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Comparison of Three Cooling Methods (Hydrocooling, Forced-Air Cooling and Slush Icing) and Plastic Overwrap on Broccoli Quality during Simulated Commercial Handling

Carina Theodore [1], Steven A. Sargent [1,*], Jeffrey K. Brecht [1], Lincoln Zotarelli [1] and Adrian D. Berry [1]

Horticultural Sciences Department, University of Florida/IFAS, Gainesville, FL 32611, USA
* Correspondence: sasa@ufl.edu; Tel.: +1-352-273-4780

Abstract: Broccoli is a highly perishable crop, due to its high respiration rate, and rapidly loses quality under inappropriate handling temperatures. The objective of this study was to evaluate the effect of commercial hydrocooling (HY), forced-air cooling (FA) or slushed-ice cooling (SI) on the quality and shelf-life of two commercial broccoli cultivars ('Marathon' and 'Eastern Crown') grown in northeast Florida during the early spring season. Following HY and FA, individual bunches ('Marathon') or crowns ('Eastern Crown') were placed in plastic film bags and stored at 1 °C for 7 days then transferred to 5 °C for 8 days to simulate retail conditions. It was found that HY removed the field heat 3.6 and 4.8 times faster than FA and SI, respectively. For both cultivars, using a texture analyzer, broccoli cooled by SI were softer (20.4 to 27.9 N) with higher head deformation than those by HY or FA (45.6 to 58.9 N) after 15 days of storage. Overall appearance of both cultivars decreased during storage if infected in the field by the fungal pathogen *Alternaria brassicicola*, which causes black spot disease. However, by the end of storage 'Eastern Crown' had a higher quality rating (6.2) than 'Marathon' (5.4). Broccoli floret moisture content was not affected during storage; however, 'Marathon' had higher moisture content (94.7%) than 'Eastern Crown' (89.2%). Yellowing was expressed more for 'Marathon', which had higher chroma* value (21.4) and lower hue* angle (h*) (122.3) value than 'Eastern Crown' after 7 days at 1 °C, plus 8 days at 5 °C. Carotenoid content was similar for both cultivars at harvest (2.3 mg/100 g) then decreased 39% for 'Marathon' and 12% for 'Eastern Crown' by day 15. Total chlorophyll was similar for both cultivars throughout storage (22.6 mg/100 g). Ascorbic acid decreased for both cultivars during storage but was higher in 'Eastern Crown' (92.0 to 101.9 mg/100 g) compared to 'Marathon' (80.7 to 88.6 mg/100 g). Hydrocooling and forced-air plus overwrapping have potential to reduce cooling costs during commercial handling.

Keywords: shelf-life; postharvest; firmness; nutrition

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1. Introduction

Broccoli (*Brassica oleracea* L.) is a brassica vegetable mostly cultivated in temperate areas. It is a highly nutritious vegetable, and its production has been increasing in the USA. Broccoli contains high levels of phytochemical compounds soluble fiber, and many nutrients, including β-carotene, vitamin C (ascorbate), vitamin K, calcium and potassium. It also contains minor amounts of thiamine, riboflavin, folate, vitamin E, and vitamin B6 [1]). In 2022, broccoli was listed in the top 6 for vegetables purchased by consumers [2]. Per capita consumption of broccoli increased from 0.64 kg in 1980 to 2.68 kg in 2021 [3]. California (CA) is the major producer of broccoli in the USA with around 90% of the total production and Monterey County, CA produces 40% of this total due to its ideal climate, which allows for constant production throughout the year [4]. According to the latest data available, [5], in 2010, Florida produced approximately 500 ha of broccoli on 52 farms for late fall, winter and spring seasons, while California produced about 12,000 ha on 416 farms each season. For eastern USA states seasonal production of broccoli is limited. Despite the environmental challenges, broccoli production along the east coast continues to increase.

Sprouting broccoli, also called Italica group, is the most common commercial type, and the heads consist of a crown formed by dense, green florets that sprout from a thick edible stalk [6,7]. Fresh market broccoli is commercially harvested in the USA as bunched or crown heads and while the florets are dark or bright green in color and still tightly closed [8]. For bunches, the heads are harvested with smaller head diameters and 2 or 3 stalks of 18 cm length are bound together and sold as a single unit. In contrast, broccoli crowns have larger head diameters (10 to 15 cm), shorter, compact florets and thicker stalk diameter, and are cut at 13 cm long. Florets are also trimmed for either fresh-cut or frozen markets.

Broccoli is a very perishable crop and its quality is dependent upon the handling procedures after harvest. Rapid removal of field heat is the primary step to maximize postharvest quality and shelf life, with proper temperature and relative humidity management being critical during subsequent handling operations [9]. Optimal conditions are 0 °C to 1 °C and high relative humidity (RH) (98% to 100%) to maintain green color and to minimize moisture and texture loss [10]. However, these recommended conditions are difficult to maintain throughout distribution; Deschene et al. [11] reported that chlorophyll content declined 80–90% after 10 days, at 10 °C, or after 4 days, at 23 °C. Previous studies have reported positive effects of several handling technologies on extending quality during handling and storage, such as plastic films, modified atmosphere packaging, 1-methylcyclopropene (1-MCP) and controlled atmosphere storage [12–14]. A comparison of vacuum cooling and package icing determined that both cooled adequately, but the latter maintained higher quality after 12 days, at 1 °C, and 85% RH [15].

According to Thompson et al. [16], most commercial broccoli growers use slush icing (SI) to cool broccoli heads after harvest even though the capital and operating costs for SI are high and the energy efficiency is low. They also noted that top icing cooled crops more slowly than forced-air cooling. Using other lower-cost cooling methods could help growers reduce operating expenses while conserving resources.

The aim of this study was to compare three cooling methods (hydrocooling, forced-air cooling and slush icing) on the quality of two commercial broccoli cultivars during storage under simulated commercial wholesale (1 °C) and retail conditions (5 °C). This research is a part of the master's thesis of Carina Theodore.

2. Materials and Methods

2.1. Cooling Treatments

Two tests were conducted with broccoli cultivars commercially harvested and field-packed in Hastings, FL, USA, on 12 February 2019 ('Marathon') and 26 March 2019 ('Eastern Crown') (Sakata Seed America, Morgan Hill, CA, USA). As recommended by the packer, 'Marathon' was cut, tied in bunches (18 cm long, 2 to 3 stalks/bunch) and packed 14 bunches per reusable plastic container (RPC), while 'Eastern Crown' was cut as crowns (13 cm long) and packed 24 to 30 heads per waxed, corrugated carton. RPC and carton volumes were standard 1 1/9 bushel (35.2 L). Stalk diameters averaged 3.2 cm for both cultivars. Shortly after harvest, the containers were transported to the nearby cooling facility. The cooling treatments were designed to achieve commercially recommended 7/8 Cooling (Thompson et al., 2008), and for each cooling method, pulp temperatures were recorded by inserting a digital probe (Pod Probe, PE1, Verigo Gainesville, FL, USA) 2 to 3 cm into the center of the cut end of three stalks. The calculated 7/8 cooling temperature was 2 °C for each cooling method.

For hydrocooling (HY), individual broccoli heads were immersed and agitated for 25 min in sanitized water (0 °C to 1 °C, 100 to 200 ppm free chlorine and pH 6.5 to 7.0), then shaken to remove excess water and immediately placed in individual plastic bags (Model S-19156, Uline, Pleasant Prairie, WI, USA), then packed into waxed, corrugated cartons. For the pallet-scale slush icing (SI) treatment, three test cartons of 'Marathon' were substituted for cartons on an existing pallet of 48 cartons, while for 'Eastern Crown', only the three cartons were placed on a single pallet; the commercial injection cycle (Post-Harvest

Technologies, Salinas, Calif.) was approximately 1 min, and uniform distribution of the crushed ice was verified in each treated carton. Forced-air cooling (FA) was accomplished using the commercial-scale tunnel system at the collaborator's facility. Six pallets were arranged in two rows with approximately 0.6 m gap between them; there were 35 RPCs per pallet for 'Marathon' and 48 cartons per pallet for 'Eastern Crown'. A tarp was lowered over the gap forming the tunnel. Ten broccoli bunches ('Marathon') or crowns ('Eastern Crown') were weighed before and after cooling to determine weight loss. Pulp temperatures (n = 6) were monitored to ensure 7/8 cooling was achieved. After FA cooling individual bunches and crowns were overwrapped with the same plastic bags used for the HY treatment and placed to fill three cartons for each cultivar. Cartons from the three cooling treatments were stored at 1 °C/95 to 100% relative humidity (RH) for 7 days in the grower's facility.

For initial analyses, a single hydrocooled carton of each cultivar was transported on the day of harvest under chilled conditions to the Postharvest Horticulture Laboratory at the University of Florida, Gainesville, and stored overnight, at 1 °C. The following day, broccoli heads were sorted for quality and allowed to reach ambient temperature before conducting evaluations. Samples stored at the grower's facility were retrieved after 7 days, transported to Gainesville in iced coolers, stored overnight at 1 °C, then transferred the next day to 5 °C/95 to 100% RH for an additional 8 days to simulate commercial handling. Quality evaluations were conducted initially and after 7 days, at 1 °C, and after 4 and 8 days, at 5 °C. Temperature was maintained using refrigerated chambers (CMP 6050, Conviron, Winnipeg, MB, Canada) equipped with a humidification system (ES100, Smart fog, Reno, NV, USA).

2.2. Nondestructive Analyses

Overall appearance was subjectively rated (n = 10) as described by Kader and Cantwell [17], employing a scale from 1 (lowest) to 9 (highest quality); a rating of 5 was considered the limit of marketability. Floret color was measured (3/head) using a Minolta colorimeter (CR-400, Konica Minolta, Tokyo, Japan) with D65 illuminant and L* C* h* color space. In this system, L* refers to lightness (0 = black, 100 = white), C* is the chroma* value which indicates color saturation and h* is hue* angle (yellow = 90°, green = 180°) [18]. Broccoli head and stalk diameters were measured for each cultivar (n = 5). It was not possible to accurately determine weight loss during storage due to presence of free moisture on the broccoli in the SI treatments or in the overwrapped HY and FA treatments.

2.3. Destructive Analyses

Crown firmness was measured using a Texture Analyzer (model TA. HDPlus, Texture Technologies Corp, NY, USA) equipped with a 50-N load cell. The stalk of each broccoli head (n = 10) was trimmed such that the upright crown was supported evenly by the cut stalk surface. The crown was then compressed using a flat plate (75 mm diameter) at a crosshead speed of 2 mm/s; the deformation force (Newton, N) was recorded at 7.5 mm depth. Moisture content (fresh weight basis, FW) was determined separately for floret and stalk tissues (n = 4) following drying.

Total chlorophyll content was determined from broccoli florets (n = 4) by absorbance (a = 666 nm; b = 653 nm) (BioTek Power wave XS2, BioTek instruments Inc., Highland Park, IL, USA) according to Wellburn [19]. Ascorbic acid (AA) content was determined by absorbance at 540 nm according to Terada et al. [20], and total carotenoids were determined at 470 nm according to Talcott and Howard [21].

2.4. Statistical Analyses

The experiments were conducted using a completely randomized design. The data were analyzed using a three-way ANOVA followed by means separation using Tukey's honestly significant difference test at $p \leq 0.05$. (SAS 9.4; SAS Institute Inc., Cary, NC, USA).

3. Results

3.1. Nondestructive Analyses

Cooling times for broccoli to achieve 7/8 cooling varied by cooling method and were considered normal. HY was the fastest method at 25 min, whereas FA and SI required 90 min and 140 min, respectively (data not shown).

Analysis of variance showed three-way interactions between cooling method, cultivar and storage period for crown firmness and carotenoid content. Other parameters showed differences by cultivar.

Overall appearance ratings for both cultivars declined significantly at each evaluation during storage, but there were no significant differences due to cooling method. 'Eastern Crown' was consistently rated higher than 'Marathon', and even after the transfer to 5 °C for 8 days, overall appearance was still rated as acceptable (6.2 and 5.4, respectively) (Table 1). The overall appearance of these cultivars decreased during storage as a result of slight preharvest infections by the fungus *Alternaria brassicicola*, most likely due to a period of excessive rain in December 2018 for 'Marathon' and a brief frost period during the later growing season for 'Eastern Crown'. Disease incidence was higher in 'Marathon', which had a larger crown than 'Eastern Crown', potentially favoring proliferation of the pathogen (data not shown).

Table 1. Overall appearance ratings, chroma (C*) value and hue angle (h*) for 'Eastern Crown' and. 'Marathon', combined for all cooling methods, during storage for 7 days at 1 °C plus 8 days at 5 °C.

Cultivar	Day 0	Day 7	Day 11	Day 15
	Overall appearance rating			
Marathon	8.7 bA [z]	7.4 bB	6.4 bC	5.4 bD
Eastern Crown	9.0 aA	7.8 aB	6.9 aC	6.2 aD
	Chroma (C*) [y]			
Marathon	23.1 aA	23.1 aA	21.7 aA	21.4 aA
Eastern Crown	16.2 bA	16.9 bA	16.3 bA	17.1 bA
	Hue angle (h*) [y]			
Marathon	121.8 bB	122.7 bAB	123.4 bA	122.3 bB
Eastern Crown	129.7 aAB	128.9 aBC	130.0 aA	128.1 aC

[z] Means within a column followed by the same lowercase letter at each given storage time, or by the same uppercase letter within a row at the same level of storage condition do not differ significantly according to Tukey's Test ($p < 0.05$). [y] Chroma value indicates color saturation and hue angle of 90° = yellow and 180° = green.

Cooling treatment and storage regime did not affect broccoli color. L* value remained similar throughout storage regardless of cooling treatment for 'Marathon' (42.1) and 'Eastern Crown' (41.9) (data not shown). Chroma* values (C*) and hue* angles (h*) remained constant throughout storage period for both cultivars. 'Marathon' had higher C* (23.1) and lower h* (121.8°) than 'Eastern Crown' (16.2 and 129.7°, respectively) which means it was lighter green in appearance (Table 1).

3.2. Destructive Analyses

Moisture content only differed by cultivar, not by the cooling treatment or storage period. After 15 days of storage, 'Marathon' had significantly higher moisture content (stalk = 94.7% and floret = 91.0%) compared to 'Eastern Crown' (stalk = 92.2% and floret = 89.2%) (data not shown).

FA and HY broccoli remained firmer during storage than SI broccoli. FA and HY 'Marathon' softened slightly to 47.6 N by day 11 and remained firm until day 15; SI broccoli was firm at day 7, but four days after the transfer to 5 °C (day 11), it softened to 20.7 N. HY or FA 'Eastern Crown' remained firm until day 15 (58.9 N and 52.2 N, respectively), while SI broccoli softened to approximately 1/3 of initial firmness (25.7 N) during storage at 1 °C, by day 7 (Table 2).

Table 2. Compression force for 'Eastern Crown' and 'Marathon' hydrocooled, forced-air cooled and slush ice cooled, then stored for 7 days at 1 °C plus 8 days at 5 °C.

Cultivar	Cooling Method [z]	Compression Force (N) during Storage			
		Day 0	Day 7	Day 11	Day 15
Marathon	HY	68.8 aA [y]	56.1 aAB	47.3 aB	49.8 aB
	FA	68.8 aA	55.9 aAB	47.9 aB	45.6 aB
	SI	68.8 aA	52.5 aB	20.7 bC	27.9 bC
Eastern Crown	HY	64.9 aA	66.9 aA	69.6 aA	58.9 aA
	FA	64.9 aA	52.7 aAB	50.5 bB	52.2 aAB
	SI	64.9 aA	25.7 bB	28.2 cB	20.4 bB

[z] Cooling method: HY = hydrocooling + plastic wrap, FA = forced-air + plastic wrap, SI = slush-iced. [y] Means within a column followed by the same lower-case letter at each given storage time, or by the same uppercase letter within a row at the same level of storage condition do not differ significantly according to Tukey's Test ($p < 0.05$).

At harvest, total carotenoids content was similar for both cultivars (2.3 mg/100 g) and was not significantly affected by cooling method. Carotenoids decreased 40% for 'Marathon' and 20% for 'Eastern Crown' after 7 d, at 1 °C. However, following the transfer to 5 °C, there was little change, and by day 15, carotenoid content averaged 1.4 mg/100 g for 'Marathon' and 2.0 mg/100 g for 'Eastern Crown' (Table 3).

Table 3. Total carotenoids content of 'Eastern Crown' and 'Marathon' hydrocooled, forced-air cooled or slush-iced and stored for 7 days at 1 °C plus 8 days at 5 °C.

Cultivar	Cooling Method [z]	Total Carotenoid Content (mg/100 g FW)			
		Day 0	Day 7	Day 11	Day 15
Marathon	HY	2.28 aA [y]	1.25 aB	1.44 abB	1.04 cB
	FA	2.28 aA	1.38 aB	1.55 aB	1.40 bB
	SI	2.28 aA	1.48 aB	0.98 bC	1.70 aB
Eastern Crown	HY	2.26 aA	1.65 aB	1.70 bB	2.03 aAB
	FA	2.26 aA	1.72 aB	2.12 abAB	1.95 aAB
	SI	2.26 aAB	2.04 aB	2.76 aA	1.95 aB

[z] Cooling methods: HY = hydrocooling + plastic wrap, FA = forced-air + plastic wrap, SI = slush-iced. [y] Means within a column followed by the same lowercase letter at each given storage time, or by the same uppercase letter within a row at the same level of storage condition do not differ significantly according to Tukey's Test ($p < 0.05$).

There was no effect of cooling method on chlorophyll content. Although 'Marathon' initially had slightly higher total chlorophyll content than 'Eastern Crown' (25.8 mg/100 g FW versus 20.7 mg/100 g), by day 7, this value decreased equal to that of 'Eastern Crown' and remained constant through day 15 (Table 4).

Table 4. Total chlorophyll and ascorbic acid content for 'Eastern Crown' and 'Marathon' combined for cooling method during storage at 1 °C plus 8 days at 5 °C.

Cultivar	Day 0	Day 7	Day 11	Day 15
	Total Chlorophyll (mg/100 g FW)			
Marathon	25.8 aA [z]	20.7 aB	23.3 aB	23.7 aB
Eastern Crown	20.7 bA	19.7 aA	23.9 aA	22.8 aA
	Ascorbic acid (mg/100 g FW)			
Marathon	88.6 bA	87.2 bA	89.7 bA	80.7 bB
Eastern Crown	101.9 aA	101.5 aA	96.6 aAB	92.0 aB

[z] Means within a column followed by the same lowercase letter at each given storage time, or by the same uppercase letter within a row at the same level of storage condition do not differ significantly according to Tukey's Test ($p < 0.05$).

With regard to ascorbic acid content (AA), there were no cooling treatment differences for either cultivar; however, 'Eastern Crown' had significantly higher initial ascorbic acid

(AA) content than 'Marathon' (101.9 and 88.6 mg/100 g FW, respectively) and throughout storage (Table 4). By day 15, both cultivars had a significant loss of AA compared to freshly harvested broccoli (80.7 and 92.0 mg/100 g FW).

4. Discussion

Cooling broccoli immediately after harvest is critical for reducing metabolic activities that accelerate the rate of deterioration leading to floret yellowing and opening. Toivonen [12] showed that hydrocooling broccoli within 2 h of harvest and wrapping with micro-perforated film maintained better color and firmness during storage at 1 °C when compared to unwrapped.

Rangkadilok et al. [22] found that broccoli stored at 4 °C retained green color for 7 days, while Toivonen and Sweeney [23] concluded that change in broccoli color is dependent on cultivar and storage temperature. In the current study, color did not change during storage; however, there were minor differences between cultivars.

Storage temperature is also critical; Heyes et al. [9] reported that broccoli florets lost 75% of the moisture content during the first 24 h when stored at 20 °C. According to Singh et al. [24], moisture content of broccoli stored at 3 °C/90–95% RH decreased 6% for packaged and 54% for unwrapped after storage for 49 days. Galgano et al. [25] reported a 10% reduction in moisture content for unwrapped broccoli stored in wooden boxes for 35 days, at 6 °C/95% RH. This demonstrates the critical importance of maintaining low temperature and high RH to conserve moisture content in broccoli during commercial handling. However, in the current study, there was no difference in moisture content regardless of cooling method during storage at 1 °C/95% RH plus 8 days at 5 °C/95% RH.

Since 7/8 cooling times for FA and HY differed by only 30 min, maintenance of crown firmness was most likely attributed to the plastic overwrap by preventing moisture loss during FA and thereafter maintaining a high RH environment around the FA and HY broccoli during storage. Since the ice in the SI treatment completely melted during storage, the benefit of humidification decreased over time. Toivonen [12] also found that broccoli firmness was retained better when hydrocooled and wrapped then stored at 1 or 5 °C.

Barth and Zhuang [26] noted carotenoid content decreased in broccoli during 6 days of storage, at 5 °C. However, Gross [27] reported that carotenoid content in vegetables can fluctuate during storage depending on the physiological maturity at harvest, meaning that carotenoid content can decrease during senescence. Thus, the decrease in carotenoid content during storage for both broccoli cultivars was most likely a consequence of senescence.

Yellowing occurs from loss of chlorophyll and is one of the main factors contributing to loss of postharvest quality in broccoli [28]. Storing broccoli at low temperature enhances phenolic compounds, which implies the inhibition of enzymes responsible for breakdown of chlorophyll, such as lipoxygenase and peroxidase [12,29]. In the present tests, despite a decrease in total chlorophyll content for 'Marathon' by day 7, hue angle remained constant throughout storage and was consistent with visible color assessments. Raseetha and Nadira [30] reported that broccoli stored in plastic bags (unspecified composition) yellowed at a slower rate than that stored in shrink wrap or plain white paper after 21 days, at 8–10 °C.

AA is a highly nutritional compound in broccoli, due to its antioxidant content and free radical scavenging activities, which plays an important role in the human diet [31]. However, AA can decrease under less-than-ideal handling and storage conditions [32]. Ballantyne et al. [33] associated losses in AA with the alteration of the cellular integrity due to dehydration, which consequently increased the oxidase enzyme activities. Additionally, Lee and Kader [32] reported that factors such as genotype can cause variations in AA content. With the conditions of this test, both broccoli cultivars experienced a significant reduction in AA after 15 days.

5. Conclusions

Cooling treatments are critical after harvest to reduce metabolic activities and subsequent deterioration of broccoli during storage. This study confirmed that hydrocooling or forced-air cooling with overwrapping can extend the quality of broccoli under simulated commercial handling conditions at 1 °C, followed by the transfer to 5 °C, as compared with slush icing. Hydrocooling removed the field heat 3.6 and 4.8 times faster than forced-air cooling and slush icing, respectively. Each commercial cultivar had distinct characteristics: 'Marathon' had considerably larger head diameter (14.7 cm) than 'Eastern Crown', but the stem thickness was similar for both cultivars. Both cultivars decreased in subjective and objective firmness during storage irrespective of the cooling treatment, but crowns that were hydrocooled or forced-air cooled with overwrapping maintained better head compactness and had less softening during storage. Overall appearance of these cultivars was negatively affected by the presence of *Alternaria brassicicola* at harvest, which proliferated during storage regardless of cooling treatment. During simulated retail handling, the overall appearance declined considerably for 'Marathon', which was more affected by the latent fungal infection. 'Marathon' had higher moisture content than 'Eastern Crown' throughout storage; however, it was not affected by the cooling method. 'Marathon' was more susceptible to yellowing as shown by higher C* and lower h*. Furthermore, chlorophyll, carotenoid and AA content were not affected by cooling method. Hydrocooling and forced-air plus overwrapping have the potential to reduce cooling costs while maintaining quality longer for retailers and eliminating the melting ice of slush-iced broccoli during handling and transport. Further studies could determine the effects of longer storage on the sensory quality of broccoli and evaluate the actual costs of these methods.

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