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Credit Author Statement

Author	Contribution
Nattawut Chaomuang	Conceptualization, Methodology, Investigation, Validation, Formal analysis, Investigation, Writing - Original Draft Preparation, Visualization, Project administration, Funding acquisition
Parinya Singphithak	Investigation, Software, Visualization
Onrawee Laguerre	Validation, Formal analysis, Writing - Review & Editing, Supervision
Rachit Suwapanich	Conceptualization, Methodology, Validation, Supervision

Temperature control in a horticultural produce supply chain in Thailand and its influence on product quality

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Abstract

The present study was conducted in order to investigate the temperature conditions in the horticultural produce cold chain in Thailand, and fresh-cut baby corn was chosen for a case study. The field investigation together with in-person interviews were performed at 4 growers' premises and one packing house. The information collected provided details on current postharvest conditions at individual stages from the growers' premises to an export distribution center. Temperature measurements were carried out to explore the time-temperature profiles throughout these stages. The results showed that the total duration of these stages was almost 32 h, and the temperature variations were between 6 and 33°C. Precooling was delayed for at least 9 h, since baby corn cobs were primarily processed by dehusking and bulk packing. The baby corn was maintained at a temperature below 6.0°C in a cold room for almost half of the total duration. The effect of the postharvest temperature conditions on the product quality evaluation was assessed by measuring various physiological quality attributes during storage. It was found that the marketability of the baby corn subjected to such postharvest temperature conditions remained possible with a salable period of up to two weeks. The result made it possible to identify the stages during which temperature control was inadequate, and recommendations were proposed to the stakeholder partner in order to modify the postharvest conditions in order to extend the product shelf life.

Keywords: Field investigation, postharvest handing, temperature, cold chain, baby corn, physiological quality

1. Introduction

The supply chain incorporating low-temperature control is referred to as the “cold chain” in which refrigeration is the prime technology used to provide a cold environment (Olatunji & East, 2020). Temperature is by far the most important environmental factor affecting the quality and safety of fruit and vegetables (Watada, Izumi, Luo, & Rodov, 2005). Insufficient use of refrigeration can result in food loss and waste. As reported by the International Institute of Refrigeration (IIR), around 360 million tons of foods are lost annually across the globe due to a lack of refrigeration (IIR, 2009). For fresh fruit and vegetables, poor temperature management may cause produce losses ranging from 25 to 50% (Kelly, Madden, Emond, & do Nascimento Nunes, 2019). Although the total percentages of losses in developed countries may not significantly differ from those in developing countries, the difference becomes significant when one looks into individual stages. In developed countries, losses of fruit and vegetables mostly occur at the supermarket and consumer stages, whereas in developing countries, the losses are mainly at the postharvest and distribution stages (Goedhals-Gerber & Khumalo, 2020; Kitinoja & Kader, 2015; Porat, Lichter, Terry, Harker, & Buzby, 2018). In Thailand, Rattanawong and Ongkunaruk (2018) observed 20 to 50% losses of fresh vegetables during long-distance transport from the production area in the northern region to the packing house in the central region. At least 27% of such losses were due to an unsuitable temperature environment. Temperature control at all stages in the cold chain makes it possible to delay the deterioration of produce quality but poses a great challenge (Mercier, Villeneuve, Mondor, & Uysal, 2017).

Although refrigeration is broadly applied in developed countries, numerous published studies show that there are temperature breaks at all stages in the cold chains, particularly at the transport and retail stages (Ndraha, Hsiao, Vlajic, Yang, & Lin, 2018). These temperature break, even for a few hours, may have a significant impact on product organoleptic quality evolution (Loisel, et al., 2021). Field studies similar to those conducted in developed countries are performed to a lesser extent in developing countries (Mercier, Villeneuve, Mondor, & Uysal, 2017). The development of cold chains has been observed recently in certain developing countries such as Brazil, China, and India (Salin, 2010, 2018). A similar trend was also observed in Thailand where the cold storage capacity has increased from 0.94 million metric tons in 2015 to 1.57 million metric tons in 2021 (DIT, 2019; Ongkittikul, Plongon, Sukruay, & Yisthanichakul, 2019). This progress requires to address the current status of time-temperature conditions in the cold chain so that the stages where temperature abuse arises are identified, and consequently suitable remedial strategy can be implemented in an effective manner (Ndraha, et al., 2018). According to the authors' knowledge, cold chain field studies together with investigation of the impact of the cold chain on food quality are rare, particularly in Thailand where the ambient temperature is high. The most relevant field study was conducted in Belgium by Rediers, Claes, Peeters, and Willems (2009). In this study, the temperature profile of fresh-cut endive in a real cold chain and its impact on product microbiological safety was evaluated. The objective and the originality of the present study was firstly to acquire knowledge of the temperature conditions in the existing horticultural produce cold chain in Thailand, and secondly to study its impact on product quality. A cold chain for fresh-cut baby corn (*Zea mays* L.) was chosen for a case study because this product is one of the major crops in Thailand and is thus important to the Thai economy. Being the largest exporter, Thailand accounts for 80% of exports of baby corn in the world (Singh, 2019). This product is highly perishable and a shelf life is only six days under ambient storage conditions (25°C) and 21 days under cold storage conditions (4°C) (Sakhornyen, 2009).

In this study, postharvest handling was investigated at several growers' premises and at a packing house. Temperature measurements were then undertaken by using temperature dataloggers to monitor baby corn from the growers' premises to an export distribution center. Finally, the effects of such postharvest handling and its temperature conditions on the product quality during storage was evaluated in a laboratory. The knowledge acquired in this study provides an insight into the current status of the cold chain operated by smallholders and could be used as a basis for future research on the development of an efficient cold chain in Thailand.

2. Materials and methods

2.1 Field investigation

Postharvest conditions in a fresh-cut baby corn cold chain were investigated from growers' premises to an export distribution center. A field investigation was conducted in December 2020 to observe product handling at a packing house and four growers' premises located in Tha Maka district (Kanchanaburi province, eastern region of Thailand). This packing house was chosen based on several reasons including the willingness of the operators to perform the field investigation and to share the data, the presence of a refrigeration facility, and the marketing mode for both the export and domestic supply chains. Interviews were conducted with the operators and the growers in order to obtain detailed information. The exporters and the domestic wholesalers who procured the baby corn from the packing house were also interviewed. The interview questionnaire used in the study was certified by the research ethics committee of King Mongkut's Institute of Technology Ladkrabang (EC-KMITL 63-017) to ensure respondent confidentiality. Based on the information acquired, temperature measurements and a quality assessment were set up with the methodologies described in the following sub-sections.

2.2 Temperature measurement

Temperature dataloggers (Elitech® RC-5, Jiangsu Jingchuang Electronics, Jiangsu, China; ±0.5°C accuracy in the range of −20°C /+40°C) were used in the study. Generally, the measured value represents the air temperature adjacent to the product because it is difficult to place this sensor on the surface and at the core of the product due to the sensor size. In order to help interpretation of temperatures measured by the datalogger, an experiment was firstly undertaken in a laboratory refrigerator (PC-1355, Power Cool Systems, Samut Prakan, Thailand, with a temperature setting of 8°C). A comparison of temperatures measured by datalogger (denoted as "DL") and by three calibrated T-type thermocouples (200 µm diameter, ±0.2°C accuracy in the range of −5°C/+30°C) was carried out. These thermocouples were installed to measure the core (denoted as "CT") and surface (denoted as "ST") temperatures of baby corn and the air temperature at 10 mm from the product surface (denoted as "AT"). The thermocouples were connected to a switching unit (34907A, Agilent Technologies, Santa Clara, California, USA) for data acquisition of every 10 s. The datalogger and the instrumented baby corn were placed together on a foam tray. Two sets of dataloggers and thermocouples (i.e., six thermocouples in total) were used simultaneously to ensure result consistency.

Field temperature measurement was carried out in the baby corn cold chain from the growers' premises to the export distribution center (referred to as "upstream stages" in this paper). The temperature was recorded every 10 s. Because of practical difficulties, the product temperature at different stages in the supply chain could not be measured continuously. According to the information of postharvest conditions (details in **Section 3.1**), the temperature measurements were therefore separated into four periods and then linked together to represent the entire temperature profile of the cold chain for exported baby corn.

In Period I (Stages 1, 2, 3, and 4, **Fig. 1a**), two dataloggers were inserted, one at the top and one at the bottom of four baskets (**Fig. 2a**) from three different growers' premises. In Period II (Stage 5, **Fig. 1a**), ten baby corn cobs were sampled, and the core temperature was measured prior to and after hydrocooling by using a digital handheld thermometer equipped with two K-type temperature probes (54-IIB, Fluke Corporation, Everett, Washington, USA; ±0.3°C accuracy in the range of −10°C /+50°C). The cooling water temperature was also measured at 20 positions in the bath (10 positions at 100 mm and another 10 positions at 400 mm from the surface of the water) using the same sensor. The measurements were undertaken on two batches to ensure result repetition. In Period III (Stages 6 and 7, **Fig. 1a**), five dataloggers were placed on the packaging tables to measure the ambient temperature in a packaging room. Before the packed products were transferred to the cold room, these dataloggers were randomly placed on the top of the five foam boxes (**Fig. 2c**) to monitor the air temperature during storage. The air relative humidity in the cold room were also measured every five minutes using a hygrometer (174H, Testo, Titisee-Neustadt, Germany; ±3%RH accuracy in the range of 2 to 98%RH). This sensor was installed underneath the return air inlet of the refrigeration unit. Due to the lack of permission for intervention with the export products, the dataloggers were withdrawn from the boxes before the boxes were loaded onto the refrigerated truck of the export distributor. Accordingly, in Period IV (Stage 8, **Fig. 1a**), two dataloggers were installed at the mid-height of the front and the rear of the truck to record the air temperature during the time interval between loading at the packing house and unloading at the distribution center. The driver was asked to return the dataloggers to the laboratory.

2.3 Quality assessment

2.3.1 Sample procurement and preparation

To evaluate the effects of postharvest temperature conditions on the product quality, a quality assessment was conducted on two groups of baby corn cobs: Group 1 (product for export) and Group 2 (product for domestic markets). The differences between these groups were the presence of precooling (hydrocooling) prior to cold storage and the time of packaging as shown in **Fig. 1**. Photos of the retail packaging of Groups 1 and 2 are displayed in **Figs. 2b** and **2d**, respectively. The products in both groups were sampled at the packing house in the same day as the temperature measurement was undertaken and were transported to our laboratory the next morning using a refrigerated truck to prevent product degradation at this stage to the greatest possible extent. The sample of Group 1 was the packed baby corn in a foam box which was randomly chosen from Stage 6 while the sample of Group 2 was fresh baby corn filled in the four instrumented baskets which were taken after Stage 4 and stored in the cold room without precooling. In the foam box, three dataloggers were also installed at the top, in the middle and at the bottom to monitor the internal temperature variation at this stage.

At the laboratory, all packs of baby corn were removed from the foam box and individually weighed using digital scales (PB1502-L, Mettler Toledo, Columbus, Ohio, USA; 0.01 g readability and ±0.02 g accuracy). This measured value was considered as the initial weight for the weight loss evaluation. Then, the packs were evenly loaded into two refrigerators (MIR-253, Sanyo, Osaka, Japan) with temperature settings of 2.1 ± 0.1°C and 4.3 ± 0.1°C respectively, prior to the quality assessment. Meanwhile, the fresh baby corn in the baskets was processed in a similar manner as in the packing house: cleaned, trimmed, and packed in a Styrofoam tray (190 mm × 105 mm) sealed with polyvinyl chloride (PVC) plastic wrap (**Fig. 2d**). Each pack was weighed and stored in the two refrigerators.

2.3.2 Quality measurement

Various physicochemical quality attributes of baby corn including weight loss, visual appearance, color, firmness, and total soluble solid (TSS) content were evaluated under temperature-controlled storage. Measurements were undertaken on the day of arrival at the laboratory (Day 0 – Control) and every two days over the 14-day storage period using the following procedures. Two packs were randomly sampled from each refrigerator (i.e. four packs for each group). The quality attributes of the baby corn in the sampled packs were then measured on each evaluation day. All data were reported as the mean value of n samples ± standard deviation (SD).

(i) Weight loss. Each pack was weighed ($n = 2$) and its weight loss was determined and expressed as the percentage loss from its initial weight: $\%\text{Loss} = (\text{W}_{\text{initial}} - \text{W}_{\text{final}}) / \text{W}_{\text{initial}}$.

(ii) Visual appearance. Ten baby corn cobs were sampled from each pack and assessed for visual quality by three trained panels ($n = 60$). The visual quality was scored on a scale of 5 to 0 according to the quality index describing the extent of browning developed on the baby corn: 5 refers to no browning, 4 to browning exhibited on 1-10% of the total ear area, 3 to 11-20%, 2 to 21-30%, 1 to 31-40%, and 0 to more than 40% (adapted from Leelaphiwat (2007)).

(iii) Color. The kernel color was measured at the mid-length on two sides of five baby corn cobs sampled from each pack ($n = 20$) by a spectrophotometer (Color Quest XE, HunterLab, Reston, Virginia, USA). The color values in the color coordinate ($L*$, $a*$, $b*$) were recorded and used to calculate hue angle and chroma value with the following formulae: $\text{Hue} = \tan^{-1}(\text{b}^{*} / \text{a}^{*})$ and $\text{Chroma} = \left(\text{a}^{*2} + \text{b}^{*2}\right)^{1/2}$. It should be noted that L^{*} value signifies the degree of lightness of which the value ranges from 0 (black) to 100 (white). Hue angle and chroma value signify the extent of browning where the angle of 0° to 90° exhibits the color span between redness and yellowness, while the chroma value indicates its saturation.

(iv) Firmness. The same baby corn cobs used for the color assessment were then determined for their firmness ($n = 10$) by using a texture analyzer (TA-XT plus, Stable Micro Systems, Surrey, UK) equipped with a knife blade (HDP/BS) to measure cutting force. The measurement was performed at 3 cm from the ear tip with the cutting velocity of 120 $\text{mm}\cdot\text{min}^{-}$

[1]. The maximum cutting force, expressed in Newton (N), was determined from the time-force profile by using the interfaced software (Exponent version 4.0.9.0, Stable Micro Systems, Surrey, UK).

(v) TSS content. All baby corn cobs in individual packs were blended and the juice was extracted. The TSS content of the juice, expressed in %Brix, was measured five times ($n = 10$) using a digital refractometer (PAL-1, Atago, Tokyo, Japan; ±0.2% accuracy in the range of 0-53%Brix).

3. Results and discussion

3.1 Description of postharvest condition

The on-site investigation and the in-person interviews took place at the growers' premises and the packing house. Product handling including equipment or facilities used at individual stages along the upstream stages (**Fig. 1**) are presented in detail as follow.

The growers begin to harvest baby corn in the morning (5:00 a.m. to 8:00 a.m.). During harvesting, the baby corn cobs are put in sacks and are later transferred using a cart, a scooter with a side trailer, or an open-bed truck to the growers' premises for primary screening and minimal processing. About 3.5 kg of non-defective baby corn cobs are wrapped in a plastic liner and placed in a plastic basket equipped with a lid (**Fig. 2a**). The basket is made of polypropylene, measures 330 mm in width × 200 mm in length × 110 mm in height and the perforation area is about 30%.

The investigated packing house is a community enterprise where most baby corn is procured from the growers engaged by contract and from other packing houses in nearby districts. Open-bed trucks are commonly used to collect the baby corn without cloth or tarpaulin covers during transport (except in the rainy season). At the packing house, the baby corn is unloaded and stored in an open hall under ambient conditions. Some baby corn is sold to domestic wholesalers in bulk (**Fig. 1b**) while the baby corn for export undergoes further processing in the evening (usually starting at 6:00 to 6:30 p.m.). The product is first precooled in a cold-water tub with the water temperature set at 10°C. No standard precooling procedures such as product quantity for each batch, cooling time, and final product temperature are applied because the operator considers that the procedure has an insignificant effect on the product quality.

After precooling, the product is sorted and sized according to the exporter's requirements. The products are then packed on a Styrofoam tray (120 mm × 120 mm) sealed with PVC plastic wrap (100-110 g per pack, **Fig. 2b**) and placed in an expanded polystyrene foam box (120 packs or about 12 kg per box, **Fig. 2c**). The filled boxes are then transferred to a cold room (with a temperature setting of 2°C). During this stage, all boxes are open in order to promote the cooling of the product by the surrounding air. The boxes are closed just before loading onto the exporter's refrigerated truck the following afternoon (~1:30 p.m.). It is to be noted that the investigated packaging room was equipped with an air conditioning system with a temperature setting of 20°C which provides a reasonable working environment, and product quality deterioration can be slowed down at this stage.

The export distributor uses a refrigerated truck (with a temperature setting of 2°C, and no strip curtains on the trailer doors) to collect the baby corn from the packing house. Based on the interviews, the distributor also collects the baby corn from other packing houses on the way back to the export distribution center located in Damnoen Saduak District, Ratchaburi Province (about 70 km and about 3 h from the studied packing house). At the distribution center, some gel packs (no information was available concerning the type and quantity of gel packs used) are placed in all foam boxes prior to transport that night by a refrigerated truck to the airport (Suvarnabhumi International Airport, Bang Phli District, Samut Prakan Province) located at around 120 km from the distribution center. No further information was available thereafter in our study.

The data obtained in this study were based on only one packing house because it proved to be difficult to find industrial partners. Despite this, the information was in good agreement with the results reported by several studies (Anonymous, 2006; Koslanund, 2006; Rattanachai, 2011; Sakhornyen, 2009) in terms of stages in the cold chain and product handling at a given stage. The methodology developed in this study for time-temperature conditions in the cold chain and its effect on baby corn quality could be applied to other horticultural produce to better represent the current situation in Thailand.

3.2 Interpretation of temperatures measured by the datalogger

As shown in **Fig. 3**, the temperature recorded by the datalogger was in between that of the surrounding air temperature and the product surface temperature measured by the thermocouples. The temperature measured by the datalogger at any given instant was about 0.5-1.6°C higher than the surface temperature and about 1.2-2.3°C higher than the core temperature. Due to the thermal inertia of the datalogger and the baby corn, the difference between the amplitude of the temperature variation of the datalogger and that of the product surface was small ($\Delta T = (T_{max} - T_{min}) / 2 \leq 0.5°C$), compared with that of the surrounding air ($\Delta T \approx$

1.3°C). Thus, the temperature measured by a datalogger in the field was considered to represent an intermediate value between the temperatures of the product surface and the surrounding air.

3.3 Time-temperature evolution

Fig. 4 shows the overall temperature conditions in the fresh-cut baby corn cold chain from the growers' premises to the export distribution center (Stages 1 to 8). It was found that these upstream supply stages accounted for approximately 31.3 h during which the temperature varied between 6 and 33°C. The periods during which temperature abuse occurred were the stages prior to precooling, corresponding to the precooling delay of around 9.2 h. For nearly half of the duration of the upstream stages (~ 16.2 h), the baby corn was stored in a cold room in which the time-averaged temperature was approximately 5.7 ± 1.4°C. This temperature is considered high for the storage of baby corn because the recommended storage temperature is at or below 4°C (Sakhornyen, 2009). A rapid temperature increase during loading onto a refrigerated truck prior to transport to the export distribution center, then substantial temperature fluctuations were also observed. This can be explained by the fact that the truck trailer was not precooled prior to loading. The following information presents the details of temperature conditions at all individual stages.

Fig. 5a depicts the temperature conditions measured from Stages 1 to 4. The temperature displayed in this figure was the average value between the temperature at the top and at the bottom of individual baskets. At the beginning of Stage 1, the temperature in each basket decreased slightly when the dataloggers were inserted in the basket and increased after the basket was fully packed. The duration of ambient storage (Stage 2) at each grower's premises was different and dependent on their work organization. An increase in temperature of 4-5°C from the initial value was observed during this stage, possibly because of the heat of product respiration which cannot be easily evacuated under calm air conditions. A decrease in temperature was observed during the transport to the packing house (Stage 3) and this could be attributed to the cooling effect of water evaporation induced by airflow during transport. Again, the temperature constantly increased during ambient storage at the packing house (Stage 4). A temperature of more than 30°C was observed in all baskets at the end of this stage. The increase in temperature in these baskets corresponded to the ambient climate conditions across these supply stages where the air temperature was 1-2°C higher than that of the product (data not shown).

Fig. 5b shows the temperature heterogeneity within the baskets during Period I. For four instrumented baskets, the temperature differences between the top and the bottom were less than 1.0°C in two baskets and more than 3°C in the other two baskets. This difference can be explained by the basket position in the stack: there was a higher temperature difference in baskets located at the top of the stack due to direct exposure to solar radiation during storage at the growers' premises and transport without thermal protection. This may also lead to quality and shelf-life heterogeneity of the product in the same basket.

Table 1 presents the precooling conditions (Stage 5). Two batches of 180-200 kg of baby corn were precooled. It took 16 minutes to cool the first batch and about 13 minutes to cool the second. The average temperature of the cooling water measured between the two batches was around 19.0°C ± 4.5°C. The average core temperature of baby corn decreased from 30.5°C ± 0.7°C to 24.1°C ± 1.0°C, corresponding to an average temperature drop of 6.4°C ± 1.0°C. The final product temperature of 24°C was still high, but further cooling was applied in the cold room during the following period.

Fig. 6 shows the temperature evolution during Period III: Stage 6 processing in the packing room and Stage 7 storage in the cold room. The duration of Stage 6 varied depending on the box number. The line confining this stage in **Fig. 6** presents its maximum duration (2 h, from the beginning up until the time at which the last instrumented box was moved to the cold room). The average initial temperature of all instrumented boxes (Boxes 1 to 6) was 21.3 ± 0.4°C. A substantial decrease in temperature was observed in all boxes once the boxes were transferred to the cold room. In the cold room (Stage 7), the small temperature fluctuations are related to the "on/off" compressor working cycles. The large fluctuations every 180 min. for a duration of 20 min. are related to the defrost operation during which the compressor was turned off. The onset temperature (4.5 to 8.7°C) and the amplitude of fluctuations (0.5 to 1.7°C) varied depending on the box position in the stack **(Fig. 6a**). The box at the top of the stack (Box 1) had a lower onset temperature and higher fluctuations than the box at the bottom (Box 5) because it was exposed to the cold air in the room to a greater extent. A temperature variation of more than 5°C was observed within the same box (Box 6) during the first few hours of storage in the cold room (**Fig. 6b**). This variation decreased progressively with time until the end of the cold storage period when the temperatures at the bottom and in the middle positions were almost identical at 5°C, whereas the temperature at the top of the box was 2-3°C lower. The results highlighted the issue of temperature heterogeneity reportedly found in a cold room (Bishnoi & Aharwal, 2020; Duret, Hoang, Flick, & Laguerre, 2014) and within a package (Gruyters, et al., 2018; O'Sullivan, et al., 2017; Wu, Cronjé, Verboven, & Defraeye, 2019).

The packaged baby corn cobs in Boxes 1-5 were picked up by the export distributor and transported to the export distribution center. **Fig. 7** shows the temperature conditions inside the truck trailer during transport (Stage 8). It was noted that the truck driver ran the refrigeration unit just before the pickup time and it took about 45 min. to cool down the temperature from its initial value (29.6°C) to 10°C. This observation underscores the importance of driver training on temperature abuse, which can be avoided by product loading only after the air temperature has stabilized inside the truck. According to the provided logistic information, the driver collected the baby corn cobs from the other four packing houses after having collected the baby corn cobs at the investigated packing house. This explained four sharp temperature rises (the spikes in **Fig. 7**) due to external air infiltration during door openings. The doors of the truck were not equipped with any protective devices such as air curtains or plastic strips, and this explained the pronounced temperature rises during this period. This effect was studied by de Micheaux, Ducoulombier, Moureh, Sartre, and Bonjour (2015). No temperature measurements were performed after the product delivery to the export distribution center.

Unlike Boxes 1-5, Box 6 was delivered to the laboratory by our refrigerated truck for quality assessment (**Fig. 6b**). During the product transfer from the cold room to the truck, temperatures rose 0.6-1.5-°C briefly inside the box and rose 6.6°C outside the box. The refrigeration unit of the refrigerated truck was operated for at least 20 min. prior to loading the products. During the journey that lasted about 3 h, the air temperature outside the box did not significantly fluctuate (average value 2.3 ± 0.3°C) and the temperature inside the box was quite homogeneous (average value of 5.6 ± 0.3°C).

3.4 Quality evolution during storage

The assessment was performed to evaluate the influence of the postharvest temperature conditions on baby corn quality, which could translate into product marketability. The physiochemical quality attributes of two groups of baby corn cobs (Group 1 for export and Group 2 for domestic markets) were measured during storage under two temperature conditions (2.1 ± 0.1°C and 4.3 ± 0.1°C) over a period of 14 days. The results are presented in **Figs. 8a** to **8f**.

Weight loss was observed in both groups of baby corn cobs and its percentage increased over the storage period (**Fig. 8a**). This could be attributed to moisture loss through transpiration (Attia, Saleh, & El-Shabrawy, 2011). No significant difference in weight loss was found between the baby corn cobs of the same group stored at 2.1°C and 4.3°C. At the end of the storage period, the weight losses seen in Groups 1 and 2 were 4.4-4.8% and 4.6-5.1%, respectively. These percentages could be considered low because no signs of wilting were detected over the course of the evaluation period. The results agreed well with Sakhornyen

(2009) who reported that the wilting of baby corn cobs is obvious when the weight loss is more than 10%. Moreover, such low weight loss would also have a negligible effect on the economic value of baby corn cobs as the product is usually purchased on a whole pack and rather than on a weight basis. By performing linear regression, the rate of weight loss was identified based on the slopes ($W = m \cdot t$ where W is weight loss percentage [%], t is time [day], and m is slope [% per day]) (adapted from Tirawat, Flick, Mérendet, Derens, and Laguerre (2017)). As reported in **Table 2,** the rates of weight loss of baby corn cobs in both groups were approximately 0.3-0.4% per day under 2-4°C storage conditions.

Fig. 8b presents the change in the TSS content of baby corn cobs during storage. An increase in TSS content was observed over the storage period in both groups. The increment might be associated with the continual decrease in moisture, thus leading to a higher sugar concentration (Mukama, Ambaw, Berry, & Opara, 2019; Sakhornyen, 2009). The result suggested that the loss of moisture through transpiration seemed to be more pronounced than the loss of dry matter (e.g. sugars) through the respiration process. The low storage temperature could be the main reason for this change since it causes a deceleration in respiration rates and an increase in the water vapor pressure deficit between the product surface and the air, thereby enhancing transpiration. At both storage temperatures, the TSS content of the baby corn cobs in Group 1 increased from 7.5-7.6 %Brix to 10.4-10.5 %Brix while it increased from 8.5-8.7 %Brix to 10.3-10.6 %Brix for the baby corn in Group 2. It was demonstrated that the initial TSS values of the baby corn cobs in Group 1 were slightly lower than those in Group 2. This might be due to the initial level of moisture content in the baby corn cobs on the day of arrival at the laboratory. The baby corn cobs in Group 2 were exposed to the cold environments without a protective layer (e.g. plastic wrap) for a relatively long period compared with the baby corn cobs in Group 1, which were already packaged during the same stages (Stage 7, **Fig. 6b**). Since low temperature exerts a great influence on the moisture loss of unwrapped fresh products (Serrano, Martinez-Romero, Guillen, Castillo, & Valero, 2006), higher moisture loss in the baby corn cobs in Group 2 would be expected when it arrived at the laboratory. It should be noted that air humidity also exerts an influence on product weight loss, but its influence is much less significant compared to that of temperature because of the high relative humidity in the cold room (average of 92.2 ± 6.0%RH).

The firmness of the baby corn cobs in terms of cutting force is shown in **Fig. 8c**. It was observed that firmness did not change appreciably with storage time for the product in Group 1. The average cutting force values of the baby corn cobs stored at 2.1°C and 4.3°C lay within the range of 15.9 N to 18.8 N and 15.1 N to 18.7 N, respectively. However, the firmness of the baby corn cobs in Group 2, regardless of the storage temperature, continuously decreased and remained relatively constant after 6 days of storage (roughly from 16 N to 11 N). Again, the moisture content of baby corn cobs might be the reason for the discrepancy in results since moisture loss plays a key role in the textural quality change of fresh horticultural products (Deak, Heaton, Hung, & Beuchat, 1987; Zhu, et al., 2018).

Figs. 8d and **8e** present the color development of the baby corn cobs in terms of L^* and hue angle, respectively. The results showed that the L^* values of the baby corn cobs in both groups, regardless of the storage temperature, remained almost constant over the storage period. Their averages were in the range of 73.0 to 76.0 (**Fig. 8d**). Despite its trivial change, the hue angle exhibited the slow development of browning on the baby corn cobs in all cases. The average hue angle decreased (i.e. redness became more pronounced) from approximately 88.0° to 86.0° (**Fig. 8e**). The chroma value appeared to be unchanged and its averages varied between 29.0 and 32.0 (data not shown). Less discoloration can be attributed to the effect of the packaging with film wrapping. Such packaging helps to slow down moisture loss which is recognized as one of the main causative factors affecting undesirable visual quality involving product discoloration (Supapvanich, Promyou, & Techavuthiporn, 2021).

The visual score signifying the extent of browning development on the baby corn cobs was evaluated. The browning reaction usually starts at the tip of baby corn cobs then spreads to the other areas (Leelaphiwat, 2007). The color evaluation was performed at the mid-length of the baby corn cobs (~40 mm); thus, less discoloration was detected in comparison with that at the tip. Browning tended to increase consistently with the prolongation of storage time, i.e. a decrease in the visual score (**Fig. 8f**). For Group 1, the product stored at both storage temperatures had a visual score decreasing from 5.0 to around 3.6-3.7. For Group 2, the final score was slightly lower (~3.1-3.3). The obtained results underlined the development of undesirable visual quality, i.e. browning, exhibited on the baby corn cobs across 10-20% of its total surface area after a 14-day storage period.

3.5 Relationship between postharvest temperature condition and product quality

Overall, the quality evolution of the baby corn cobs in both groups was similar to some extent. The product seemed to be marketable following a 14-day storage period. The weight loss did not exceed the limit that could cause a wilted appearance. The TSS content remained relatively high throughout the storage period, while alteration in the textural quality was minor with some variability. Browning was barely perceived at the mid-length surface of products as the change in hue of color from yellow to red was extremely subtle. However, it was more obvious at the tips according to a consistent decline in visual score. Notwithstanding this decline, the score remained above the tolerable limit (score > 3.0). These results could be translated into a salable lifespan of baby corn cobs of almost two weeks.

The results from such analyses should be considered carefully, since quality evolution was based on the field temperature conditions only in the upstream stages (Stages 1 to 6 and three-fourths of the duration of Stage 7). After these stages, the temperature conditions were artificially controlled during transport (< 8.0°C, 3 h) and storage (2.1°C and 4.3°C, 14 days) in our laboratory. These time-temperature conditions during the product transfer to our laboratory seem to be better than the real ones. Under real conditions, the product was subjected to a high temperature with large fluctuations during transport to the export distribution center (Stage 8, **Fig .7**). This stage should have a great impact on product quality but it was not possible to take samples at the end of this stage for quality evaluation due to the lack of exporter participation. According to Rattanachai (2011), the baby corn cobs were exposed to high temperature during storage at the airport cargo terminal, during air transport, and during domestic land transport in destination countries. High temperature during retailing in refrigerated display cabinets can be also expected (Chaomuang, Flick, & Laguerre, 2017). Moreover, microbial contamination can result in an even shorter shelf life (Tikhamram, Prempree, Seewilai, Siri-arayaporn, & Thammavijya, 2016). Therefore, the results from this study could only suggest that the presented postharvest conditions at the upstream supply stages are satisfactory.

Furthermore, the results revealed some room for improvement that would allow the prolongation of salable and safe conditions for baby corn cobs. The recommendations include 1) minimization of the time interval between primary processing and precooling (~9 h currently); 2) use of thermal protection (e.g. cloth or tarpaulin covers) during ambient storage and non-refrigerated transport to minimize solar radiation effect; 3) a consistent and effective precooling procedure (e.g. cooling temperature, cooling duration, and product quantity in each batch, and use of a temperature monitoring system); 4) pre-cooling of the trailer to the desired temperature before the loading process; and 5) installation of air infiltration protection (e.g. air curtain, plastic air strip) on the truck doors.

4. Conclusions

The fresh baby corn cold chain in Thailand was investigated in the present study. The field investigation together with in-person interviews were performed at the growers' premises and the packing house. The acquired information revealed the details of postharvest conditions at each supply stage from the growers' premises up to the export distribution center.

Temperature measurements were carried out for four periods covering the upstream stages of the baby corn cold chain. The results showed that the total duration of these upstream stages was almost 32 h. The baby corn cobs were subjected to temperature variations of 6 to 33°C along these supply stages. The cold storage stage accounted for almost half of the total duration, during which the product was kept at an average temperature below 6.0°C with moderate fluctuations due to the working cycles of the compressor and regulated defrost cycles. The time interval prior to precooling was about 9 h, where the products exposed to the temperature above 20°C. Intermittent temperature rises of 5-10°C were also observed in the truck trailer due to the door openings during product loading/unloading. According to the recommended storage temperature for the baby corn (4°C), the monitored temperature condition in these upstream stages appeared to be too high and required improvements.

The effect of temperature conditions on the product quality was evaluated. Various physiological quality attributes potentially influencing the marketability of baby corn cobs were measured during storage. Given that the storage temperature was well below 4.0°C and no temperature abuse occurred after the baby corn cobs were dispatched from the packing house, the product subjected to the current temperature control could be commercialized for a salable period of up to two weeks. Under the same conditions, the same salable period was obtained in the case of the product for domestic markets where precooling was absent prior to cold storage and the packaging was done at 18 h behind the case for export. The results lead to a suggestion that the temperature conditions during the upstream stages had significant influence on the product quality at the sale point. Some corrective measures should be therefore implemented so that the postharvest temperature conditions could be improved, thus increasing the salable period. This field study approach could be applied to other products in order to enrich knowledge of the cold chain in Thailand and other developing countries particularly in Southeast Asia where the ambient temperature is high.

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Table 1. The observed precooling conditions at the packing house

Batch	Water temperature[(i)]	Core temperature of baby corn[(ii)]			Precooling time
		Before precooling	After precooling	Temperature drop	
	(Mean ± SD, °C)	(Mean ± SD, °C)			(min)
1	19.8 ± 4.7	30.6 ± 0.7	24.5 ± 0.8	6.1± 0.8	16
2	18.2 ± 4.1	30.4 ± 0.7	23.6 ± 1.0	6.8 ± 1.0	13
Average	19.0 ± 4.5	30.5 ± 0.7	24.1 ± 1.0	6.4 ± 1.0	14.5

[(i)]Mean and standard deviation (SD) of 20 measured positions (ten positions at 100 mm and another ten positions at 400 mm from the surface of the water)

[(ii)]Mean and SD of ten samples of baby corn

Table 2. The slope value of weight loss variation with time

Group	Storage temperature (°C)	Slope value* (% per day)	R-squared
1	2.1 ± 0.1	0.34	0.9846
	4.3 ± 0.1	0.32	0.9686
2	2.1 ± 0.1	0.33	0.9940
	4.3 ± 0.1	0.37	0.9877

*Based on linear regression

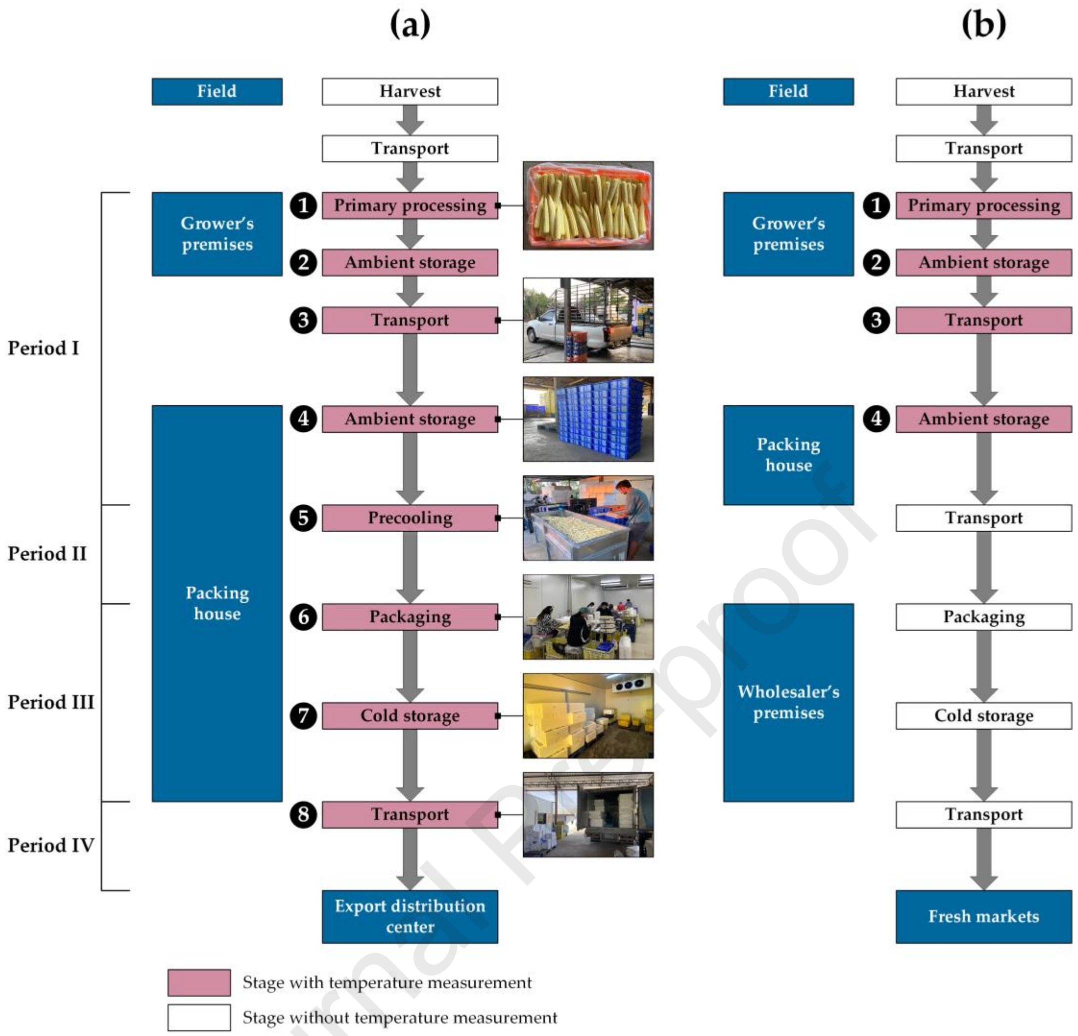

Fig. 1 Flow diagram showing a fresh-cut baby corn supply chain (a) for export and (b) for domestic markets

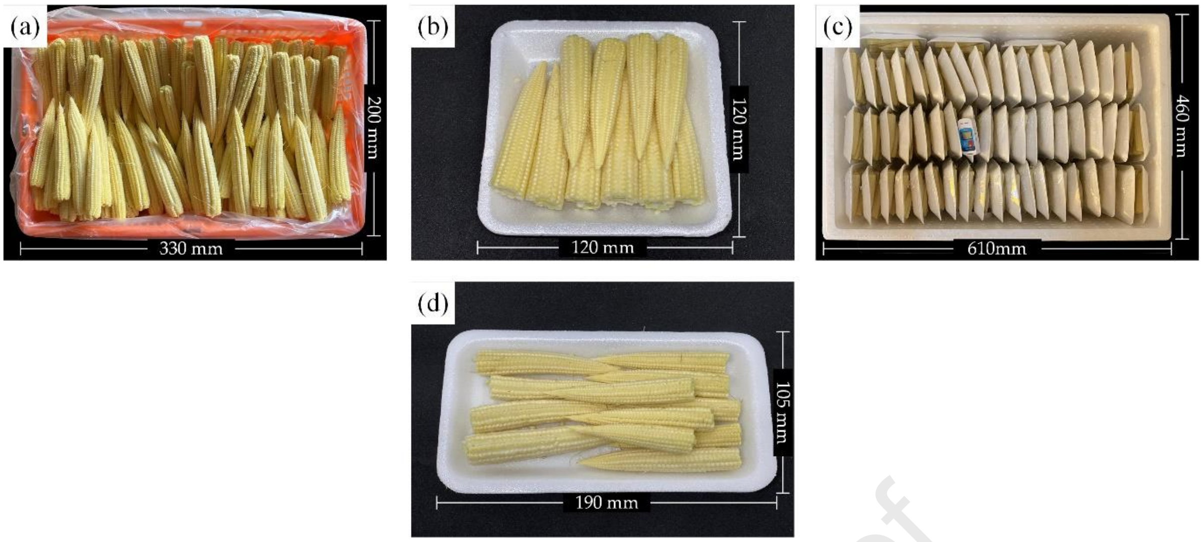

Fig. 2 Forms of baby corn packaging at different supply stages: (a) bulk packaging after processing at growers' premises, (b) retail packaging for export, and (c) bulk packaging after processing at a packing house, and (d) retail packaging for domestic markets.

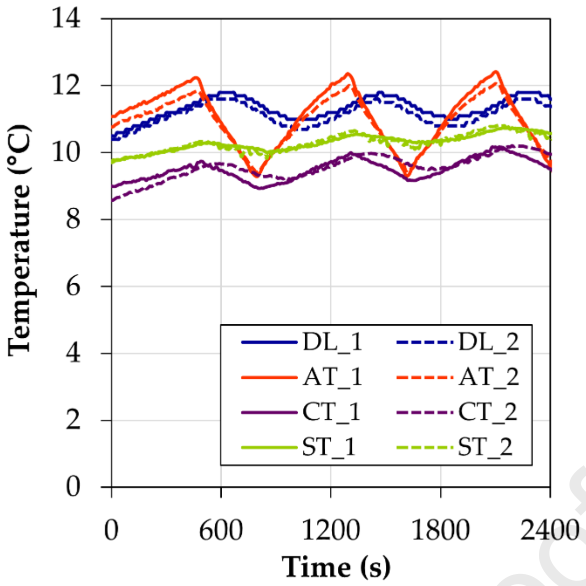

Fig. 3 Comparison between the temperature profiles recorded by dataloggers (Elitech® RC-5) and calibrated T-types thermocouples in a refrigerator (temperature setting: 8°C). DL is the temperature recorded by the dataloggers; AT, CT, and ST are the temperatures recorded by the thermocouples for the air, product core, and product surface, respectively. Numerals are the number of the dataloggers or thermocouples used.

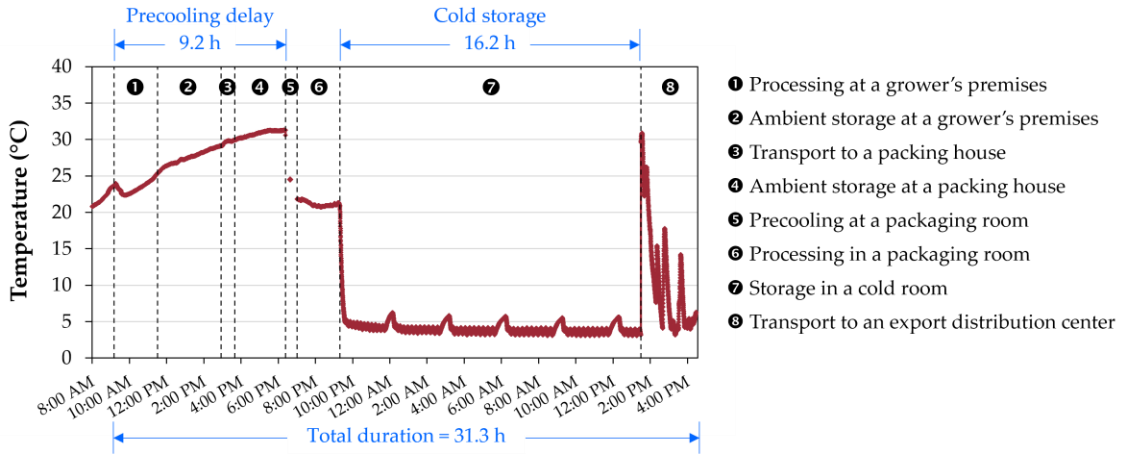

Fig. 4 Temperature evolution of a fresh-cut baby corn from the grower's premises to the export distribution center. The curve is composed of measurements performed during several stages: Stages 1 to 4, temperature recorded in a plastic basket; Stage 5, discrete measured temperature of the first precooled batch; Stages 6 to 7, temperature recordings in a polystyrene box; Stage 8, temperature recorded at the back door of refrigerated truck.

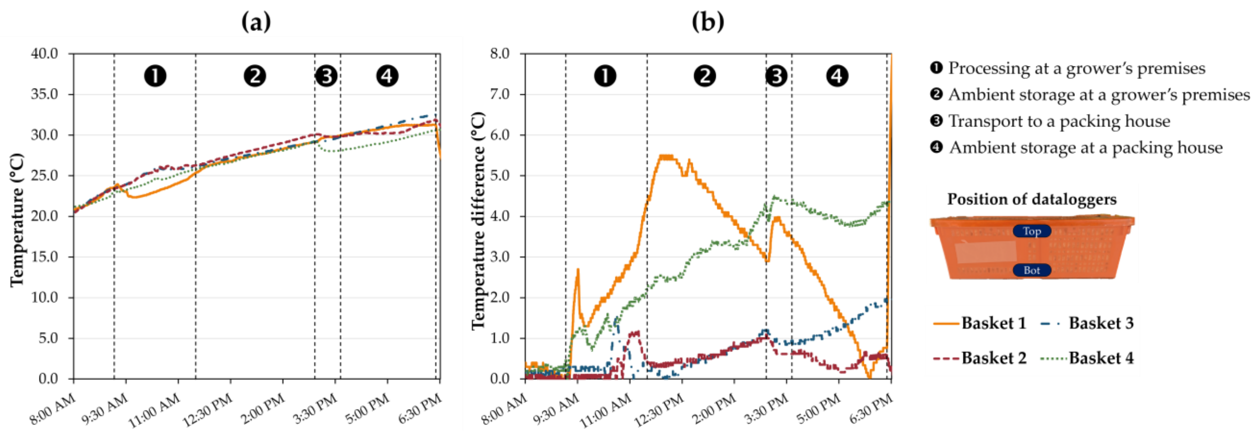

Fig. 5 Temperature conditions in the baskets containing dehusked and silk-removed baby corn cobs from the growers' premises to the packing house: (a) average temperature between the top and the bottom positions of individual baskets and (b) temperature difference between the two positions.

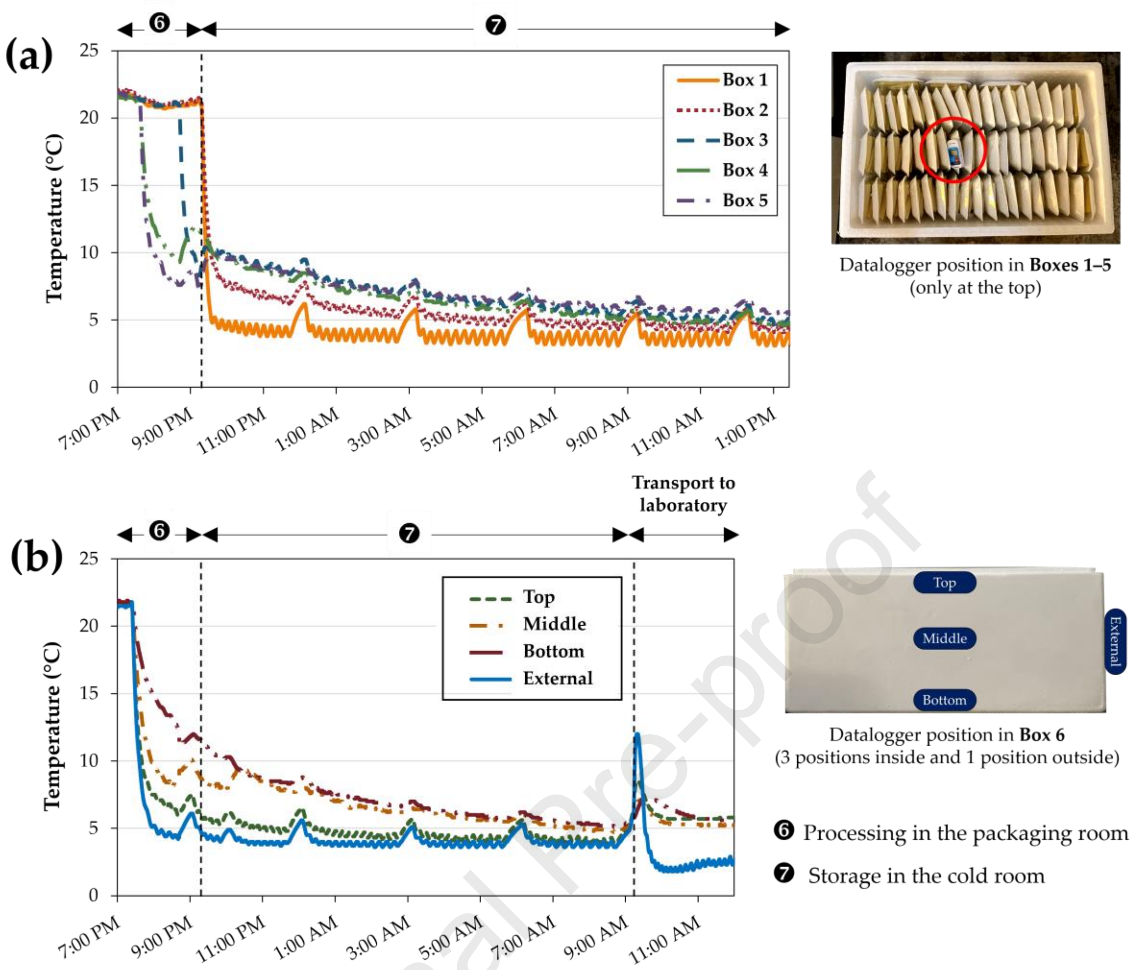

Fig. 6 Temperature evolution in the packaging room (Stage 6) and the cold room (Stage 7). (a) Boxes 1-5 sent to the export distribution center; (b) Box 6 for quality assessment in a laboratory.

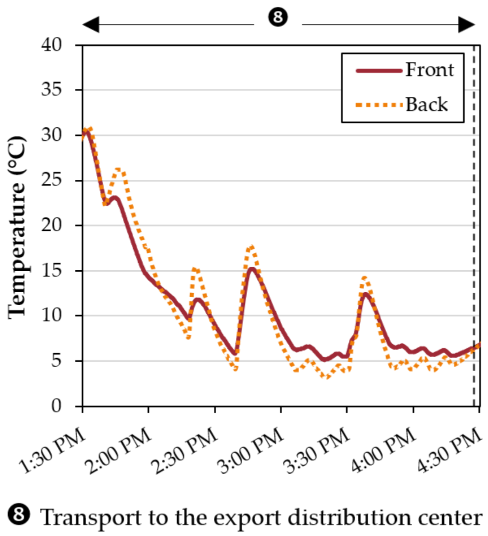

Fig. 7 Temperature conditions at the front and the back positions inside the refrigerated truck trailer during transport to the export distribution center.

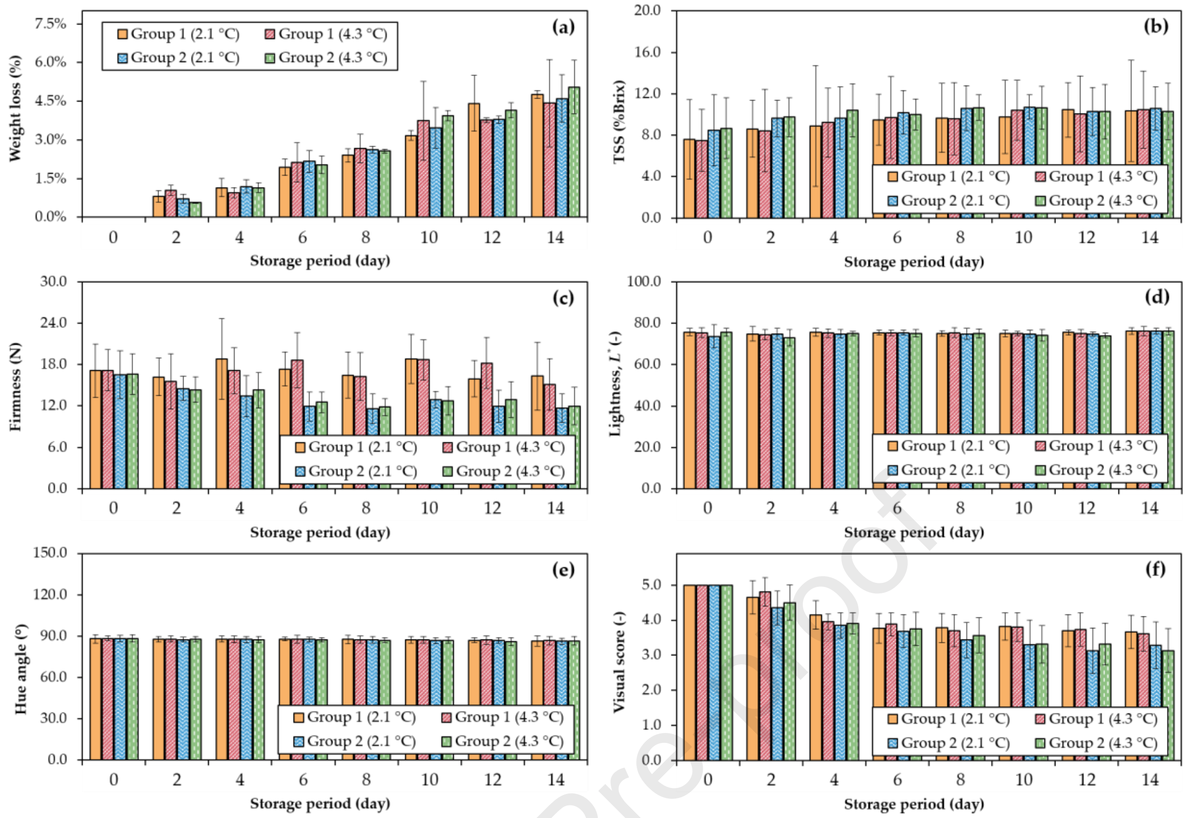

Fig. 8 Evolution of the quality attributes of the baby corn cobs for export (Group 1) and for domestic markets (Group 2) stored at 2.1°C and 4.3°C temperature conditions over a 14-day storage period: (a) Weight loss ($n = 2$), (b) total soluble solids (TSS) content ($n = 10$), (c) firmness (cutting force, $n = 10$), (d) lightness (L^*, $n = 20$), (e) hue angle ($n = 20$), and (f) visual score ($n = 60$). Data are presented as the mean value of n samples with a standard deviation (SD) bar.

Highlights

- The export and domestic fresh baby corn cold chains were investigated.
- Time-temperature profiles at different stages were examined.
- A substantial time interval between harvest and precooling was reported.
- Quality assessment was performed in order to evaluate product marketability.
- Given the storage conditions, the baby corn cobs remained salable for up to two weeks.

Conflict of Interest and Authorship Conformation Form

Please check the following as appropriate:

☑ All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

☑ This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

☑ The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript

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