Effect of Forced-air Cooling, Hydrocooling, or their Combination on Fruit Quality of Two Southern Highbush Blueberry Cultivars

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Abstract. Blueberry is widely grown around the world, and the United States is the leading producer. A strategy to maintain fruit quality during commercial handling is rapid cooling using the forced-air system. Hydrocooling (HY) is an effective cooling method widely used for many crops and has potential as a cooling method for blueberry. The objective of this study was to compare the cooling efficiency of conventional forced-air cooling (FA), the current commercial method, with immersion HY alone or HY in combination with FA (HY + FA), and to determine effects on blueberry fruit quality during subsequent cold storage. ‘Emerald’ and ‘Farthing’ southern highbush blueberry were commercially harvested and packed into plastic clamshell containers. FA was accomplished by simulating commercial conditions using a small-scale unit within a cold room at 1 °C/80% relative humidity (RH) until 7/8 cooling was achieved (27 minutes). For HY, fruit in clamshells (125 g) were immersed in chlorinated ice water (200 ppm free Cl⁻¹, pH = 7.0) and 7/8 cooling occurred in 4 minutes. For HY + FA, fruit were 7/8 hydrocooled then transferred to FA for 30 minutes to remove free water from the fruit. After the cooling treatments, clamshells were evaluated weekly for selected quality parameters during 21 days storage at 1 °C. For HY treatment, the 1/2 cooling time was 1.13 minutes for ‘Emerald’ and 1.19 minutes for ‘Farthing’, whereas for FA treatment, the 1/2 cooling times were 4.5 and 6.8 minutes, respectively. For ‘Farthing’, cooling method did not affect fruit firmness; after 21 days, there was a slight softening in fruit from all treatments. However, ‘Emerald’ fruit cooled by HY + FA were softer than those from either HY or FA after 14 days of storage. For all cooling methods ‘Emerald’ was less acidic (0.3% citric acid) and was sweeter [10.2% soluble solids content (SSC)] than ‘Farthing’ (0.6% citric acid, 9.4% SSC). There were no differences in bloom among cooling methods. Bloom ratings for ‘Emerald’ remained >4.5 (70% to 80% coverage) whereas that for ‘Farthing’ cooled by HY or HY + FA was 3.7. Anthocyanin concentration in ‘Emerald’ fruit from HY + FA cooling method decreased by 33% during 21 days of storage, whereas that for ‘Farthing’ remained constant (8.3 mg cyanidin-3-Glicoside/g) irrespective of treatment during storage. Compared with ‘Farthing’, ‘Emerald’ was more sensitive to HY, where ≈15% of fruit developed visual skin breaks (split) after 7 days storage. HY shows potential as an alternative method to rapidly and thoroughly cool southern highbush blueberries such as ‘Farthing’, thus, maintaining fruit quality, while introducing a rinsing and sanitizing treatment. HY needs to be tested on commercial cultivars to determine the incidence of fruit splitting.

The production of blueberry (*Vaccinium* spp.) has increased over the last decades all around the world (Michalska and Lysiak,

2015). In the United States, it is one of the most popular small fruits, second only to strawberry (Giongo et al., 2013), and as a source of anthocyanins, contributes antioxidants to the diet (Cantín et al., 2012; Lacombe et al., 2015; Routray and Orsat, 2011).

Blueberry fruit appear to have a weak climacteric response but this is still being debated (Sargent et al., 2006) because it is not known whether positive or negative autocatalytic ethylene mechanisms are in place to regulate fruit development and ripening (MacLean and NeSmith, 2011). For this reason, blueberries are harvested at full-ripe stage for maximum flavor. Shelf life depends on the cultivar, harvest method, and field and

storage conditions (Duan et al., 2011; Sargent et al., 2006). The respiration rate for blueberry was reported to reach between 2.0–10 mg·kg⁻¹·h⁻¹ at 0 °C and 52–87 mg·kg⁻¹·h⁻¹ at 20 °C (Perkins-Veazie, 2016); ethylene production ranged from 0.5 to 2 μL·kg⁻¹·h⁻¹ at 20 °C for northern highbush fruit harvested fully ripe (Suzuki et al., 1997).

A strategy to maintain the fruit quality during commercial handling is application of rapid cooling (precooling) before cold storage (Chiabrando and Giacalone, 2011; Gunther et al., 2015). Cooling is the most important of all processes to maintain post-harvest quality of fresh fruit by rapidly removing field heat shortly after harvest (Baird and Gaffney, 1976). The recommended storage conditions for blueberries are 0 °C/90% to 95% RH (Perkins-Veazie, 2016). Currently, blueberries are commercially packed into rigid, vented clamshell containers, placed into corrugated cartons, palletized, then cooled by forced air for 60–90 min to achieve 2 to 3 °C pulp temperature (Sargent et al., 2006). One important quality characteristic of blueberry fruit is the presence of the surface “bloom,” a white, powdery coating, formed by epicuticular wax platelets that reduce water loss and reflect light (Mukhtar et al., 2014). If the fruit are not harvested and handled, the bloom may disappear because of polishing, compacting the platelets to form a dark, shiny layer, and potentially lowering the price.

Hydrocooling stands out as a cooling technology in which fruit is exposed to chilled, sanitized water by immersion or spraying; the cooling time usually takes a few minutes, depending on the size of the product (Becker and Fricke, 2002; Cortez et al., 2002). Ferreira et al. (2006) stressed the critical importance of maintaining a constant minimum concentration of sanitizer in HY water to avoid cross contamination of decay pathogens.

Hydrocooling is efficient because of the low application cost and high energy efficiency compared with FA. Hydrocooling is capable of cooling large amounts of fruit, while sanitizing the fruit surface (Ferreira et al., 2009). It is recommended for many crops, such as cherry, melon, lychee, peach, apple, and orange (Alike et al., 2006; Becker and Fricke, 2002; Liang et al., 2013; Teruel et al., 2004). Preliminary tests to hydrocool loose blueberry immersed in a circulating water bath removed the bloom; however, when hydrocooled in clamshell containers they maintained the bloom (M.A.G. Carnelossi, unpublished data). Sreedharan et al. (2015) reported 4.4 log reduction in *Salmonella* colony forming unit (CFU)/berry following HY of strawberry with 200 ppm chlorine, raising the possibility that blueberry could also be sanitized *via* HY.

The objective of this study was to determine the cooling efficiency of HY, FA, and HY plus forced-air cooling (HY + FA), and the effects on quality of southern highbush blueberry fruit (*Vaccinium corymbosum*) during subsequent storage.

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Materials and Methods

Plant material

Two identical experiments were conducted in Apr. 2013 using two commercial cultivars. 'Emerald' (U.S. Patent PP12,165) was harvested in the first test and is described as a vigorous, high-yielding cultivar with large fruit and good shipping quality. For the second test, 'Emerald' was no longer available, so 'Farthing' (U.S. Patent PP19,341) was harvested. 'Farthing' has high quality, with medium to very large fruit, dark skin color and exceptionally firm texture that ripens from mid-April to mid-May in North Central Florida (Williamson et al., 2014). For both tests, fruit were randomly harvested at commercial maturity (fully ripe stage, 100% blue) into plastic field lugs in midmorning at a farm in Archer, FL (lat. 29.5300°N, long. 82.5190°W) and immediately transported for ≈ 25 min at ambient temperature (20 ± 1 °C) to the Post-harvest Horticulture Laboratory, Horticultural Sciences Department, University of Florida, Gainesville. Berries were manually sorted for uniform color (100% blue) and absence of bruising. The fruit were randomly distributed into rigid, vented "clamshell" packages (APET, A9744; Pactiv LLC, Lake Forest, IL) (dimensions: lid: 120.7×112.7 mm; closed height: 44.5 mm). Each clamshell was weighed to 125 g and fruit size was uniform between the two cultivars with 52–55 fruit per clamshell, resulting in an overall mean of 2.36 g per fruit.

Treatments and storage conditions

Treatments ($n = 12$ clamshells/treatment). a) FA: Six clamshells were packed in a single layer in each of two commercial, corrugated cartons (flats), stacked, then placed lengthwise in a small, forced-air unit in a 1 °C cold room. The pressure drop across the plenum was set to 125 mm, simulating commercial airflow conditions; b) HY: Individual clamshells were immersed for 4 min (time for pulp temperature to reach 1 °C) in a circulating water bath maintained at 1 °C and 200 ppm free Cl^- ; c) HY and forced air (HY + FA). Individual clamshells were subjected to HY, then placed in cartons and cooled by FA for an additional 30 min. The purpose of this extra FA treatment was to determine if the removal of free water from the fruit would not only affect the fruit quality during storage, but also the effect for each of the variables of single treatments and the interaction.

Temperatures of the cooling media and fruit pulp were logged every 15 s during cooling using thermistor probes fitted to a Squirrel data logger (SQ2020; Grant Instruments Ltd., Cambridgeshire, UK). The probes (2-mm tip) were inserted into the fruit center according to the $r/4$ (spherical products) relationship, $n = 4$ fruit per treatment. The sphere volume (E) was calculated based on the formula ($E = rT/rL$), where rT is the transversal radius and rL is the longitudinal radius as measured with a caliper (Teruel et al., 2004). The 1/2 cooling time and 7/8 cooling time were determined by the dimen-

sionless temperature rate (TAT) based on the formula ($\text{TAT}_{1/2} = T_p - T_a/T_i - T_a = 0.5$ and $\text{TAT}_{7/8} = T_p - T_a/T_i - T_a = 0.125$, where T_p is the pulp temperature measured during cooling, T_i is the initial temperature of the fruit, and T_a is the temperature of the cooling medium according to Mohsenin (1980). Following the cooling treatments, fruit were stored at 1 °C/80% RH and evaluated at 0, 7, 14, and 21 d ($n = 3$ clamshells per treatment per evaluation).

Nondestructive analyses

Weight gain (+) or loss (-). Each clamshell was weighed (model Fx 5000i; A&D Company, Korea) before and after cooling and weekly throughout storage. Weight gain (+) or loss (-) was calculated based on the initial weight, and expressed as percentage of the initial weight. The water from the hydro-cooled fruit in clamshells was allowed to drain for 3 min before being reweighed.

Freshness rating. Fruit from each clamshell were subjectively rated according to the following scale: 9 = excellent: full fresh appearance, high sheen; 7 = good: still looks fresh, still shiny; 5 = fair: not fresh appearance, low sheen, limit of marketability; 3 = poor: dull, limit of usability; 1 = extremely poor: shriveled appearance. The results were expressed in average grade for each replication.

Bloom coverage. The bloom was evaluated with the following scale according to the estimated percentage of surface area showing bloom: 5 = 81% to 100%; 4 = 61% to 80%; 3 = 41% to 60%; 2 = 21% to 40%; 1 = 0% to 20%.

Decay and bruising incidence. The number of fruit (10 fruit per clamshell) with any incidence of visible mycelial growth, or mechanical damage, was recorded and expressed in percent.

Destructive analyses

Pulp firmness. Whole fruit firmness was measured at 0, 7, 14, and 21 d for each fruit ($n = 3$ fruit/clamshell; nine fruit/treatment/analyses/d) using a Texture Analyzer Plus (Stable Micro Systems, Godalming, Surrey, UK) fitted with a convex probe (3-mm diameter) affixed to a 5-kg load cell and driven with a crosshead speed of $2.0 \text{ mm}\cdot\text{s}^{-1}$; maximum force [Newton (N)] was determined at 7-mm penetration into the pulp.

Fruit (10–15 per clamshell) were frozen at -20 °C, later defrosted, homogenized, and centrifuged at $16,128 g_n$ for 20 min at 5 °C. The supernatant was filtered through cheesecloth, and the filtrate (juice) was used to assess SSC and total titratable acidity (TTA).

Soluble solids content. SSC was determined by placing several drops of juice on the prism of a Mark II Abbe refractometer (Model 10480; Cambridge Instruments, Inc., Buffalo, NY) and reported in percent.

Total titratable acidity and pH. TTA and pH were determined using a Metrohm titrimeter (Model 719 S Titrino; Metrohm, Herisau, Switzerland). Aliquots (6 g) of blueberry juice were diluted in 50 mL distilled water and pH was first determined before starting the titration with 0.1 N sodium hydroxide (NaOH) to

an endpoint of pH 8.2, for the TTA determination. The TTA was expressed as percent citric acid basis (Ehlenfeldt et al., 1994).

Total anthocyanins. Total anthocyanins was determined according to Nunes et al. (2006) with the following modifications. The aliquots (2 g) of homogenate blueberry tissue were mixed with 18 mL 0.5% HCl in methanol (v/v). Anthocyanin pigments were extracted by holding samples at 4 °C for 1 h in darkness. The samples were then filtered using single layer tissue (Kimwipe) to remove flocculate and absorbance of the solution was measured at 520 nm (BioTek PowerWave XS2; BioTek Instruments, Inc., Winooski, VT). Pigment concentration was calculated using the following formula: $\{\text{Abs}_{520} \times \text{dilution factor} \times [\text{molecular weight (MW) of cyanidin 3-galactoside (Cy-3-Gal)}]\} / \epsilon$ (molar extinction coefficient of Cy-3-Gal), in which MW of Cy-3-Gal = $445.2 \text{ g}\cdot\text{mol}^{-1}$; $\epsilon = 34,300 \text{ L}\cdot\text{mol}^{-1}\cdot\text{cm}^{-1}$. Results are expressed as $\text{mg}\cdot 100 \text{ g}^{-1}$ fresh weight of Cy-3-Gal.

Statistical analyses

The experiment was carried out for each cultivar in a completely randomized design in factorial scheme (3×4), with three cooling methods and four storage evaluations (0, 7, 14, and 21 d); there were three clamshells/treatment/evaluation. Data were analyzed using analysis of variance on Sisvar 5.6 (DEX/UFLA, 2015). Treatment means were compared using Tukey's test at $P \leq 0.05$ for each cultivar. All the data are reported as the means $\pm$ SE.

Results and Discussion

Cooling rates and weight gain/loss during cooling. The average initial pulp temperature was 21.1 ± 0.3 °C. For HY treatment, the 1/2 cooling time was 1.13 min for 'Emerald' and 1.19 min for 'Farthing' (Fig. 1). The 7/8 cooling time had a similar pattern to the 1/2 cooling time and ranged from 2.35 min for 'Emerald' to 2.63 min for 'Farthing' (Fig. 1). 'Farthing' showed slightly greater resistance to heat transfer when compared with 'Emerald', which may be related to the firmer texture of the former (Williamson et al., 2014). This rapid temperature reduction was due to the high thermal conductivity of the cooling water, the agitation of the ice/water mixture, and the uniform contact of the whole surface of the fruit (Brosnan and Sun, 2001; Liang et al., 2013). Teruel (2008) noted that high heat transfer rates from HY accelerated cooling times up to five times faster than FA; Ryall and Pentzer (1982) stated that cooling with ice water was 2–23 times faster than FA.

Five growing seasons of data for these cultivars from the University of Florida blueberry breeding program had slightly higher average fruit weights for these cultivars, although they were not significantly different from each other (2.59 g for 'Emerald' and 2.72 g for 'Farthing').

For the FA treatment, the 1/2 cooling times were 4.5 min for 'Emerald' and 6.8 min for 'Farthing'. 7/8 cooling times

Fig. 1. Pulp temperatures (A and C) and dimensionless temperature rates (TAT) (B and D) of 'Emerald' and 'Farthing' blueberry cultivars subjected to forced-air cooling (A and B) or hydrocooling (C and D) (0.125 kg clamshell). The (*) represents the temperature of the cooling medium at 1 °C and (–) represents the T_{1/2} and T_{7/8} cooling times.

were 9.6 and 16.3 min for 'Emerald' and 'Farthing', respectively (Fig. 1A and B). Fruit pulp in the FA reached the 7/8 cooling time in 16.3 min, whereas in the HY it was reached in ≈ 2.63 min (Fig. 1C and D). The variation between cultivars in the 1/2 cooling time may have been influenced by the cooling technology and by the cooling transfer rate, which can modify the cooling gradient speed of the product (Brosnan and Sun, 2001; Jacomino et al., 2011; Liang et al., 2013).

Carneiros et al. (2013) observed that FA cooling of strawberries in cold rooms may not be uniform because of the variability in the airflow characteristics. Individual strawberries ('Strawberry Festival') subjected to FA reached lowest temperatures at different times, depending on the position of the fruit within the clamshell. For blueberry fruit, the airflow rate can be influenced by several factors, including fruit size and thermal properties, as well as the affected ventilation area and the initial pulp temperature (Brosnan and Sun, 2001).

There were significant effects ($P \leq 0.05$) of treatment and storage time on weight for both cultivars. FA-cooled fruit lost an average of 1% of initial clamshell weight during cooling, whereas HY fruit gained up to 7% weight (Fig. 2). Fruit weight loss during postharvest handling is caused by the vapor

Fig. 2. Effect of hydrocooling, forced-air cooling, or hydrocooling + forced-air cooling on weight gain/loss (%) in 'Emerald' and 'Farthing' blueberry stored for 21 d at 1 °C after. Bars represent $\pm$ SE of means, and bars are invisible where values are smaller than the symbols ($n = 3$ replications; 10 fruit/replication). Tukey's honestly significant difference ($P < 0.05$) for weight gain/loss: treatments (T) = 0.000, storage periods (SP) = 0.000, and T $\times$ SP = 0.000.

pressure deficit between the fruit interstitial air space (100% RH) and the surrounding air (<100% RH), and by metabolic processes of respiration during postharvest handling and storage (Joo et al., 2011). Weight gain in HY fruit was mainly due to free water on the fruit surface, although small amounts may have been absorbed through the fruit stem scar. This is one of the main benefits of HY, the prevention of water loss during the cooling process (Gillies and Toivonen, 1995). The gain in fruit weight following HY was previously reported by Jacomino et al. (2011) for strawberries, where HY fruit gained >4% more weight than FA-cooled fruit due to the drier cooling environment of the latter.

During subsequent 21 d of storage, fruit weight remained fairly constant, irrespective of cultivar or cooling treatment. The exception was 'Emerald' fruit subjected to FA that lost weight; HY fruit maintained weight, being 3% heavier than HY + FA after 21 d (Fig. 2). Hydrocooled strawberries lost less weight than the fruit subjected to FA, and even gained weight when stored in packages (Ferreira et al., 2006).

'Farthing' fruit subjected to FA lost $\approx 1\%$ more fresh weight during storage than 'Emerald' (Fig. 2). Losses can be influenced by some characteristics of the cultivar, such as epicarp permeability, respiratory process, or surface/volume ratio. Cantin et al. (2012) reported that 'Emerald' lost up to 3% of its weight after 35 d of cold storage at 1 °C, whereas 'Snow' and 'Star' lost 6% to 7%; in the present study, these losses were not evident throughout the first 21 d of storage.

Freshness rating, bloom coverage, decay, and bruising. Significant differences ($P \leq 0.05$) were observed in freshness ratings among treatments for both cultivars (Fig. 3A). Blueberry from all cooling treatments maintained excellent overall fresh appearance (freshness rating >8.5) for 7 d at 1 °C/80% RH for both cultivars and for 14 d for 'Farthing' (Fig. 3A). 'Emerald' fruit was minimally acceptable in freshness after 14 d (>5.0); FA-cooled fruit was rated significantly higher (6.5) than either HY- or HY + FA-treated fruit (Fig. 3A). After 21 d, FA-treated 'Farthing' fruit retained excellent freshness rating, and HY and HY + FA fruit were rated as moderately acceptable (6.6) (Fig. 3A). HY-treated 'Emerald' fruit was rated unacceptable after 21 d (Fig. 3A). The decrease in the freshness rating is associated with several factors, such as water loss, mechanical injuries, changes in the epicuticular wax and decay (Jacomino et al., 2011).

In this study, the freshness rating was also related to bloom conservation, which was evaluated according to the percent of surface area coverage (Fig. 3B). There were no significant differences in bloom among treatments for both cultivars, nor was there a significant effect of storage period on 'Farthing' (Fig. 3B). Bloom ratings remained >4.5 throughout 21 d of storage for all treatments and for both cultivars with the exception of 'Farthing' cooled by HY or HY + FA (3.7). Although 'Emerald' had greater

Fig. 3. Effect of hydrocooling, forced-air cooling, or hydrocooling + forced-air cooling on fresh appearance rating (A), bloom rating (B) bruising incidence (C) for 'Emerald' and 'Farthing' blueberry stored for 21 d at 1 °C. A: Rating scale from 9 = excellent (completely fresh appearance, high sheen) to 1 = extremely poor (shriveled appearance). B: Rating scale (5 = 81% to 100%; 4 = 61% to 80%; 3 = 41% to 60%; 2 = 21% to 40%; 1 = 0% to 20%). Vertical bars represent $\pm$ SE of means, and bars are invisible where values are smaller than the symbols ($n = 3$ replications; 10 fruit/replication). Tukey's honestly significant difference ($P < 0.05$) for appearance and freshness: treatments (T) = 0.000, storage periods (SP) = 0.000, and T $\times$ SP = 0.000; Bloom: treatments (T) = 0.010, SP = 0.000, and T $\times$ SP = 0.680; Bruising: treatments (T) = 0.000, SP = 0.000, and T $\times$ SP = 0.001.

loss in fresh appearance, this cultivar maintained up to 25% higher bloom coverage compared with 'Farthing' at the end of the storage period (Fig. 3B).

There were significant effects of treatment on fruit bruising rating in both cultivars after 7 d of storage (Fig. 3C). Fruit bruising was generally lower in HY and HY + FA treatments, although 'Emerald' showed more bruising (15%) after 7 d because of its higher fragility as compared with 'Farthing' (Fig. 3C). Fresh fruit bruising is a concern due to the impact bruising that occurs during harvest and handling (Demir et al., 2011).

Because of this characteristic and to high water absorption during HY, 'Emerald' fruit cooled by HY or HY + FA showed visual skin breaks (splits) in $\approx 15\%$ of fruit after 7 d of storage. There were no visual skin breaks in 'Farthing' fruit. It was inferred that these breaks were caused by rapid water absorption, with an increase of turgor pressure that exceeded the expansion capability of the blueberry pericarp (Wang and Long, 2015).

Although blueberry is naturally susceptible to infection by microorganisms (Lacombe et al., 2015), fruit in the present tests developed no visible decay during the 21-d storage period for any of the cooling methods (data not shown). The cooling treatments and low storage temperature minimized conditions necessary to favor pathogen growth; fruit surfaces were dry following FA and HY + FA, although the sanitized water in HY has been shown to lower pathogen load on fruit surfaces (Sreedharan et al., 2015).

Pulp firmness, SSC, pH, and titratable acidity. Regardless of the cooling method, blueberry firmness was higher after 7 d ('Farthing') and 14 d ('Emerald') of storage, then fruit gradually softened (Table 1). For 'Farthing', firmness was not significantly affected by cooling method (data not shown); there was a slight softening after 21 d (Table 1). For 'Emerald', only HY+FA fruit softened after 14 d, unlike those cooled by HY or FA, which maintained firmness during storage (Table 1).

Firmness is a significant indicator of quality for blueberry, and its loss is one of the main limiting factors for the marketing of the fresh fruit (Angeletti et al., 2010). Variations in firmness may be attributed to cultivars and to the interaction with postharvest storage conditions (Chiabrando et al., 2009).

Fruit softening has been attributed to the changes in cellular substances, such as pectin, cellulose, and other polysaccharides, and this effect is generally associated with fruit ripening (Joo et al., 2011; Sharma and Singh, 2000). On the other hand, fruit water loss can lead to fruit hardening. The possible reason is that the change in "skin texture" could increase mechanical resistance of the epidermis, which can affect the overall fruit firmness (Jackman and Stanley, 1992). However, as reported by Paniagua et al. (2013) moisture loss is the major cause of softening during postharvest storage of blueberry and that, once the fruit has lost 1.5% to 2.0%, there is a linear drop in firmness thereafter. Nev-

ertheless, these authors stated that further research in critical variables such as turgor, skin toughness, and cell wall modifications may elucidate the mechanism for this relationship between moisture loss and firmness.

For 'Farthing', SSC, pH and TTA were not significantly affected by any of the three cooling methods, nor by storage time (Table 1). 'Emerald' fruit had higher SSC than 'Farthing' (Table 1). TTA statistically varied only for 'Emerald' fruit cooled by FA, increasing after the first week then remaining stable (0.5%) until the end of the stor-

age period. The pH essentially mirrored TTA and for 'Emerald' was slightly higher than that for 'Farthing'; pH remained fairly constant for both cultivars throughout storage (Table 1).

Total anthocyanin content. 'Emerald' had higher initial anthocyanin concentration (ANTH) than 'Farthing' but from 14 to 21 d it decreased (Table 2). 'Farthing' ANTH was unaffected by cooling treatment or storage period (Table 2). For 'Emerald' fruit cooled by HY + FA, ANTH remained constant for up to 14 d; however, at 21 d of storage, fruit from this

Table 1. Effect of hydrocooling (HY), forced-air cooling (FA), or hydrocooling plus forced-air cooling (HY + FA) on firmness, SSC, TTA, and pH of 'Emerald' and 'Farthing' blueberry during storage for 21 d at 1 °C and 80% relative humidity.

Treatment	Storage period (Days)			
	0	7	14	21
Firmness (N)				
Emerald				
HY	2.78 aA ^z	2.36 aA	2.39 aA	2.73 aA
FA	2.78 aA	2.49 aA	2.40 aA	2.80 aA
HY + FA	2.78 aA	2.33 aAB	2.24 aB	2.18 bB
Farthing				
HY	3.56 aA	3.63 aA	3.36 aA	2.81 aB
FA	3.55 aA	3.58 aA	3.42 aAB	3.07aB
HY + FA	3.56 aA	3.55 aA	3.59 aA	2.95 aB
SSC (%)				
Emerald				
HY	10.2 aB	10.6 aB	10.8 aB	11.7 aA
FA	10.4 aBC	10.2 aC	11.2 aAB	11.5 aA
HY + FA	10.1 aC	10.3 aBC	11.2 aA	11.2 aAB
Farthing				
HY	9.2 aA	8.9 aA	9.4 aA	9.3 aA
FA	9.81 aA	9.4 aA	9.4 aA	9.8 aA
HY + FA	9.4 aA	9.6 aA	9.3 aA	9.8 aA
TTA (% citric acid)				
Emerald				
HY	0.40 aA	0.36 aA	0.40 bA	0.38 bA
FA	0.38 aBC	0.37 aC	0.50 aA	0.49 aAB
HY + FA	0.34 aA	0.41 aA	0.36 bA	0.42 abA
Farthing				
HY	0.65 aA	0.65 aA	0.66 aA	0.61 aA
FA	0.61 aA	0.60 aA	0.63 aA	0.65 aA
HY + FA	0.60 aA	0.60 aA	0.65 aA	0.66 aA
pH				
Emerald				
HY	3.7 aA	3.8 aA	3.8 aA	3.9 aA
FA	3.8 aA	3.8 aA	3.6 bB	3.6 bAB
HY + FA	3.8 aAB	3.7 aB	3.8 aA	3.7 abAB
Farthing				
HY	3.2 aA	3.3 aA	3.3 aA	3.3 aA
FA	3.3 aA	3.3 aA	3.3 aA	3.3 aA
HY + FA	3.3 aA	3.3 aA	3.3 aA	3.3 aA

^zDifferent letters indicate significant differences according to the Tukey's test at $P \leq 0.05$. For each cultivar, lowercase letters in columns indicate differences between treatments; uppercase letters in rows indicate differences during storage for each treatment.

SSC = soluble solids content; TTA = total titratable acidity.

Table 2. Effect of hydrocooling (HY), forced-air cooling (FA), or hydrocooling plus forced-air cooling (HY + FA) on anthocyanin concentration of 'Emerald' and 'Farthing' blueberry during storage for 21 d at 1 °C and 80% relative humidity.

Treatments	Anthocyanin (mg 100 g ⁻¹)			
	Storage Period (Days)			
	0	7	14	21
Emerald				
HY	9.09 abA ^z	8.86 bA	8.41 bA	7.72 aA
FA	8.61 bAB	6.90 bB	10.99 aB	7.10 aB
HY + FA	10.93 aA	10.51 aA	11.42 aA	6.32 aB
Farthing				
HY	7.68 aA	6.52 aA	7.33 aA	6.92 aA
FA	7.38 aA	6.87 aA	7.52 aA	7.23 aA
HY + FA	6.86 aA	8.34 aA	6.97 aA	7.18 aA

^zDifferent letters indicate significant differences according to the Tukey's test at $P \leq 0.05$. For each cultivar, lowercase letters in columns indicate differences between treatments; uppercase letters in rows indicate differences during storage for each treatment.

treatment had the lowest concentration. ANTH for HY fruit decreased from 9.1 to 7.7 mg pelargonidin-3-glucoside (PGN)/100 g during 21 d storage, whereas fruit cooled by FA or HY + FA, decreased by 15%, 18%, or 42%, respectively (Table 2).

Anthocyanins are water-soluble glycosides with high therapeutic value and are also responsible for the coloring of fruits (Norberto et al., 2013). Basiouny (1995) and Joo et al. (2011) observed a reduction in total ANTH in blackberries during 18 d stored at 3 °C. It is believed that anthocyanins polymerize during storage; additionally, oxidative reactions caused by enzymatic activity could have resulted in anthocyanins degradation (Reque et al., 2014), although the conditions used in this study cannot identify the activities mentioned.

Conclusions

Fruit quality plays an important role in determining consumer acceptance, and the three cooling methods affected the quality of the two blueberry cultivars analyzed in this study. For HY treatment, the 1/2 cooling time was 1.13 min for 'Emerald' and 1.19 min for 'Farthing', whereas for the FA treatment, the 1/2 cooling times were 4.5 and 6.8 min, respectively. No decay was observed for either cultivar or cooling method during storage. 'Farthing' maintained more uniform quality in all cooling treatments during storage but with lower bloom rating. Compared with 'Farthing', 'Emerald' was more sensitive to HY, where $\approx 15\%$ of fruit developed visual skin splits after 7 d of storage. 'Emerald' fruit also had significant differences ($P \leq 0.05$) in freshness rating, but were less acidic (0.3% citric acid), had higher bloom rating (>4.5), and were sweeter (10.2% SSC). The anthocyanin concentration for 'Emerald' decreased by 33% during storage, when cooled by HY + FA, whereas it remained constant for 'Farthing' in all treatments. According to the data obtained in this work for 'Farthing' fruit, HY showed potential as an alternative method to rapidly cool and sanitize in blueberries packed in clamshells, thus, maintaining the quality of fruit and reducing postharvest losses. For 'Emerald' fruit, splitting could be a limiting factor for adoption of HY; other commercially grown southern highbush blueberry cultivars should be investigated for their tendency to split.

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