Forced air cooling system for *Zea mays*

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Abstract

Three cultivars of sweet corn were precooled immediately after harvest using a forced-air cooler system. Combinations of two air flow rates, 1 and 3 $L \cdot s^{-1} \cdot kg^{-1}$ of produce, and two cob orientations, parallel and perpendicular to the air flow were tested. Both precooled and room cooled corn cobs were stored for 7 and 21 days at 1°C and 90-95% RH. Half cooling time and quality attributes were measured to assess the performance of the forced-air cooler compared to room cooling. Higher air flow rate (3 $L \cdot s^{-1} \cdot kg^{-1}$) and perpendicular orientation of corn cobs reduced significantly the cooling time. On the other hand, forced-air precooling extended the storage life of sweet corn cobs for a period of 21 days by conserving high total soluble solids and moisture content and maintaining fairly good general quality. The three cultivars of sweet corn were shown to be different in their keeping quality over time.

Key words: Cultivar, sweet corn, precooling, forced-air, air flow rate, cob orientation, half cooling time, performance and keeping quality.

Introduction

Sweet corn or *Zea mays* L. spp. *saccharata* is recognized as an important horticultural crop in North America. After harvest, its metabolism continues to use its energy to maintain its essential living function. Due to its high perishability, an adequate control of the corn cob temperature remains essential to extend its quality life. Thus, sweet corn must be precooled, or cooled down quickly as soon as possible after harvesting, and maintained at low temperature during storage to protect its quality and marketability[1].

Precooling may be accomplished using several techniques including forced-air, water, liquid ice and vacuum [2]. All these methods are widely used and the selection of the most appropriate one is based on several parameters including the rate of cooling, the nature of the commodity and the container, further storage and shipping conditions, and the capital and labour costs [2, 3]. For example: vacuum cooling is best suited for leafy vegetables with high surface-to-mass ratio; and hydrocooling and liquid icing can not be used for high moisture sensitive container [4] or produce [2].

Studies have shown that forced-air precooling can be adapted to a wide range of horticultural crops such as berries, citrus and cut flowers. Commercial forced-air is the most important precooling technology during horticultural crop postharvest processes in North America [2]. During forced-air cooling process, cold air is pulled through individual produce container rather than around container unit resulting in a faster heat removal and reducing cooling times to one quarter (25%) to one tenth that of room cooling [2, 5]. Forced-air precooling method is achieved by sucking cold air through produce container and creating an air static pressure gradient resulting in heat removal from the commodity [4, 6]. Critical components for forced-air cooling are the refrigeration capacity and the air velocity. According to Fraser [7], an adequate ventilation system must circulate 0.5 to 3 L of air $s^{-1} \cdot kg^{-1}$ of produce. Greater air flow rate requires higher static pressure, increasing the total energy consumption [8].

The main disadvantages of this precooling method are excessive dehydration or, sometime, produce freezing injuries in case of poor precooler temperature control and heterogeneous air distribution or poor precooling management [9]. If corn is not transported immediately after precooled, forced-air cooling process should be followed by storage at 0°C and 95% relative humidity room to maintain its good quality [10]. Several studies were conducted to optimize the performance of forced-air cooling for fruits and vegetables. Vigneault and Goyette [4] have developed a new version of reusable plastic container for handling horticultural crops. Their work demonstrated that the relative surface area of the openings directly affects the air circulation through the commodity but this effect becomes negligible when increasing the opening area over 25% of the container walls. Other related research studies demonstrated different effects on efficacy when comparing vertical and horizontal air flow directions[5].

The main objective of the present study was to assess the performance of a forced-air cooler system for sweet corn. The specific objectives of the study were to determine the effect of airflow rates and cob orientations on the half cooling time of the produce; to evaluate the effect of those parameters on keeping quality of sweet corn stored at 1°C for 7 and 21 days; to assess and compare the keeping quality of three precooled sweet corn cultivars after 7 and 21 days of storage at 1°C.

Materials and Methods

Plant material: Sweet corn (*Zea mays* L. spp. *saccharata*) produced on a local commercial farm was manually harvested at optimum maturity stage. The corn was maintained under shed and then transported to the Postharvest Quality Laboratory of Agriculture and Agri-Food Canada (St-Jean-sur-Richelieu, QC, Canada) within one hour after harvest. The harvest was performed at mid July, mid August and mid September. The sweet corn cultivars were chosen based on their availability at each period which resulted in using early, mid-late and late maturity sweet corn (Table 1). The initial produce temperature before precooling was generally near 24°C.

At each test day, eight experimental units of sixteen ears were randomly picked from the field. The mass and diameter of every ear were measured before any treatment. An additional corn cob was added to each experimental unit and used to follow the temperature profile of the produce during the precooling process. Two type-T thermocouples were positioned in this cob, one between the corn leaves and the kernels, and the other between the kernels and the core of the ear. Two experimental units ready for precooling were put at the same time in a standard plastic container [4].

Experiment set-up: The experiment set-up is presented in Fig. 1. Two 406 mm square plywood boxes, with 15 mm thick wall and 482 mm in height, were built to contain 34 ears of sweet corn each. On both sides of air pathway, the walls of the boxes were built from uniformly perforated aluminium plates with 3 mm diameter openings covering 51% of their surface. Once filled, each box was attached to a different ventilation system used to circulate the desired air flow rates. The air-tightness was ensured using sealant tape.

Each ventilation system used a direct drive radial blade fan powered by a 0.75 kW variable speed electric motor controlled by a computer. The static and total air pressures were measured according to the standard method [11] using a home made calibrated Pitot system [12]. An electronic pressure transducer (Dwyer, 607 series) was used to measure the difference of the total and static pressure resulting in the air velocity dynamic pressure. The transducer was connected to a data acquisition system (Agilent Technology Packard, Loveland, Colorado, USA) driven by a portable computer [13]. The same data acquisition system was also recording the air and corn temperature profiles at every 30 s during the precooling process. Data logger software (Benchlink, Agilent Technologies, Loveland, Colorado, USA) was used to visualize obtained data. The half cooling time (HCT) was calculated from the temperature data using a dedicated Excel Macro™ [14].

Experimental procedure: For each experiment set-up, four combinations of two air flow rates (1 and 3 $L{\cdot}s^{-1}{\cdot}kg^{-1}$) and two produce orientations (parallel and perpendicular to the air flow) were tested. The corn ears were placed in their respective plywood boxes and cooled down until the temperature of the warmest cob reached the seven-eighth of the difference between the initial temperature of the corn and the air temperature inside the room [14]. The corn ears were then removed from both systems at the same time.

Each test was repeated at two consecutive days for each of three different survey periods during the summer. Two other experiment units were placed inside a corrugated carton box to represent refrigerated room cooling method and used as control units. Four temperature data loggers, Hobos (Onset, T-type, H 12), were used to measure the temperature of two corn samples. The thermal sensors were placed in the produce at the same locations than described for forced air cooling process. A 5 min-interval was used to record the temperature measurements. The box was then put in a cold room at 1°C and 90-95% RH, generating a 20 hours cooling process.

Storage and quality evaluation: Once cooled, all the corn cobs were placed in a conditioned room at 1°C and 90-95% RH for 7 and 21 days of storage. The plastic boxes containing the corn cobs were covered with perforated plastic bags to ensure high humidity and to avoid desiccation.

The mass loss of the corn cobs was measured immediately after harvest; after being precooled and after each storage period. The mass losses during the cooling process and the storage period were calculated as the percent difference between initial and final mass of the produce divided by the initial mass.

The moisture content and the total soluble solids percentage (TSS) of the corn were also measured as follows. From each experiment unit, 150 g of whole kernels were taken out, mixed together and then separated into six sub-samples of 25 g each. Three sub-samples were dried using a lab-scale oven (Isotemp® Premium Ovens, Fisher Scientific, 700 series) for 72 hours at 60°C, and then put in a vacuum desiccator cabin for one hour before measuring their mass using a 0.001 g precision scale. Moisture content (MC) was obtained from mass difference of before and after drying process according to the standard method [15].

Three other sub-samples were dipped into liquid nitrogen and kept into a freezer chamber at -20°C until TSS analysis. TSS was measured using a handheld refractometer (Fisher Scientific, Ottawa, Canada). Each sub-sample was blended for 1 min and centrifuged for 15 min at 3500 rpm. Few drops of the supernatant were used for this measurement.

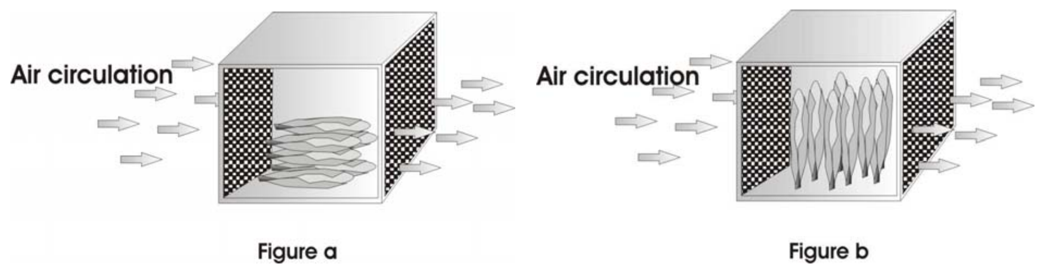

Figure 1. Experiment set-up used to measure the effects of air flow rates and a) parallel and b) perpendicular orientations of the sweet corn cobs on the cooling time.

Table 1. General characteristics of the sweet corn cultivars used for the forced-air precooling study.

Cultivar	Date of harvesting	Maturity period	Diameter size (mm)	Sweetness	Color
Fleet	Mid July	Early	44 to 51	High	Bicolor
Sensor	Mid August	Medium	53 to 58	Very high	Bicolor
Promise	Mid September	Late	48 to 54	High	Bicolor

Visual quality was evaluated for individual cobs before any cooling and on days 7 and 21 using a nine point hedonic scale for the subsequent parameters [16]: husk color, husk drying, silk appearance, kernel appearance and presence of defects. A quality index (QI) (Table 2) summarising all these parameters was determined and the total score for each parameter was calculated according to the method described by Rodov *et al.* [17].

To evaluate the performance of the different precooling combinations and their effect on cob quality, an analysis of variance (ANOVA) followed by a Duncan's Multiple Range test for comparison of the means was conducted using XLSTAT – Pro 7 software (Addinsoft, Paris, France).

Results and Discussion

Initial quality: The initial quality attributes of corn cobs measured immediately after harvest were used as reference for quality evolution (Table 5). Despite high quality index observed for the three cultivars, Fleet was significantly lower in quality compared to others. Although the three cultivars were classified as sugar enhanced (se) sweet corn, they were significantly different in their degree of sweetness. TSS level reached up to 27% in Sensor cultivar while reaching only 23 and 21% for cultivars Fleet and Promise, respectively. Since the juiciness may play a role in keeping quality of corn; one could expect better quality conservation from the higher moisture cultivars, Fleet and Promise, compared to Sensor.

Precooling performance evaluation

Air flow rate: The results of the HCT (min) and mass loss (% of initial mass) for the four combination of produce position and air flow rates compared to room cooling are reported in Table 3. The results showed a decrease of 49.3 % in the HCT as the air flow was increased from 1 to 3 $L{\cdot}s^{-1}{\cdot}kg^{-1}$. Moreover, there was no significant difference in the HCT between core and kernel position measurement which supporting the theoretical assertion that the cooling rate at any point in a uniform produce should be the same[18]. During the experiment, cooling time was noticed to be lower for cultivars Fleet and Promise compared to Sensor (data not shown). This lower cooling time, for these cultivars, is likely due to their smaller diameter size (Table 1). Goyette *et al.* [14] effectively demonstrated that cob of larger diameter took longer time to cool down.

The average mass loss during forced-air precooling process was 2.69% of the initial mass. Although, the difference in weight loss was not significant between the two flow rates evaluated, the higher flow rate showed a tendency to increase weight loss; more trial would be necessary to determine if the observed difference is only due to experimental error or is associated with flow rate increase.

Orientation of corn cobs: Data in Table 3 show the effect of cob orientation on HCT and mass loss during the cooling process. The perpendicular orientation showed a reduction in the HCT of sweet corn compared to parallel orientation when using higher air flow rate. This effect may be due to a higher turbulent air movement reducing the immobile film of air at the surface of the produce as the air hits the produce perpendicularly. Furthermore, the perpendicular ears are likely more exposed at a maximum degree of contact and the cooling is achieved in all locations through the entire length of the cob at the same time, resulting in high uniformity of cooling through different parts of the cooled produce. Moreover, under perpendicular orientation, cold air is passed from side to side through smaller area (diameter) compared to other orientation resulting in lower cooling time. In the case of parallel orientation, the surface of contact is minimal and only the end facing the air entering in the container is exposed to the cold air, requiring much time to cool down the entire ear. However, to validate this assumption, more tests should be performed. The data presented in Table 3 showed no difference in mass loss during cooling between the two cob orientations. However, a slight tendency to higher increase was noticed for perpendicular orientation.

Table 2. Full description of quality index scales of sweet corn [12].

Quality index	Quality	Description
9	Excellent	Husks of freshly harvested turgid appearance, dark green, slightly moist. Silks light-colored (greenish-yellow) and turgid. Kernels bright and very turgid. Absence of major defects.
7	Good	Green husks, slightly wilting. Silks light-colored, slight loss of turgidity. Kernels reasonably bright and turgid. Absence of major defects.
5	Average	Pale green husks, withered or slightly dry. Silks lightly browning, some dried. Kernels dull but not dented. Absence of major defects.
3	Poor	Husks very pale, some yellowing and perhaps browning, much withered and partly dry. Silks brown, soft and possible dry. A few dented kernels. Major defects possible.
1	Unmarketable	Husks yellow, straw-colored or brown. Very withered or dry. Many dented kernels. Major defects present.

Table 3. Half cooling time (HCT) and mass loss (%) for different forced-air precooling combinations compared to room cooling.

Precooling parameter		HCT (min)		Mass loss during cooling (%)
Corn cob orientation	Air flow rate (L·s^{-1}·kg^{-1})	Core	Kernel	
Parallel	1	93.4^{b*}	91.2^{b}	1.81^{a}
Perpendicular	1	92.1^{b}	92.1^{b}	3.14^{a}
Parallel	3	68.1^{c}	67.8^{c}	2.84^{a}
Perpendicular	3	47.3^{d}	47.1^{d}	2.96^{a}
Room cooling		436.7^{a}	434.6^{a}	0.38^{b}

*Values in the same column with the same letter are not significantly different at á = 0.05.

Table 4. Quality attributes of sweet corn for different forced-air precooling combinations compared to room cooling after 7 and 21 days of storage at 1°C.

Precooling parameters		Mass loss during storage (%)	TSS (%)	Moisture content (%)	Quality index
Corn cob orientation	Air flow rate (L·s^{-1}·kg^{-1})				
7 days					
Parallel	1	2.65^{ab*}	22.56^{a}	74.02^{a}	6.54^{a}
Perpendicular	1	4.52^{b}	22.22^{a}	73.99^{a}	6.16^{a}
Parallel	3	3.63^{ab}	22.36^{a}	74.20^{a}	6.44^{a}
Perpendicular	3	3.73^{ab}	22.13^{a}	74.16^{a}	6.06^{a}
Room cooling		1.96^{a}	20.90^{a}	74.20^{a}	6.04^{a}
21 days					
Parallel	1	3.94^{b}	21.47^{a}	73.93^{a}	5.70^{a}
Perpendicular	1	4.11^{b}	21.75^{a}	73.58^{a}	6.14^{a}
Parallel	3	4.58^{b}	21.66^{a}	73.63^{a}	5.94^{a}
Perpendicular	3	3.46^{b}	21.67^{a}	73.79^{a}	5.92^{a}
Room cooling		2.29^{a}	19.76^{a}	73.26^{a}	5.48^{a}

*Values in the same column with the same letter and storage duration are not significantly different at á = 0.05.

Table 5. Quality attributes for different precooled cultivars of sweet corn after storage at 1°C.

Storage duration (days)	Mass loss during storage (%)	TSS (%)	Moisture content (%)	Quality index
Fleet				
0	0.00^{a*}	22.70^{a}	75.70^{a}	7.75^{a}
7	3.97^{b}	21.56^{b}	75.69^{a}	6.66^{b}
21	3.71^{b}	20.41^{c}	74.75^{a}	6.52^{b}
Sensor				
0	0.00^{a}	27.10^{a}	68.80^{a}	8.87^{a}
7	2.93^{b}	25.83^{b}	68.05^{a}	5.74^{b}
21	3.52^{b}	25.62^{b}	68.03^{a}	5.62^{b}
Promise				
0	0.00^{a}	21.50^{a}	76.50^{a}	8.69^{a}
7	2.99^{b}	19.21^{b}	76.42^{a}	6.74^{b}
21	3.81^{b}	18.29^{c}	76.12^{a}	5.36^{c}

*Values in the same column with the same letter and sweet corn cultivar are not significantly different at á = 0.05.

Room cooling: When compared to forced-air, HCT obtained in room cooling (436 min) was by far higher than all other combinations used (Table 3). It reached up to nine times the HCT (47 min) obtained for perpendicularly orientation cobs with 3 L·s^{-1}·kg^{-1} airflow. Regardless of cobs orientation, when using the lower flow rate, HCT (92 min) of sweet corn was approximately reduced to one quarter compare to room cooling.

As for mass loss during cooling process, no significant difference was found for any of the airflow rate and orientation combinations. However, room cooling process resulted in a much lower mass loss. This lower mass loss obtained after room cooling was likely due to a higher relative humidity maintained in the closed box containing the corn cobs.

Storage duration: The effect of forced-air precooling parameters on the quality attributes of sweet corn stored for 7 and 21 days at 1°C is presented in Table 4. Generally, keeping quality of sweet corn was inversely related to the length of storage. For the same storage duration, the data demonstrated that quality factors including TSS, moisture content and quality index were similar for all combinations tested; although room cooled cobs displayed lower mass loss, TSS and quality index values. Sweet corn benefited from forced-air and room cooling as it was possible to store this highly perishable commodity for duration up to 21 days at 1°C while maintaining high TSS and moisture content with good market quality.

Cultivar effects: Table 5 shows the effect of precooling on quality factors of the three sweet corn cultivars after storage. For all three cultivars mass loss significantly increased over time as expected. There was also a significant TSS reduction for all cultivars. However, this loss of sweetness was higher after 21 days of storage in case of Promise with 14.9% followed by Fleet and Sensor cultivars with 10.1 and 5.4% respectively. Moisture content was maintained at a high level for all three cultivars with a tendency to decrease over time. During storage, the overall quality index was markedly reduced for all cultivars with a higher reduction for Promise.

Conclusions

Sweet corn cobs under perpendicular orientation and 3 L of cold air ·s^{-1}·kg^{-1} of produce were precooled faster then parallel orientation and lower air flow rate. Under these precooling conditions, HCT was reduced to almost 90% of that of room cooling. Precooling parameters had no effect on the quality attributes of sweet corn which still maintained high after 7 and 21 days of storage at 1°C except for general quality index; therefore, the assessment of the performance of the forced-air cooler system can be limited to cooling time and mass loss during cooling process.

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