) 'Madness Double Red' petunia, (D) 'Antigua Yellow' african marigold, (E) 'Taishan Orange' african marigold, and (F) 'Bonanza Yellow' french marigold.

the visual wilting rating of herbaceous and woody ornamentals compared with nontreated controls, but in a species-dependent manner. The authors mentioned that the species-dependent responses might be due to the different application rates, retention, and accumulation of chemicals in soilless media. SACs are expected to lower water potential in growing media to induce water stress. In our research, all plants treated with either SAC showed no delay in wilting symptoms even at twice the recommended rate, indicating that SACs failed to trigger a water stress response.

Although application of β P was effective in certain plant species, β P caused floral damage in all plants tested regardless of application rate (Fig. 3). Floral damage was first observed within a few hours after β P treatment, and the floral damage seemed to accelerate flower senescence, resulting in poor quality bedding plants. However, no damage was observed in shoots, flower buds, or leaves. Steinberg et al. (1990) reported that β P did not significantly reduce growth or bud and fruit initiation in peach tree. Therefore, application of β P should be recommended before flower opening. On the other hand, s-ABA caused chlorosis on the margin of leaves in impatiens. Foliar chlorosis and leaf abscission have been frequently mentioned as side effects of ABA application (Agehara and Leskovar, 2012; Astacio and van Iersel, 2011; Kim and van Iersel, 2011; Waterland et al., 2010a, 2010c; Weaver and van Iersel, 2014). Chlorosis has been known to accelerate with increasing ABA concentration (Agehara and Leskovar, 2012; Astacio and van Iersel, 2011; Weaver and van Iersel, 2014).

The efficacy of five antitranspirants to increase temporary tolerance to water stress was evaluated in six species of bedding plants. Among five antitranspirants, β P and s-ABA treatment enhanced temporary water stress tolerance in severely water-stressed plants by blocking and closing stomata, respectively. This explanation was supported by the observation that g_s was quickly decreased on application of either antitranspirant. Consequently, shelf life was increased by 1 to 3.7 d depending on species and application rates. The application of β P or s-ABA as an antitranspirant

would allow some bedding plants to withstand temporary water stress during postproduction such as the shipping and retailing environments. However, the efficacy of β P appears to be species dependent in our research, possibly due to the difference in trichome patterns of leaf surface. Caution should be applied, given that the application of β P and s-ABA could cause floral damage or leaf chlorosis. Floriculture growers should evaluate the effects of antitranspirants on their crops to maximize aesthetic quality and longevity of their products without any side effects.

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