Extended Storage of Cut Flowers Using Sub-zero Temperature

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Abstract. **The cut flower industry needs postharvest techniques that allow for extended storage of fresh cut flowers to meet consumer demands. We compared the use of a sub-zero storage temperature (−0.6 °C) to maintain viable flowers with improved or comparable vase life to flowers stored at the industry standard (4 °C). The vase life of 17 commercially important cut flower species, alstroemeria (*Alstroemeria*), anemone (*Anemone coronaria*), campanula (*Campanula medium*), carnation (*Dianthus caryophyllus*), chrysanthemum (*Chrysanthemum*), delphinium (*Delphinium elatum*), freesia (*Freesia*), gerbera (*Gerbera jamesonii*), gypsophila (*Gypsophila paniculata*), larkspur (*Consolida*), lily (*Lilium*), lisianthus (*Eustoma grandiflorum*), ranunculus (*Ranunculus asiaticus*), rose (*Rosa hybrida*), stock (*Matthiola incana*), sunflower (*Helianthus annuus*), and tuberose (*Polianthes tuberosa*), when stored dry at −0.6 °C for durations of 4, 8, and 12 weeks was comparable to or longer than that when stored at 4 °C. Tuberose stems were not viable after holding for any storage duration or temperature. Experiment 2 compared the use of a prestorage pulsing treatment of water, hydrating solution, or holding solution containing carbohydrates for 8 hours before extended storage for carnation, chrysanthemum, delphinium, lily, and rose stems. Stems of carnation benefitted from pulsing with a hydrating solution and maintained vase life similar to that of nonstored control stems when stored for 4 weeks at −0.6 °C. Conversely, rose stems only maintained vase life similar to that of nonstored control stems when held at 4 °C for all pulsing solutions. Lily and chrysanthemum stems had a decline in vase life with all pulsing solutions and only remained viable after 8 weeks of storage when held at −0.6 °C. Additionally, stored chrysanthemum and lily stems had a longer vase life when stored at −0.6 °C than that when held at 4 °C after 4 and 8 weeks of storage, respectively, with all pulsing solutions. Delphinium stems were not viable after any storage duration. Experiment 3 further evaluated carnation, lily, and rose stems with and without a prestorage acclimation period at 4 °C for either 24 hours or 1 week before extended storage of 4, 6, or 8 weeks. Holding stems at 4 °C for 1 week before extended storage reduced the vase life of all species. Rose stems remained viable after 8 weeks of extended storage when held at −0.6 °C, but only when no prestorage hold was used. Lily and rose stems were not viable beyond 4-week storage durations when held at 4 °C, but they remained viable with no prestorage holding period after 8 weeks at −0.6 °C. Carnation stems maintained a longer vase life irrespective of a prestorage holding period when stored at −0.6 °C. Through this analysis, we showed that many species of cut flowers may be held at a sub-zero temperature with vase life better than or comparable to that with the industry standard of 4 °C.**

Cold storage is vital during postharvest production and transport of perishable cut flowers to maintain quality and minimize abiotic and biotic factors that can reduce aesthetic appeal and vase life. Although limited information regarding cut flower losses during postharvest handling is available, one estimate indicated that the loss rate is 20% or more (FlowerWatch, personal communication). Holding most cut flower species, other than those sensitive to chilling damage, at cold temperatures of 2 to 4 °C reduces respiration and transpiration, thus allowing flowers to maintain vase life (Reid and Jiang 2012). The duration that flowers can be stored before vase life declines varies with the species and can range from a few days to several weeks. However, storage is usually necessary because most flower farms are not capable of harvesting enough cut flowers daily to satisfy the immediate needs of their markets. Therefore, if flower quality could be maintained for longer durations to allow them to accumulate product for periods of high consumer demand (i.e., holiday sales) and allow storage of cut flowers when warm weather conditions result in unexpectedly large harvests, then it would be beneficial to growers.

Sub-zero temperatures may be useful for extending the storage duration without sacrificing vase life, which was a chief complaint of customers during a recent production and postharvest survey of North American specialty cut flower producers (Loyola et al. 2019). Research on the use of a sub-zero temperature to maximize the maintenance of quality of cut flowers is limited. Hardenburg et al. (1986), Nichols and Wallis (1972), and Post and Fischer (1952) reported that a number of species, including chrysanthemum (*Chrysanthemum*), daffodil (*Narcissus pseudonarcissus*), lily of the valley (*Convallaria majalis*), gardenia (*Gardenia jasminoides*), sweet pea (*Lathyrus ordoratus*), and tulip (*Tulipa* hybrids), store better at −0.6 °C than at 0.6 °C. Jahnke et al. (2022) showed that tulips could be held at −0.6 °C up to 6 weeks with no loss of vase life. and that Dutch iris (*Iris ×hollandica*) flowers retained their ability to fully expand after prolonged storage at −0.6 °C. Additionally, holding cut peony (*Paeonia lactiflora*) at a sub-zero temperature resulted in faster flower opening without freezing injury or sacrificing vase life and improved the quality of the open flowers (Jahnke et al. 2020).

Injury from cold storage has been reported for several cut flower species, including lily (*Lilium*), basil (*Ocimum*), celosia (*Celosia*), and zinnia (*Zinnia*) (Dole et al. 2009, 2017; van Doorn and Han 2011). van Doorn and Han (2011) suggested that sugar and gibberellic acid treatments might help reduce cold damage. Prisa et al. (2013) reported cold damage on "very young floral buds" of lilies, and they noted that a pulse treatment with sucrose prevented some of the cold damage symptoms. With cut carnation buds, sucrose pulses decreased freezing points of cut carnation petals from −2.3 to −4.7 °C (Heins et al. 1981). The use of either

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hydrating or holding solution may allow cut stems to tolerate sub-zero storage without damage.

Hydrating and holding solutions contain acidifiers and antimicrobial compounds, but only holding solutions include carbohydrates. Hydrating solutions are most often used during the short term to encourage water uptake and turgidity, whereas holding solutions are used to hold flowers until distributed to the consumers and are typically used poststorage and during shipping. Clark et al. (2010) demonstrated a variable response to the use of hydrating and holding solutions for extending vase life of different species, but pulsing before extended storage was not evaluated.

An acclimation period before extended storage may make cut flowers more tolerant of sub-zero temperatures. Acclimation is commonly used to increase cold tolerance of woody plants (Lindstrom and Dirr 1989), but the literature is limited to using this technique for fresh cut flowers. Storing cut stems at cold temperatures of 0 to 4 °C might increase the ability of cut stems to tolerate cold storage.

Successful storage of cut flowers has been linked with temperature and storage method (Çelikel and Reid 2004). Wet storage is most suitable for short storage periods when flower opening is needed, and for species that do not tolerate dry storage. Dry storage, during which flowers are wrapped and stored in boxes, is more suitable for extended durations, allowing for more efficient use of refrigerated space, limited microbial activity (van Doorn and de Witte 1991), slowing flower opening (Gupta and Dubey 2018), delayed senescence (Da Silva 2003), and sea freight. Research conducted by Ahmad et al. (2012) found that dry handling resulted in more favorable water relations for rose (*Rosa hybrida*) with vase life similar to that of wet-stored stems and less severe wilting and senescence at termination than wet-stored stems of marigold (*Tagetes erecta*).

Therefore, this study aimed to determine the feasibility of using sub-zero storage temperatures to enable the long-term dry storage of commercially important cut flower species and evaluate the potential benefits of premixed commercial hydrating solutions or an acclimation period at 4 °C before extended storage. Through this analysis, we demonstrated different techniques to optimize extended storage periods and maintain acceptable vase life and aesthetic appeal of cut flowers.

Materials and methods

Cut flower acquisition. Cut flower stems were obtained from a wholesale florist during the first year (Expt. 1) for the initial evaluation of extended storage duration and temperature. During years two and three (Expt. 2 and 3), stems were acquired directly from Sunshine Bouquet (Bogota, Colombia) for prestorage pulsing and holding experiments. Stems were held at 4 °C for up to 8 h during processing for each experiment.

Storage duration and temperature (Expt. 1). Treatments consisted of two storage temperatures (−0.6 ± 0.2 or 4 ± 0.5 °C) and three storage durations (4, 8, or 12 weeks) for a 2 × 3 factorial arrangement, and an untreated control was placed directly into the postharvest evaluation environment. A total of 7 groups of 15 replicate stems of each species were made: alstroemeria (*Alstroemeria*; cultivar unknown, lavender flowers); carnation (*Dianthus caryophyllus* 'Hot Pink Fancy'); chrysanthemum (*Chrysanthemum* 'Cushion Arctic Queen White'); delphinium (*Delphinium elatum* 'Belladonna Dark Blue'); freesia (*Freesia;* cultivar unknown, yellow flowers); gerbera (*Gerbera jamesonii*; cultivar unknown, black center coral flowers); larkspur (*Consolida;* cultivar unknown, purple flowers); lily (*Lilium;* cultivar unknown, yellow); lisianthus (*Eustoma grandiflorum;* cultivar unknown, purple flowers); ranunculus (*Ranunculus asiaticus*; cultivar unknown, yellow flowers); rose (*Rosa hybrida* 'Freedom'); sunflower (*Helianthus annuus*; cultivar unknown, yellow); and tuberose (*Polianthes tuberosa;* cultivar unknown, white). Additionally, seven groups of anemone (*Anemone coronaria*; cultivar unknown, red), campanula (*Campanula medium*; cultivar unknown, purple flowers), gypsophila (*Gypsophila paniculata* 'Overtime White'), and stock (*Matthiola incana*; cultivar unknown, lavender flowers) stems consisting of 10, 14, 12, and 13 stems, respectively, were made. One group from each species was used as a nonstored control (duration = 0) and taken directly to postharvest evaluation after processing. Stems were cut to a uniform length by removing 2.5 to 10 cm from the basal stem, depending on the species. Groups were wrapped in newspaper and placed in cardboard boxes lined with polyvinyl wrap. One box per species was held dry at −0.6 °C and one box was held dry at 4 °C. Relative humidity (RH) was maintained at 80% to 90%. One group per species was removed from each temperature after 4, 8, and 12 weeks of storage.

Prestorage pulses (Expt. 2). The stems of carnation 'Bizet Hot Pink', chrysanthemum 'Alma', delphinium 'Tritan Lavender', lily 'Robina', and rose 'Orange Crush' were used to further evaluate the effect of prestorage pulses with a hydrating solution on stored cut stems. Stems were only hydrated with water after harvest from the grower. Stems of each species were cut to a uniform length before sorting into 21 groups of 15 stems each, except rose, with 17 stems per group. Groups were placed into treatments arranged in a 3 × 2 × 3 factorial design consisting of three prestorage pulses, two storage temperatures, and three storage durations. Groups were pulsed by placing stem ends into one of three pulse solutions, tap water, hydrating solution Express Clear 100 (C100), or holding solution Express Clear 200 (C200) (Floralife Inc., Walterboro, SC, USA), for 8 h at 4 °C, with an average RH of 86%. Both commercial hydrating products were mixed according to the manufacturer's instructions at a rate of 2 or 10 mL·L^{-1}, respectively, in 2.5-gal containers. Each container held 1 L of solution per 25 stems. After pulsing, stems were patted dry with paper towels, exposed to air for 15 min, wrapped in newspaper, and held dry at either −0.6 or 4 °C in cardboard boxes lined with polyvinyl wrap. RH was maintained at 80% to 90%. One group of each species and pulse treatment was removed from storage at 4, 8, and 12 weeks. A nonstored group of each species and pulse treatment was placed directly into postharvest evaluation (duration = 0).

Prestorage holding period (Expt. 3). The stems of carnation 'Pomodoro', lily 'Pavia', and rose

'Freedom' were sorted into 21 groups of 15 stems and assigned to treatments. Stems were treated with holding solution containing carbohydrates after harvest by the grower. Treatments consisted of three prestorage holding periods, two storage temperatures, and three storage durations arranged in a 3 × 2 × 3 factorial design. Before storage, stems were held dry at 4 °C for 24 h while exposed to air and lying flat on racks with at least 3 inches between stems, wrapped in newspaper, and placed in cardboard boxes lined with polyvinyl wrap for 1 week, or they were moved directly to extended storage at either −0.6 or 4 °C. Then, groups initially exposed to air for 24 h were wrapped in newspaper and held at either −0.6 or 4 °C in separate floral cardboard boxes for extended storage durations of 4, 6, or 8 weeks. Stems wrapped and contained in floral cardboard boxes for 1 week were either maintained at 4 °C or moved to −0.6 °C for extended storage durations. Stems were removed from storage after each respective duration was completed after the end of holding period. Initial fresh weight loss (FWL) was determined for stems that were held for either 24 h or 1 week before moving to extended storage. A nonstored group of each holding treatment served as control stems and were placed directly into postharvest evaluation (duration = 0). No initial FWL measurement was performed for nonstored control stems.

Poststorage evaluation. Stems were recut after each storage duration, with 2.5 cm removed from the stem end before evaluation. An additional 2.5 cm was cut from control stems before placement for evaluation. The stems were individually placed into separate vases filled with 400 mL of tap water. The evaluation environment was maintained at a 20 ± 2 °C with 40% to 60% RH and a 16-h photoperiod at 15 $\mu mol \cdot m^{-2} \cdot s^{-1}$.

Vase life, the number of days that a flower remained presentable in tap water, was calculated as the number of days until flowers become >50% wilted or necrotic or stems collapsed or incurred bent neck. Flower and bud senescence was recorded when >50% of petals or buds were slightly wilted, translucent, or any petals or buds abscised. Stems were considered viable if they remained upright in water with <50% wilt or petal/bud senescence at 24 h poststorage and exhibited no signs of mold. Flower opening was rated as failed to open, partially open, or fully open. A wilt rating was assigned to all flowers poststorage as tight (0), slightly wilted (1), moderately wilted (2), or severely wilted (3). The FWL percentage after storage was determined for all species except when stems were of such poor quality after storage (mushy or molded) that they did not remain upright.

Experimental design and statistics. A completely randomized design was used for each experiment. Data, as mentioned, from each cultivar and year were analyzed and subjected to an analysis of variance

Table 1. Poststorage evaluation of 17 cut flower species to determine the effects of long-term storage durations and temperatures on vase life (including controls) and viability after durations of 4, 8, or 12 weeks at either −0.6 °C or 4 °C (30.9 °F or 39.2 °F) (Expt. 1).

	Vase life (d)[i]							Viability (%)[ii]						
		Storage temperature (°C)												
	Control[iii]	−0.6			4.0			Control	−0.6			4.0		
		Storage duration (wk)												
Species	0	4	8	12	4	8	12	0	4	8	12	4	8	12
Alstroemeria	16.9 a[iv]	14.7 a	8.5 b	NV[v]	12.3 ab	4.0 b	NV–[vi]	93	93	67	0	20	13	0
Anemone	3.9	3.5	3.3	NV	NV	NV	NV	100	90	40	0	0	0	0
Campanula	12.6	11.0	11.9	NV	10.8	NV	NV	86	93	57	0	93	0	0
Carnation	12.2 a	7.4 b	4.0 b	4.7 b	7.0 b	4.3 b	8.8 ab	100	100	27	67	93	40	60
Chrysanthemum	11.9 a	7.0 b	3.4 c	2.0 c	2.8 c	NV–	NV–	100	100	93	27	33	0	0
Delphinium	13.7 a	3.2 b	NV–	NV–	4.0 b	NV–	NV–	100	73	0	0	20	0	0
Freesia	8.1 a	2.8 b	NV–	NV–	3.1 b	NV–	NV–	100	67	0	0	67	0	0
Gerbera	11.5 a	2.0 b	NV–	NV–	3.4 b	NV–	NV–	100	13	0	13	0	0	0
Gypsophila	15.8 a	5.0 b	NV–	NV–	8.9 b	NV–	NV–	100	83	0	0	92	0	0
Larkspur	8.7 a	6.7 ab	5.0 bc	NV–	3.6 c	NV–	NV–	100	100	73	0	80	0	0
Lily	8.1 a	4.9 b	4.1 b	3.5 bc	2.4 c	NV–	NV–	100	100	73	13	53	0	0
Lisianthus	7.0 a	2.3 b	NV–	NV–	2.4 b	NV–	NV–	93	20	0	0	33	0	0
Ranunculus	8.3 a	6.6 ab	3.3 c	2.3 c	4.8 bc	NV–	NV–	100	93	40	20	27	0	0
Rose	7.1	6.9	6.0	5.0	3.4	4.3	3.0	100	100	60	40	100	27	7
Stock	6.0 a	3.1 b	NV–	NV–	NV–	NV–	NV–	93	87	0	0	0	0	0
Sunflower	6.7 a	2.0 b	NV–	NV–	NV–	NV–	NV–	100	27	0	0	0	0	0
Tuberose	7.2	NV	NV	NV	NV	NV	NV	100	0	0	0	0	0	0

[i] Vase life = the number of days a flower remained presentable in tap water and was calculated as the number of days until flowers became >50% wilted or necrotic or stems collapsed or incurred bent neck.

[ii] Viability = percent of stems that remained upright in water with <50% wilt or petal/bud senescence after 24 h poststorage and exhibited no signs of mold.

[iii] Control stems were not stored and placed directly into vases for evaluation.

[iv] Means that share similar lowercase letters for each species variable interaction across a row are not significantly different according to Tukey's honestly significant difference test at $P \leq 0.05$; the absence of lowercase letters indicates no significance.

[v] NV= stems were not viable poststorage to quantify variable.

[vi] – indicates that the designated group was not included in the statistical analysis because of nonviable stems.

Fig. 1. Visual representation of the average vase life of stored rose 'Freedom' flowers compared with nonstored control flowers after 4- and 8-week storage durations held at −0.6 °C or 4 °C (30.9 °F or 39.2 °F) (Expt. 1).

separately using the generalized linear model procedure with SAS 9.4 statistical software (SAS Institute, Cary, NC, USA). Post hoc tests were implemented using Tukey's honestly significant difference test with $P \leq 0.05$ for significant interactions and main effects. Reported values are the least squared means to account for missing samples, such as flowers that failed to rehydrate or flowers that incurred bent neck or stem collapse after

storage, which were not used for vase life calculations.

Results

Storage duration and temperature (Expt. 1). Chrysanthemum, lily, and ranunculus flowers remained viable after 12 weeks of storage when held at −0.6 °C, maintaining vase life of 17%, 43%, and 28%, respectively, compared with the control, but they only remained viable up to 4 weeks when stored at 4 °C, with control vase life of 24%, 30%, and 58%, respectively (Table 1). Carnation and rose stems were the most tolerant of storage with viable stems at either −0.6 or 4 °C after 12 weeks (39% and 72% and 70% and 42%). However, other than the control, the visual appearance and quality of roses were best after 4-week storage durations when held at −0.6 °C (Fig. 1).

Anemone flowers remained viable, with 85% of control flower vase life after the 8-week storage duration when held at −0.6 °C, but they were not viable after 4 weeks of storage at 4 °C. Campanula and larkspur flowers remained viable through 8-week storage durations when held at −0.6 °C, with control vase life of 94% and 58%, respectively, but vase life of only 86% and 41%, respectively, when stored 4 weeks at 4 °C. Alstroemeria flowers also remained viable after 8 weeks of storage when held at −0.6 °C, with 50% vase life of the control flowers and 33% after 8 weeks when held at 4 °C.

Tuberose stems were not viable after 4-week storage durations regardless of the holding temperature. Stock and sunflower stems remained viable after 4-week storage at −0.6 °C, maintaining 52% and 30% of the control vase life, respectively, but they were not viable after 4-week storage when held at 4 °C. Delphinium, gerbera, and gypsophila flowers remained viable after 4-week storage when held at −0.6 °C, maintaining 23%, 17%, and 32% of the control vase life, respectively, and 29%, 30%, and 56% of control vase life, respectively, when held at 4 °C. Freesia and lisianthus flowers maintained vase life similar to that of control flowers when held at either −0.6 or 4 °C for 4 weeks (35% and 38% and 33% and 34%, respectively).

Campanula, chrysanthemum, delphinium, gerbera, lily, lisianthus, and ranunculus stems had similar FWL at either temperature after 4 weeks of storage. Alstroemeria and gypsophila stems had similar FWL at either temperature after 8 weeks of storage. Carnation and rose stems had similar FWL at either temperature after 12 weeks of storage (Table 2). Freesia and larkspur stems had significantly less FWL when held at −0.6 °C after a 4-week storage duration. Anemone, stock, and sunflower stems were not viable after 4 weeks when held at 4 °C; therefore, no FWL comparison could be performed for these species.

At −0.6 °C, 50% of the anemone flowers and 33% of the ranunculus flowers failed to open after 8 weeks of storage, whereas all the anemone and all but 4% of the ranunculus flowers opened at 4 weeks of storage. After 4 weeks of storage, 68% of the lisianthus flowers failed to open at 4 °C, whereas only 32% did not open after 4 weeks of storage (Table 3). The occurrence of mold was more prevalent when stems were stored at 4 °C than at −0.6 °C. However, as the duration increased, mold became more common for stems stored at −0.6 °C, except for carnation, lily, and rose, which had little to no instances of mold (Table 3). Bent neck or bent stem occurred more frequently in anemone and lily when stored at 4 °C. Bent neck or bent stem occurred more frequently in lisianthus and ranunculus after 4 weeks of storage at −0.6 °C. Bent neck or bent stem occurred more frequently in rose stems after 8 weeks of storage at −0.6 °C (Table 3). Most flowers across species were ended because of flower/leaf wilt and/or senescence as the main criteria.

Prestorage pulses (Expt. 2). The viability of stems of both carnation and rose stems poststorage declined to less than 20% after 8 weeks of storage when held at −0.6 °C (Table 4). However, stems of roses held at 4 °C and pulsed with C100 before storage maintained 73% viability after 12 weeks, whereas stems of

Table 2. Poststorage evaluation of 17 cut flower species to determine the effects of long-term storage duration and temperature on fresh weight loss (FWL) after durations of 4, 8, or 12 weeks at either −0.6 °C or 4 °C (30.9 °F or 39.2 °F) (Expt. 1).

	FWL (%)[i]					
	Storage temperature °C)					
	−0.6			4.0		
	Storage duration (wk)					
Species	4	8	12	4	8	12
Alstroemeria	12.4 a[ii]	14.3 a	NV[iii]–[iv]	12.2 a	5.6 a	NV–
Anemone	14.4 a	13.8 a	NV–	NV–	NV–	NV–
Campanula	24.0 b	45.7 a	NV–	15.4 b	NV–	NV–
Carnation	8.3 d	16.2 bc	22.3 a	20.7 ab	13.5 cd	22.8 a
Chrysanthemum	13.1 ab	18.8 a	15.6 ab	6.8 b	NV–	NV–
Delphinium	22.0 a	NV–	NV–	20.1 a	NV–	NV–
Freesia	10.3 b	NV–	NV–	19.6 a	NV–	NV–
Gerbera	16.5 a	NV–	NV–	12.9 a	NV–	NV–
Gypsophila	45.7 b	58.1 a	NV–	29.2 c	52.7 ab	NV–
Larkspur	17.1 b	25.7 ab	NV–	28.2 a	NV–	NV–
Lily	15.2 b	16.3 b	25.3 a	20.6 ab	NV–	NV–
Lisianthus	10.6 a	NV–	NV–	10.9 a	NV–	NV–
Ranunculus	12.7 b	28.2 a	42.3 a	7.3 b	NV–	NV–
Rose	14.1 c	24.1 b	41.4 a	15.4 c	25.0 b	40.4 a
Stock	12.9	NV	NV	NV	NV	NV
Sunflower	6.8	NV	NV	NV	NV	NV
Tuberose	NV	NV	NV	NV	NV	NV

[i] FWL = [(prestorage FW − poststorage FW)/prestorage FW] × 100%.

[ii] Means that share similar lowercase letters for each species variable interaction across a row are not significantly different according to Tukey's honestly significant difference test at $P \leq 0.05$; the absence of lowercase letters indicates no significance.

[iii] NV = stems were not viable poststorage to quantify variable; – indicates that the designated group was not included in the statistical analysis because of nonviable stems.

[iv] The designated group was not included in statistical analysis due to non-viable stems.

Table 3. Percent of stems exhibiting termination criteria of 17 cut flower species. Stems underwent evaluation of vase life after extended storage durations of 4, 8, or 12 weeks at either −0.6 °C or 4 °C (30.9 °F or 39.2 °F) for petal wilt, leaf senescence (leaf sen.), petal/bud senescence (petal/bud sen.), bent neck/stem, mold, or failure to open (Expt. 1).

Treatment		>50% Petal wilt	>50% Leaf sen.	>50% Petal/ bud sen.	Bent neck/ stem	Mold	Failure to open[i]
Temperature (°C)	Duration (weeks)	(%)					
		Alstroemeria					
Control		7	53	87	13	0	1
−0.6	4	80	80	87	20	0	2
4	4	100	100	100	80	0	0
−0.6	8	80	100	73	27	0	0
4	8	93	100	100	87	87	0
−0.6	12	100	100	100	100	100	[ii]
4	12	100	100	100	100	100	–
Significance[iii]		NS	NS	NS	***	***	NS
		Anemone					
Control		90	60	100	0	0	0
−0.6	4	100	30	100	0	0	0
4	4	100	100	100	0	100	–
−0.6	8	90	90	100	0	40	50
4	8	100	100	100	0	100	–
−0.6	12	100	100	100	0	100	–
4	12	100	100	100	0	100	–
Significance		NS	***	NS	NS	***	**
		Campanula					
Control		100	100	100	7	0	15
−0.6	4	100	93	100	0	0	18
4	4	100	100	100	0	0	19
−0.6	8	93	100	100	0	7	23
4	8	100	100	100	0	100	–
−0.6	12	100	100	100	0	100	–
4	12	100	100	100	0	100	–
Significance		NS	NS	NS	NS	***	NS
		Carnation					
Control		100	0	100	7	0	0
−0.6	4	100	7	100	7	0	0
4	4	93	27	93	13	0	0
−0.6	8	93	27	93	7	0	25
4	8	100	67	100	0	0	17
−0.6	12	53	73	60	47	0	30
4	12	80	80	80	47	20	0
Significance		**	***	*	*	*	NS
		Chrysanthemum					
Control		100	100	67	0	0	40
−0.6	4	100	100	100	0	0	42
4	4	33	87	33	0	67	44
−0.6	8	100	100	100	0	0	50
4	8	100	100	100	0	100	–
−0.6	12	100	100	100	0	47	47
4	12	100	100	100	0	100	–
Significance		***	NS	***	NS	***	NS

(Continued on next page)

Table 3. (*Continued*)

Treatment		>50% Petal wilt	>50% Leaf sen.	>50% Petal/ bud sen.	Bent neck/ stem	Mold	Failure to open[i]
Temperature (°C)	Duration (weeks)	(%)					
		Delphinium					
Control		100	33	100	0	0	4
−0.6	4	73	67	93	0	0	12
4	4	87	7	100	0	73	18
−0.6	8	100	0	100	0	100	–
4	8	100	100	100	0	100	–
−0.6	12	100	100	100	0	100	–
4	12	100	100	100	0	100	–
Significance		*	***	NS	NS	***	NS
		Freesia					
Control		93	80	100	0	0	50
−0.6	4	100	93	100	0	7	47
4	4	100	40	100	0	33	46
−0.6	8	100	100	100	0	100	–
4	8	100	100	100	0	100	–
−0.6	12	100	100	100	0	100	–
4	12	100	100	100	0	100	–
Significance		NS	**	NS	NS	***	NS
		Gerbera					
Control		60	0	100	0	0	–
−0.6	4	93	0	100	0	0	–
4	4	100	0	100	7	7	–
−0.6	8	100	100	100	0	100	–
4	8	100	100	100	0	100	–
−0.6	12	100	100	100	0	100	–
4	12	100	100	100	0	100	–
Significance		NS	NS	NS	NS	***	NS
		Gypsophila					
Control		92	100	100	0	0	5
−0.6	4	17	100	100	0	0	12
4	4	0	100	100	0	0	21
−0.6	8	0	0	100	0	0	–
4	8	58	75	100	0	58	–
−0.6	12	100	100	100	0	100	–
4	12	100	100	100	0	100	–
Significance		***	**	NS	NS	***	**
		Larkspur					
Control		100	93	100	0	0	60
−0.6	4	100	93	100	0	0	65
4	4	100	100	100	0	20	61
−0.6	8	93	100	93	7	13	59
4	8	100	100	100	0	100	–
−0.6	12	100	100	100	0	100	–
4	12	100	100	100	0	100	–
Significance		NS	NS	NS	NS	***	NS

(Continued on next page)

Table 3. (*Continued*)

Treatment		>50% Petal wilt	>50% Leaf sen.	>50% Petal/ bud sen.	Bent neck/ stem	Mold	Failure to open[i]
Temperature (°C)	Duration (weeks)	(%)					
				Lily			
Control		0	93	100	0	0	71
−0.6	4	87	93	100	13	0	66
4	4	100	100	100	87	0	87
−0.6	8	80	100	100	0	0	86
4	8	100	100	100	100	100	–
−0.6	12	67	100	100	7	13	63
4	12	100	100	100	100	100	–
Significance		*	NS	NS	***	***	NS
				Lisianthus			
Control		87	87	80	53	7	57
−0.6	4	100	100	100	87	13	32
4	4	100	87	100	27	47	68
−0.6	8	100	100	100	0	100	–
4	8	100	100	100	0	100	–
−0.6	12	100	100	100	0	100	–
4	12	100	100	100	0	100	–
Significance		NS	NS	NS	***	***	*
				Ranunculus			
Control		87	0	93	53	0	0
−0.6	4	87	7	100	27	0	4
4	4	100	0	100	13	0	0
−0.6	8	80	73	80	20	60	33
4	8	100	100	100	0	100	–
−0.6	12	80	60	100	0	60	33
4	12	100	100	100	0	100	–
Significance		NS	***	NS	*	***	NS
				Rose			
Control		33	100	60	47	0	0
−0.6	4	100	100	100	0	0	0
4	4	100	73	93	0	0	7
−0.6	8	93	100	100	47	0	0
4	8	100	53	53	7	0	0
−0.6	12	100	100	100	13	0	0
4	12	100	27	33	27	0	0
Significance		NS	***	***	*	NS	NS
				Stock			
Control		69	100	100	0	0	17
−0.6	4	100	100	100	0	0	13
4	4	100	100	100	0	0	–
−0.6	8	100	100	100	0	100	–
4	8	100	100	100	0	100	–
−0.6	12	100	100	100	0	100	–
4	12	100	100	100	0	100	–
Significance		NS	NS	NS	NS	NS	NS

(Continued on next page)

Table 3. (*Continued*)

Treatment		>50% Petal wilt	>50% Leaf sen.	>50% Petal/ bud sen.	Bent neck/ stem	Mold	Failure to open[i]
Temperature (°C)	Duration (weeks)	(%)					
		Sunflower					
Control		100	60	93	0	0	–
−0.6	4	60	60	60	7	87	–
4	4	100	100	100	0	100	–
−0.6	8	100	100	100	0	100	–
4	8	100	100	100	0	100	–
−0.6	12	100	100	100	0	100	–
4	12	100	100	100	0	100	–
Significance		***	**	**	NS	NS	NS
		Tuberose					
Control		93	7	100	0	0	8
−0.6	4	100	100	100	0	100	–
4	4	100	100	100	0	100	–
−0.6	8	100	100	100	0	100	–
4	8	100	100	100	0	100	–
−0.6	12	100	100	100	0	100	–
4	12	100	100	100	0	100	–
		NS	***	NS	NS	NS	NS

[i] Only viable stems were used in the analysis; stems were considered nonviable if vase life was ≤1 d.
[ii] Empty cells indicate that the designated group was not included in the statistical analysis because there were no viable stems.
[iii] Significance between treatments is indicated within columns for each individual species and termination criteria; NS, *, **, *** = not significant or significant at $P < 0.05$, 0.01, or 0.001, respectively.

carnation maintained more viability after 12 weeks when pulsed with C200 at the same holding temperature. Chrysanthemum and lily stems were not viable after 12-week storage durations when maintained at −0.6 °C or after 8-week storage durations when maintained at 4 °C. Delphinium stems were not viable at any duration or temperature regardless of pulsing solution (data not presented).

The vase life of carnation was statistically similar when pulsed with C200 for all storage durations when held at 4 °C, but only for the 4-week durations when held at −0.6 °C (Fig. 2A). Rose stem vase life was maintained regardless of pulsing solution when held at 4 °C, but only for 4 weeks when held at −0.6 °C (Fig. 2C). Stored chrysanthemum and lily stems had a significant decline in vase life when compared with nonstored stems (Fig. 2B and D). However, chrysanthemum stems held at −0.6 °C maintained significantly higher vase life than stems held at 4 °C after 4-week storage durations (Fig. 2B). The ability of flowers to open was not significantly affected among carnation, lily, or rose stems with any treatments, but significantly more chrysanthemum flowers failed to fully expand (3%) when pulsed with C200 and held at −0.6 °C for an 8-week storage duration (data not presented).

Pulsing solution was only significant in the FWL calculations for chrysanthemum, wherein flowers pulsed with C100 before long-term storage lost significantly less FW (28%) than when pulsed with C200 (33%) or water (35%) (Table 4, data presented were averaged over temperature and storage duration). Alternatively, carnation stems lost significantly more FW when pulsed with C100 before storage and held at −0.6 °C (40%) than stems pulsed with C200 and held at the same temperature (36%).

All species lost significantly more FW when stored at −0.6 °C, regardless of pulsing solution (Table 4). The temperature × duration interaction was significant for all species. Carnation and rose stems had significantly more FWL when stored at −0.6 °C for 8 or 12 weeks (40% and 59% and 29% and 50%, respectively) than when stored at 4 °C (21% and 38% and 20% and 30%, respectively). Lily stems had significantly more FWL when stored at −0.6 °C for 4 or 8 weeks (12% and 24%) than those stored at 4 °C (8% and 16%). Additionally, chrysanthemum stems held at all storage durations (4, 8, and 12 weeks) had significantly more FWL when held at −0.6 °C (17%, 45%, and 58%) than when held at 4 °C (12%, 21%, and 36%).

Prestorage holding period (Expt. 3). Vase life was significantly lower for nonstored lily stems when held for 1 week at 4 °C before evaluation and after 4-week storage durations at either holding temperature (Table 5). Lily stems were not viable when held for 1 week at 4 °C followed by an 8-week storage duration at −0.6 °C, or when held at 4 °C for extended storage after 6 weeks. (Table 5). Although carnation stems remained viable through all storage durations, stems experienced significantly lower vase life when held for 1 week before extended storage of 6 weeks at −0.6 °C. Rose stems stored for 8 weeks at −0.6 °C were not viable when held before storage for 24 h or 1 week (Fig. 3). Rose stems were not viable after 6- or 8-week storage durations when held at 4 °C with or without a prestorage

Table 4. Poststorage viability and fresh weight loss (FWL) of four cut flower species prepulsed with tap water, commercial hydrating solution Express Clear (C100), or holding solution Express Clear (C200) (Floralife Inc., Walterboro, SC, USA) for 8 h before long-term storage durations of 4, 8, and 12 weeks at either −0.6 °C or 4 °C (30.9 °F or 39.2 °F) (Expt. 2).

		Viability[i] (%)						FWL[ii] (%)					
		Storage temp (°C)											
		−0.6			4.0			−0.6			4.0		
		Storage duration (weeks)											
	Pulse	0	4	8	12	4	8	12	4	8	12	4	8	12
Species														
Carnation	Water	100	80	0	0	100	93	67	12.1 d[iii]	41.0 b	NV[iv] –	13.9 d	21.7 c	41.2 b
	C100	87	100	7	0	100	93	33	18.7 cd	40.0 b	61.4 a	10.9 d	17.1 cd	38.8 b
	C200	80	80	13	0	80	100	60	12.2 d	37.4 b	57.3 a	12.0 d	22.8 c	34.5 b
Chrysanthemum	Water	100	87	53	0	100	0	0	19.5 ghi	49.3 bcd	64.6 a	15.6 ghij	25.1 fg	35.7 e
	C100	100	100	40	13	100	0	0	10.1 ij	42.8 de	53.3 bc	6.6 j	17.5 ghi	35.1 ef
	C200	100	93	47	0	93	0	0	22.0 gh	43.7 cde	56.8 ab	13.9 hij	21.3 gh	38.2 e
Lily	Water	100	93	7	0	33	0	0	13.3 ef	25.6 bc	28.6 b	5.9 h	10.6 fgh	NV –
	C100	100	93	80	0	27	0	0	10.2 fgh	21.2 cd	27.5 b	6.9 gh	17.3 de	NV –
	C200	100	93	40	0	53	0	0	11.8 efg	25.2 bc	34.6 a	10.4 fgh	21.2 cd	NV –
Rose	Water	100	67	13	0	100	100	40	14.3 efg	32.8 b	50.5 a	9.3 g	21.9 cde	27.3 bcd
	C100	100	80	7	0	100	80	73	13.2 efg	25.0 bcd	47.8 a	11.8 fg	20.7 cdef	28.5 bc
	C200	100	73	7	0	100	100	7	12.8 efg	30.5 bc	51.6 a	11.5 fg	18.2 defg	32.8 bc

[i] Viability = percent of stems that remained upright in water with <50% wilt or petal/bud senescence after 24 h poststorage and exhibited no signs of mold.
[ii] FWL = [(prestorage FW − poststorage FW)/prestorage FW] × 100%.
[iii] Means that share similar lowercase letters for each species variable interaction across a row are not significantly different according to Tukey's honestly significant difference test at $P \leq 0.05$; the absence of lowercase letters indicates no significance.
[iv] NV= stems were not viable poststorage to quantify variable; – indicates that the designated group was not included in the statistical analysis because of nonviable stems.

holding period, but they were viable when held at −0.6 °C.

The abilities of carnation flowers to partially open or fully expand were unaffected by pretreatment holding period, storage duration, or holding temperature (data not presented). Alternatively, extended storage of lily flowers held for 1 week before a duration of 4 weeks at −0.6 °C significantly ($P \leq 0.01$) affected the ability of flowers to fully expand compared with stems that did not have a prestorage holding period, and rose stems were able to open more fully when stored at −0.6 °C than when stored at 4 °C regardless of the prestorage holding period (Fig. 3).

After a prestorage holding period, FWL was significantly higher for all species when held for 1 week at 4 °C (Table 5). After extended storage, FWL remained significantly lower for carnation stems that were held 24 h prestorage and stored at −0.6 °C for 4 weeks and for lily stems when stored at 4 °C for 8 weeks (Table 5). Rose stems had significantly more FWL after 8 weeks of extended storage when held at −0.6 °C preceded by a prehold period of 24 h. The wilt rating was significantly higher poststorage for all species when stems were held for 1 week before entering extended storage (carnation, $P \leq 0.05$; lily and rose, $P \leq 0.001$). The wilt rating was also significantly higher for lily ($P \leq 0.01$) and rose ($P \leq 0.001$) when stems were held at 4 °C for extended storage.

Discussion

Vase life and viability. Extended storage using a sub-zero (−0.6 °C) temperature proved to be feasible for six species (alstroemeria, anemone, campanula, larkspur, ranunculus, and rose), with no compromise to vase life when stored for 4 weeks at the sub-zero temperature during Expt. 1. Additionally, 70% to 100% of stems of six species (carnation, chrysanthemum, delphinium, gypsophila, lily, and stock) remained viable after 4 weeks of storage below freezing. However, only carnation and chrysanthemum stems maintained a vase life at least half that of the nonstored stems.

Previous work conducted by Marousky and Nanney (1972) showed that dry-stored stems of gypsophila were not viable when held for 1 to 2 weeks at 0 °C (32 °F), and they speculated that the cause was the inability to rehydrate after storage. However, it is unclear if the stored bunches were individually wrapped to prevent desiccation or simply stored in cardboard boxes. Wrapping cut flowers in paper or cellophane may reduce water loss. Conversely, Çelikel and Reid (2002) demonstrated that nonstored stock flowers maintained vase life and respiration rates similar to those of flowers wrapped in newspaper and contained within cardboard boxes when stored at 0 °C (32 °F), supporting our findings of the viability of cut stock flowers.

Even though lily stems remained viable, vase life significantly declined after 4 weeks at either storage temperature, but less so when held at −0.6 °C. The instance of bent flower stem was significant for stems stored at 4 °C and was likely caused by higher respiration rates than when stored below freezing (Reid and Jiang 2012).

Delphinium stems were not viable during Expt. 2, regardless of treatment. Delphinium stems in Expt. 1 were

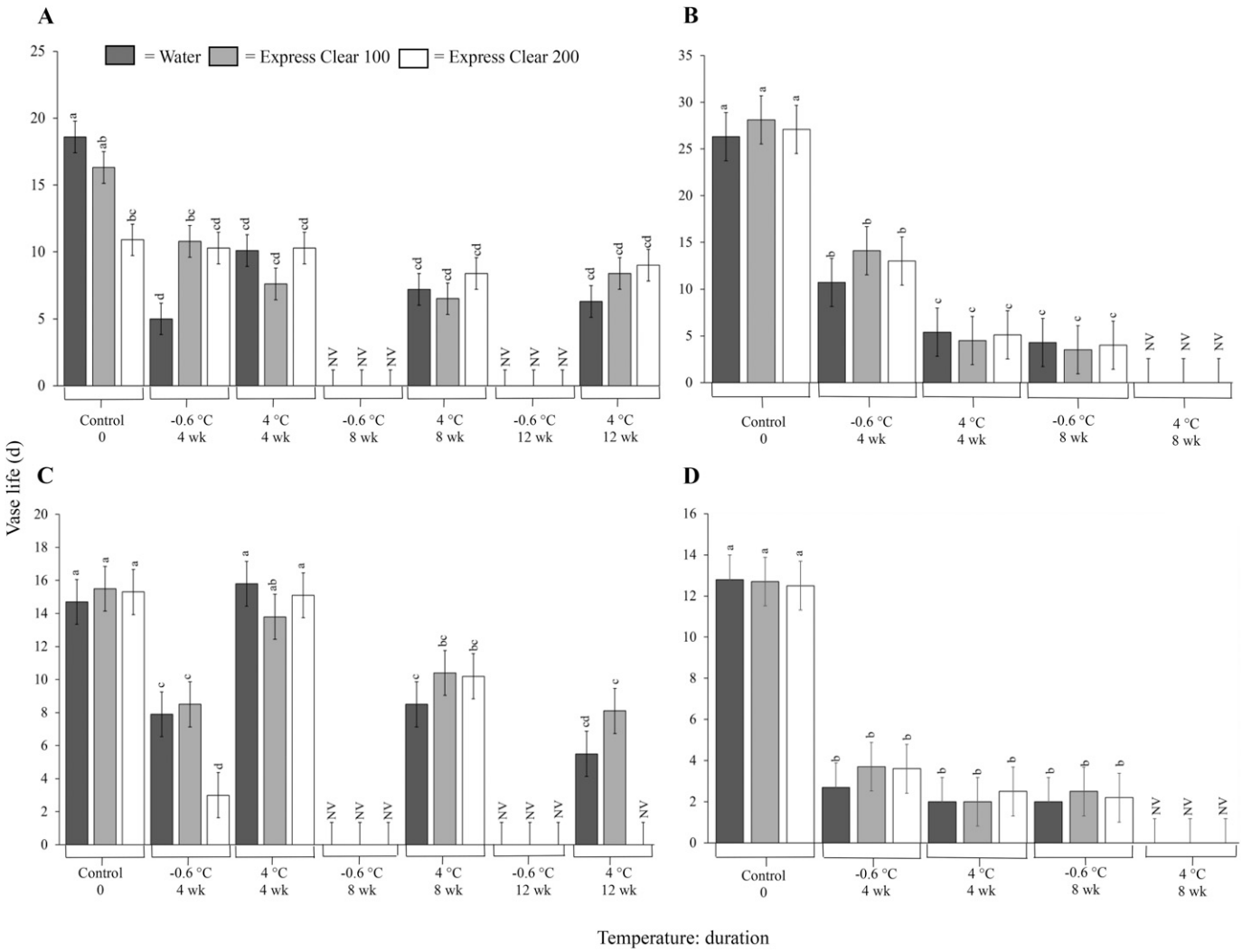

Fig. 2. Average vase life of viable stored stems prepulsed with tap water, hydrating solution C100, or holding solution C200 (Express Clear 100 or 200; Floralife Inc., Walterboro, SC, USA) for 8 h at 4 °C (39.2 °F) with average relative humidity (RH) of 86%. Commercial products were mixed according to the manufacturer's instructions at a rate of 2 or 10 mL·L^{-1} (0.26 or 1.28 fl oz/gal), respectively, in 2.5-gal containers. After pulsing, stems were held dry, wrapped in newspaper, and placed in cardboard boxes lined with polyvinyl wrap for durations of 4, 8, or 12 weeks and held at −0.6 °C (30.9 °F) or 4 °C, or they served as nonstored controls. (A) Viable carnation 'Bizet Hot Pink' stems stored up to 12 weeks. (B) Viable chrysanthemum 'Alma' stems stored up to 8 weeks. (C) Viable rose 'Orange Crush' stems stored up to 12 weeks. (D) Viable lily 'Robina' stems stored up to 8 weeks. Mean interaction effects among treatments followed by the same lowercase letter are not significantly different according to Tukey's honestly significant difference test at $P > 0.05$. Interval bars represent *SE* constructed using one *SE* from each mean. NV = no stems were viable poststorage to quantify variable (Expt. 2).

obtained from a commercial florist and were likely treated postharvest with a hydrating and/or a holding solution with carbohydrates, whereas stems in Expt. 2 were hydrated with only water before reaching our facility 3 to 4 d postharvest. This is concurrent with research conducted by Clark et al. (2010), who found that vase life was not significantly different with the use of water or hydrating solution. Therefore, the declines in vase life and viability are more likely caused by the inability of delphinium to tolerate extended storage durations.

In Expt. 2, temperature had a mixed effect on flower viability, which was higher for lily and chrysanthemum flowers at −0.6 °C, but much higher for rose and carnation flowers at 4 °C for up to 8 weeks of extended storage. Carnations maintained vase life similar to that of control flowers when pretreated with hydrating solution pulse, and a hydrating solution without carbohydrates proved more beneficial than only water hydration when stored for 4 weeks at sub-zero temperatures. Vase life was slightly higher when pulsed with C200 for all storage durations when held at 4 °C, and stems remained viable after 12 weeks of storage.

Rose stems maintained vase life similar to that of control stems only when stored at 4 °C, and holding solution was not significantly different with up to 8 weeks of storage. However, when stored at −0.6 °C, vase life was significantly less with the use of holding solution containing carbohydrates. This could be attributable to carbohydrates in C200 slowing water uptake during the pulsing period

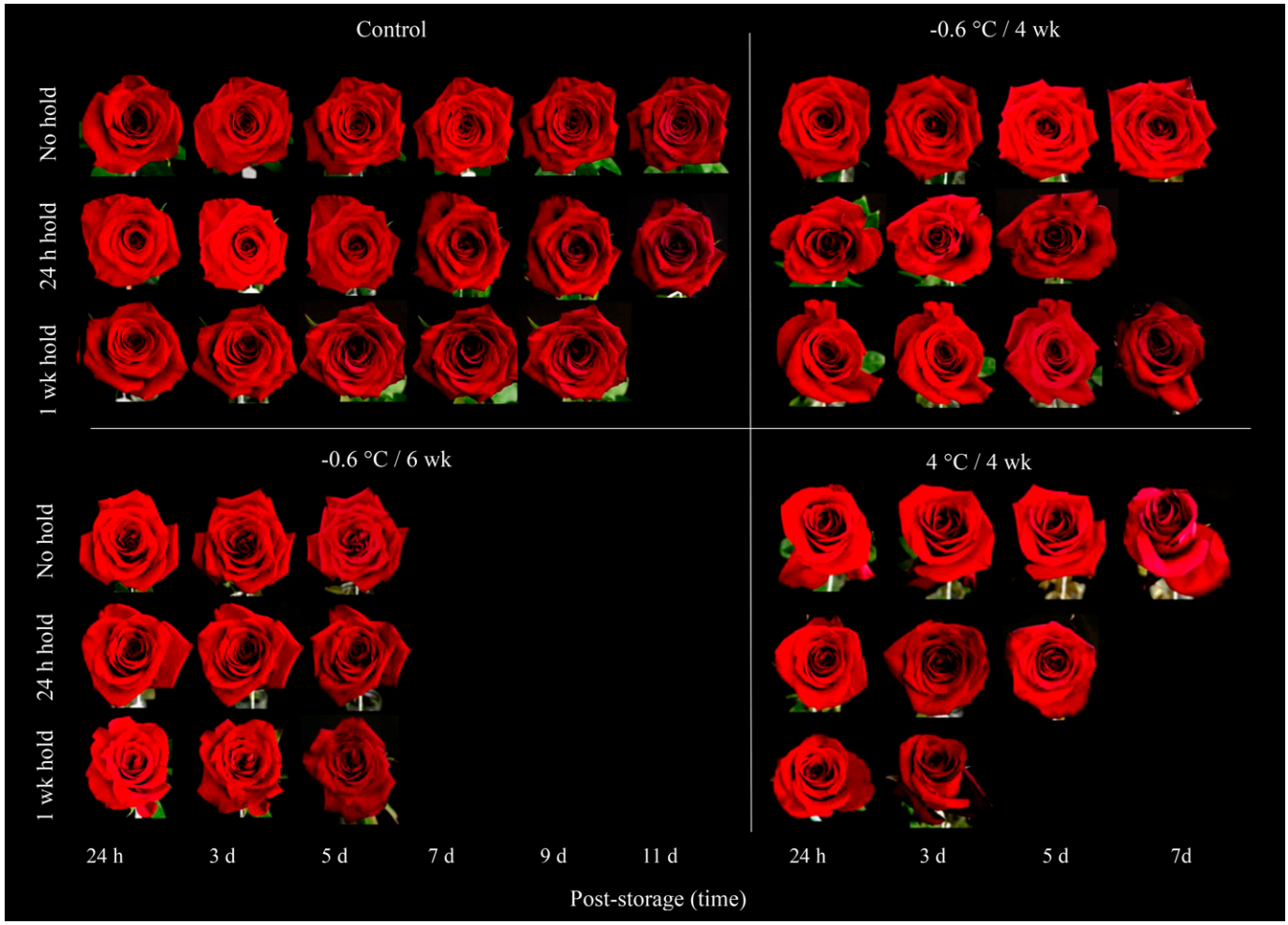

Fig. 3. Flower opening comparison of rose 'Freedom' buds after extended storage. Stems were placed directly into extended storage (no holding period), held dry for 24 h at 4 °C (39.2 °F) on racks, or wrapped in newspaper and stored in cardboard boxes lined with polypropylene wrap for 1 week at 4 °C before moving to storage at −0.6 °C (30.9 °F) or 4 °C. Figure shows nonstored control stems, stems stored for 4 weeks at −0.6 °C, stems stored for 6 weeks at −0.6 °C, and stems stored for 4 weeks at 4 °C (Expt. 3).

(Marousky 1971; Moody et al. 2014) and lower metabolic processes at sub-zero temperatures.

Alternatively, stored lily and chrysanthemum had a shorter vase life than control stems regardless of storage temperature or pulsing solution. However, viability was higher for both species when stored at sub-zero temperatures for up to 8 weeks. Chrysanthemum stems were more tolerant of sub-zero temperatures and had a longer vase life than when held at 4 °C, regardless of pulsing solution.

In Expt. 3, vase life and viability of rose and lily stems were best maintained at the sub-zero temperature, and carnation stems were unaffected by either temperature. Stems used in Expt. 3 received complete hydration and carbohydrates postharvest before shipment. Therefore, the more favorable response of rose to the sub-zero temperature was likely attributable to the immediate need to store carbohydrates and adequate hydration postharvest for maintaining viability at the sub-zero temperature; however, it also could be attributable to differences in cultivars.

Holding stems at 4 °C for either 24 h or 1 week before long-term storage did not acclimate the stems to sub-zero storage. The prestorage treatments had no effect on vase life or decreased it.

Percent FW change and flower opening. In Expt. 1, the stems (viable and not viable) of most species had significantly more FWL when stored at 4 °C poststorage, except for gypsophila, which had significantly more FWL when stored at the sub-zero temperature, and rose, which had no significant difference related to the storage temperature. Alternatively, in Expt. 2, significantly more FWL occurred at the sub-zero storage temperature and with the use of holding solution containing carbohydrates for chrysanthemum stems. Carnation flowers incurred higher instances of stem collapse below freezing temperatures, but FWL was still able to be measured poststorage, thereby highlighting the cause of reduced viability. Stem collapse on viable carnation flowers occurred poststorage or before flower opening. However, the occurrence of stem collapse during Expt. 3 was minimal. This may be attributable to differences in cultivar and production conditions from year to year.

Additionally, carnation stems treated with C100 before extended storage incurred significantly less instances of

Table 5. Fresh weight loss (FWL) of three cut flower species after a preholding acclimation period at 4 °C and after long-term storage durations with corresponding vase life following 4-, 6-, and 8-week storage durations at either −0.6 °C or 4 °C (30.9 °F or 39.2 °F) (Expt. 3).

	FWL[i] posthold (%)	FWL[ii] poststorage (%)						Vase life (d)						
		Storage temp (°C)												
	4.0	−0.6			4.0				−0.6			4.0		
		Storage duration (weeks)												
Hold time	Prestorage	4	6	8	4	6	8	Control 0	4	6	8	4	6	8
		Carnation												
0	ND[iii]	15.7	18.1	21.1	11.6	13.0	22.7	10.6	5.9	7.9	4.3	6.1	5.7	3.5
24 h	2.9	6.8	13.1	19.4	7.4	14.5	19.3	9.5	7.2	6.9	5.0	5.5	6.3	3.9
1 wk	5.5	10.1	16.7	23.6	11.2	13.0	19.9	8.9	6.3	4.3	4.7	5.9	4.2	4.0
Significance[iv]	***	*	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS
		Lily												
0	ND	12.6	16.6	23.7	18.3	22.1	32.7	12.6	5.8	4.0	2.0	3.5	NV[v]	NV
24 h	1.8	13.5	22.2	22.5	10.8	13.8	19.4	12.4	6.0	2.9	2.5	3.8	NV	NV
1 wk	3.1	7.9	13.5	15.2	11.9	15.7	24.3	9.7	3.5	4.0	NV	2.5	NV	NV
Significance	***	NS	NS	NS	NS	NS	*	*	*	NS	*	NS	NS	NS
		Rose												
0	ND	22.5	32.9	30.0	23.4	31.8	27.3	11.0	7.9	5.1	4.4	5.4	2.9	NV
24 h	3.5	17.7	28.9	42.9	22.4	30.0	34.9	11.1	6.9	4.5	NV	4.6	NV	NV
1 wk	4.8	16.8	27.2	32.9	16.3	22.9	32.5	9.2	6.6	4.6	NV	4.1	3.0	NV
Significance	**	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[i] FWL = [(prehold FW − posthold FW)/prehold FW] × 100%.
[ii] FWL = [(posthold FW − poststorage FW)/posthold FW] × 100%.
[iii] ND = No data; these stems had no holding period; therefore, there was no FWL to report.
[iv] Significance between treatments is indicated within columns for each individual species and variable; NS, *, **, *** = not significant or significant at $P < 0.05$, 0.01, or 0.001, respectively.
[v] NV= stems were not viable poststorage to quantify variables.

stem collapse when held at sub-zero temperatures than stems pulsed with water or C200. However, stem collapse occurred significantly more often ($P < 0.001$) when stored at −0.6 °C than when stored at 4 °C for all storage durations, and significantly less ($P \leq 0.01$) when pulsed with C100 before extended storage rather than C200. This could also be attributable to the lack of adequate hydration prestorage with C200 caused by carbohydrates restricting adequate flow of water uptake (Marousky 1971; Moody et al. 2014). Stem collapse was only significant in Expt. 3 when stems were held for 1 week before storage or when held at the sub-zero temperature for 8 weeks.

Alternatively, the occurrence of bent neck in rose occurred significantly more when pulsed with C200 before storage at the sub-zero temperature, regardless of duration. In Expt. 3, the occurrence of bent neck was significant, with 100% occurrence on all stems held for 1 week before extended storage regardless of temperature. Bent neck occurred significantly more after 6- and 8-week storage durations at the sub-zero temperature, but only after the 8-week storage durations when held at 4 °C.

Lily flowers are known to have different degrees of chilling sensitivity, with symptoms including failure to open, hastened tepal wilting, and leaf yellowing (van Doorn and Han 2011). Although failure to open in lily increased with storage duration, temperature was integral because many buds rotted and abscised during the postharvest evaluation after a 4-week storage duration when held at 4 °C; however, when held at −0.6 °C, flower opening was less inhibited.

In Expt. 2, lily experienced significantly less instances of bud senescence or abscission (0%) at termination after 4-week durations, irrespective of hydration treatment before extended storage, when held at −0.6 °C, and instances of bud senescence or abscission were more prevalent when held at 4 °C. Additionally, lily incurred significantly more instances of collapsed flower stems when held for 1 week before extended storage and when stored at 4 °C.

Both carnation and chrysanthemum flowers were able to expand or fully open regardless of temperature or duration. However, for carnation, significantly more stems had mold poststorage when held at 4 °C after 12 weeks; for chrysanthemum stems, significantly more stems had mold poststorage when held at 4 °C after all durations. There was some evidence of mold at −0.6 °C, but only for chrysanthemum and only after 12 weeks of storage.

In Expt. 3, the pretreatment effects of the holding period and poststorage FWL were significantly lower poststorage when stems were held for 1 week at 4 °C. This is likely attributable to the initial FWL with preholding of the

stems, which was significantly higher after a 1-week holding period. However, lily and rose flowers were able to open more fully when maintained at −0.6 °C than when stored at 4 °C. This is likely attributable to continued higher rates of transpiration and respiration after a prestorage holding period maintained at the same temperature than when stems were moved to the sub-zero temperature, thus slowing those processes, as expected.

Conclusions

The cut flower industry needs to optimize longevity of fresh cut flowers to meet consumer demand and reduce shrinkage during postharvest handling. Almost all species of cut flowers sampled remained viable for similar or longer durations at the sub-zero (−0.6 °C) temperature and, in many instances, had longer vase life than when stored at the industry standard of 4 °C (Table 6). When stored at the sub-zero temperature for extended periods, many species incurred less FWL and significantly less occurrences of mold than when held at 4 °C. The length of storage that freshly cut flowers can withstand without loss of viability or quality varied among species and cultivars. Rose and carnation stems were the most tolerant of extended storage durations, up to 12 weeks, whereas tuberose was not tolerant of any storage duration, regardless of the holding temperature.

Prepulsing stems with hydrating or holding solution before extended storage at the sub-zero temperature was not beneficial for maintaining longevity or decreasing FWL. However, when pulsed with hydrating solution and stored at 4 °C, rose stems had increased rates of viability, whereas chrysanthemum stems maintained longer vase life after storage at the sub-zero temperature. Cut carnation benefited more from a holding solution with carbohydrates, maintained vase life similar to that of nonstored control stems, and had improved turgidity when held at the sub-zero temperature. Further research of more cultivars of these species would help determine if these results are species- or cultivar-specific. However, it may be more cost-effective to store stems dry directly from harvest with an acclimation period. Prestorage treatments did not have a positive effect on cut flower longevity. In addition, extending the holding period to 1 week was detrimental to viability, FWL, and the ability of flowers to fully expand.

Through this research, we substantiated that many species of cut flowers may be held at sub-zero temperatures with improved vase life or vase life comparable to that achieved with the industry standard of 4 °C. New cultivars are frequently released, and growers should consider potential decreases in viability with extended storage and variability in responses by both species and cultivars. It is always recommended that growers should evaluate these techniques among a small sample before implementing these findings. In addition, growers should consider two technical issues

Table 6. Summary of results for each species compared with 4 °C.

Alstroemeria	−0.6 °C increased vase life, stems could be stored 4 weeks with 93% viability and up to 8 weeks, but with viability reduced to 67%; −0.6 °C reduced bent neck and mold
Anemone	Similar vase life; −0.6 °C increased viability of stems stored for 4 or 8 weeks, −0.6 °C reduced leaf senescence and mold
Campanula	−0.6 °C increased vase life; stems could be stored 4 weeks with 93% viability and up to 8 weeks, but with viability reduced to 57%; −0.6 °C reduced mold
Carnation	Similar vase life and viability; −0.6 °C reduced petal wilt, leaf senescence, petal/bud senescence, and mold, but it increased bent neck; hydration and holding solutions should be used; preholding treatments had either no effect or a negative effect on vase life
Chrysanthemum	−0.6 °C increased vase life, stems could be stored 8 weeks with 93% viability and up to 12 weeks, but with viability reduced to 27%; −0.6 °C reduced bent neck but increased petal wilt, leaf senescence, and petal/bud senescence; hydration and holding solutions had little effect on vase life
Delphinium	Similar vase life; −0.6 °C increased viability of stems stored for 4 weeks; −0.6 °C reduced petal wilt, leaf senescence (at 8 weeks), and mold
Freesia	Similar vase life and viability; −0.6 °C reduced mold but increased leaf senescence
Gerbera	Similar vase life and viability; −0.6 °C reduced mold
Gypsophila	Similar vase life and viability; −0.6 °C reduced petal wilt, leaf senescence, and mold
Larkspur	−0.6 °C increased vase life, stems could be stored 4 weeks with 100% viability and up to 8 weeks, but with viability reduced to 73%; −0.6 °C reduced mold
Lily	−0.6 °C increased vase life, stems could be stored 4 weeks with 100% viability and up to 12 weeks, but with viability reduced to 13%; −0.6 °C reduced petal wilt, bent neck, and mold; hydration and holding solutions had little effect on vase life; preholding treatments had either no effect or a negative effect on vase life
Lisianthus	Similar vase life and viability; −0.6 °C reduced mold but increased bent neck
Ranunculus	−0.6 °C increased vase life, stems could be stored 4 weeks with 93% viability and up to 12 weeks, but with viability reduced to 20%; −0.6 °C reduced leaf senescence and mold but increased bent neck
Rose	−0.6 °C increased vase life, stems could be stored 4 weeks with 100% viability and up to 12 weeks, but with viability reduced to 40%; −0.6 °C increased leaf and petal senescence and bent neck; hydration and holding solutions had little effect on vase life; preholding treatments had no effect on vase life
Stock	−0.6 °C increased vase life, stems could be stored 4 weeks with 87% viability
Sunflower	−0.6 °C increased vase life; however, only 27% of stems were viable after 4 weeks of storage; −0.6 °C reduced petal wilt and leaf and petal senescence
Tuberose	Did not tolerate storage at either −0.6 °C or 4 °C

when using sub-zero storage. The lower temperature will increase energy costs relative to standard storage temperatures, and some refrigeration units may not be able to adequately maintain −0.6 °C.

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