CENTER for PRODUCE SAFETY

CPS 2020 RFP
FINAL PROJECT REPORT

Project Title
Using low-cost smartphone-based infrared cameras to evaluate cooling and storage conditions of fresh produce

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Objectives

1. *To compare the performance and accuracy of smartphone-based infrared (SBIR) cameras against a professional-grade IR camera for evaluation of proper cooling and storage conditions of whole and fresh-cut produce.*
2. *To develop effective user-friendly methods to operate SBIR cameras in produce handling facilities.*

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FINAL REPORT

Abstract
Populations of pathogens may increase in refrigerated fresh produce when subjected to temperature abuse. Thermal imaging (TI) is a non-contact and non-invasive technology that converts invisible radiation emitted by target objects into thermal images in real-time. The objective of this proof-of-concept study was to compare the performance of smartphone-based infrared (SBIR) cameras against conventional temperature acquisition devices for evaluation of proper hydrocooling and storage conditions of fresh produce including lettuces and cantaloupes. Four SBIR cameras (FLIR and Seek) attached to iOS and Android devices were independently evaluated for performance, accuracy, image quality, and battery life. Additionally, two independently operated and low-cost infrared (IR) thermal imagers (FLIR and Seek) were evaluated. Then, lettuce heads (iceberg and romaine) of varied sizes, and cantaloupes were immersed in chilled water for hydrocooling simulation after 20 h of incubation at 40 °C. Thermal images of hydrocooled produce were acquired with SBIR cameras and IR thermal imagers. Surface (ST) and internal (IT) temperatures of produce, as well as air and water temperatures, were recorded using type-K thermocouples connected to a data acquisition system. Afterwards, cardboard boxes containing fresh produce were stored in a walk-in cooler at different heights and thermal images of the refrigerated produce were taken for 3 days. Triplicate experiments were conducted, and data was statistically analyzed at α=0.05. In general, FLIR SBIR cameras attached to Android devices were more effective and easier to operate than Seek SBIR cameras to capture temperature profiles of fresh produce during simulated hydrocooling and storage. IR thermal imagers were also effective at capturing temperature profile of fresh produce; however, the resultant thermal images were of lower resolution than those captured by SBIR cameras. Cooling curves showed a fast, followed by a moderate, temperature drop in the first hour of simulated hydrocooling of fresh produce. After 1.5 h of hydrocooling, the IT of small lettuce heads reached 5 °C (target temperature) while the IT of large lettuce heads never reached 5 °C. Temperature data obtained with SBIR cameras and IR thermal imagers were confirmed with the data obtained with thermocouples. Interestingly, thermal images facilitated the observation of the heat transfer phenomena during simulated hydrocooling and storage. After 3 days of storage in the walk-in cooler, the thermal images showed that the ST of the fresh produce stored on higher shelves had significantly (P<0.05) higher temperatures than that of the produce stored on lower shelves. The study demonstrated that SBIR cameras are cost-effective temperature acquisition instruments that can be used by the fresh produce to quickly monitor surface temperature profiles of produce commodities during hydrocooling, packing and storage.

1. Background
The microbial safety of fresh fruits and vegetables is always a concern for the fresh produce industry. Ready-to-eat (RTE) fresh products have been increasingly implicated in outbreaks and are considered as vectors for the transmission of pathogenic microorganisms (Umutoni et al., 2020). The consumption of fresh produce has increased since the 1980s due to the recent health and wellness trends seen among modern consumers (Carstens, Salazar, & Darkoh, 2019). According to Doona et al. (2015), fresh produce is a fast-growing food segment that appeals to the health-conscious consumer as healthy, nutritional, convenient and tasty. Nevertheless, higher demand of fresh produce brings new challenges to the industry because these products are minimally processed and often eaten raw which increases the probability for foodborne pathogens to cause outbreaks that could affect consumers. Hence, controlling microbial growth in fresh produce during packing and storage is essential to ensure quality and safety.

According to the Centers for Disease Control and Prevention (CDC) around 10% of the total foodborne outbreaks in the U.S. were associated with the consumption of raw vegetable crops (prepackaged leafy greens, salad mixes and romaine lettuce) and fruits in 2016 (Dewey-Mattia et al., 2018). Currently, no chemical/physical/biological treatments are available that can eliminate all foodborne pathogens present in raw fruits and vegetables without affecting the quality of the products. Therefore, developing effective food safety interventions is necessary to reduce or prevent pathogen survival and growth in whole and fresh-cut produce during post-harvest handling and refrigerated storage.

Post-harvest processing of fresh produce includes, but is not limited to, rapid cooling, washing, disinfecting, slicing/cutting, packaging, and storing at temperatures between 3–5 °C to extend shelf life and minimize product damage, quality deterioration and microbial growth. Produce can carry significant microbial loads upon harvest. Postharvest handling of raw produce can only reduce microbial counts by 1–2 Logs (Doona et al., 2015). Concernedly, microbial contamination may occur during the post-harvest processing of produce through contaminated water, equipment, containers, knives, human hands, and gloves (Carstens et al., 2019). This indicates that foodborne pathogens can survive post-harvesting handling and low levels of them may even reach the final products.

Rapid cooling is a critical step in postharvest handling of fresh produce because it minimizes microbial growth and spoilage (Carstens et al., 2019). Fruits and vegetables are often cooled after harvesting to reduce “field heat.” This step minimizes quality deterioration due to the growth of spoilage bacteria and prevents the growth of foodborne pathogens. Rapid cooling of harvested produce is normally carried out with chilled water and/or ice. During this process, the temperature of the coolant is the only parameter monitored, while the temperature of the produce is often ignored. It is conventionally assumed that the coolant temperature is comparable to that of produce; however, this may not always be the case and could result in improper cooling.

In storage, produce generates heat primarily by respiration (Kader, 2002). During this process, fruits and vegetables utilize their local reserves (e.g., carbohydrates) as a source of energy and use the oxygen from the air to keep them alive; this heat is commonly known as “vital heat” (Saltveit, 2016). According to the US United Fresh Produce Association (2019), some fruits and vegetables have high respiration rates (e.g., spinach and asparagus) than others (e.g., grapes, apples, potatoes).

Respiration rates and shelf life of fruits and vegetables are controlled (to some extent) by the storage temperature. In general, higher storage temperatures induce higher respiration rates; and therefore, heat generation. According to Saltveit (2016), respiration rates of fresh produce increase 2- to 3-fold for every 10°C increment. Heat generation during storage may not be an issue if produce is free of pathogens. However, recognizing that low levels of pathogens may be present; vital heat may play a significant role on increasing the temperature of fresh produce and promoting the growth of foodborne pathogens if storage temperatures are not properly monitored.

Temperature measurements in food processing facilities are acquired with conventional thermometers, thermocouples, single-point infrared thermometers, and resistance temperature devices. However, these instruments can only collect the temperature of one specific point at a time and may require contacting the target object. Temperature of cold rooms is normally monitored by a single or set of temperature sensors. However, these measurements cannot be easily correlated to the real temperatures of produce. Therefore, leading to poor temperature control strategies that may result in products subjected to temperature abuse during storage.

According to Vadivambal and Jayas (2011), thermal imaging (TI) or infrared thermography, is a two-dimensional, non-invasive, and non-contact technique use to create thermal images in real-time (Gowen, Tiwari, Cullen, McDonnell, & O'Donnell, 2010). Thermal images are produced with infrared (IR) cameras that collect electromagnetic radiation (wavelengths of 0.9–14 μm) emitted by the target objects. Higher emitted radiation results in higher temperature values. Unlike other high-tech cameras that have recently been introduced into the market (e.g., hyperspectral), the performance of IR cameras is not affect by visible light and they do not require the use of special light sources (Gowen et al., 2010). Hence, they are powerful devices that can be used to collect temperature variations across an object or scene under different environmental conditions. TI has recently been introduced to quantify the changes in superficial temperature of objects with high spatial and temporal resolution (Das et al., 2021; ElMasry et al., 2020). The electromagnetic spectrum consists of gamma rays, X-rays, ultraviolet rays, visible light, IR, microwaves, and radio waves (**Fig. 1**). The infrared region (0.7–1000 μm) is further divided into near infrared (0.7−1.4 μm), short-wavelength infrared (1.4−3 μm), mid-wavelength infrared (3−8 μm), and far-wavelength infrared (8−1000 μm) regions. This subdivision is based on transmission windows where the atmosphere is transparent to IR. TI systems can detect radiation from the short wavelength to long wavelength infrared (0.9−14 μm) for industrial food applications. Normally, long-wavelength IR systems show maximum sensitivity around room temperature, while mid-wavelength IR systems have peak sensitivities at higher temperatures (e.g., 400 °C). Therefore, they may be more suitable for food processing and industrial operations involving elevated temperatures (Gowen et al., 2010). TI systems typically contain the following components: thermal cameras, optical systems (e.g., focusing lens, collimating lenses, and filters), detector arrays such as microbolometers, signal processing units, and image processing systems. Detectors (the most important part in TI systems) absorb the IR emitted by the target object in a specified waveband (e.g., 8−12 μm) and convert it into electrical signals proportional to the amount of radiation captured by them. The electrical signals are then sent to the signal processing units which translate the information into a chromatic or monochromatic thermal image (Gowen et al., 2010). The thermal image was captured in a form of a matrix of numerous color levels each of which indicate a specific temperature, showing the temperature patterns of the object (Chandel, Khot, Osroosh, & Peters, 2018).

Because of its prohibitive cost and complexity, TI has not been widely used by the food industry; whereas other fields such as construction, industrial maintenance, aerospace, military, and medicine have adopted the technology faster. Recently, TI is gaining popularity in the food industry due to the development of new thermal technologies that have significantly reduced the cost of IR cameras and simplified their operation (Vadivambal & Jayas, 2011). Even more, the development of high-tech smartphones, the availability of modern communication networks and the introduction of low-cost smartphone-based infrared (SBIR) cameras into the market have created a whole new realm of possibilities and opportunities to develop applications of these technologies aimed to improve the microbial safety of the food supply.

Different SBIR camera models are built with distinct features (e.g., lenses and infrared detectors), temperature ranges and frame rates are readily available at different costs. Even more, they have different accuracy and thermal resolution levels. This creates an opportunity to select the proper SBIR cameras for a specific application. Historically, professional-grade IR cameras have required the use of specialized post-processing software to analyze temperature profiles of object or scenes which may be time consuming. However, modern SBIR cameras can operate with image processing applications installed in smartphones that allows to easily import, edit, and analyze thermal images.

Nevertheless, the effectiveness of using these newly developed technologies as temperature monitoring tools in the fresh produce industry has not been reported yet. SBIR cameras should be evaluated before recommending their use in the post-harvest handling of fresh produce. SBIR cameras are different than standard cellphone cameras; for example, they require proper calibration, understanding of heat transfer and IR radiation to obtain accurate and precise measurements. Hence, we evaluated the performance of SBIR cameras to assess simulated hydrocooling and cold storage conditions of fresh produce.

2. Research Methods and Results

2.1 Materials

SBIR cameras: Four SBIR cameras were evaluated, including the FLIR ONE Pro (Arlington, VA, USA) (for Android and iOS devices) and Seek Thermal CompactPRO (Santa Barbara, CA, USA) (for Android and iOS devices).

IR thermal imagers: Two IR thermal imagers were acquired, including the FLIR CX5 (Arlington, VA, USA) and the Seek Thermal ShotPRO (Santa Barbara, CA, USA). The specifications of both SBIR cameras and IR thermal imagers are shown in **Table 1**.

Fresh produce: Iceberg, large and/or small romaine lettuce heads, and fresh cantaloupes were obtained from a local supermarket in Griffin, GA. Upon receipt, the lettuces and cantaloupes were stored in a cold room at 4 °C up to one day until use.

2.2 Methods

2.2.1 Simulation of hydrocooling of iceberg and romaine lettuces

Simulated hydrocooling of lettuces: Refrigerated lettuces were incubated at 42 °C for 20 h in an environmental chamber to increase the temperatures of the fresh produce and mimic field temperatures after harvesting. Then, eight lettuce heads were immersed in 15 L of chilled water (~0.4 °C) up to 90 min to simulate immersion hydrocooling. The procedure was conducted in triplicate.

Simulated hydrocooling of cantaloupes: Refrigerated cantaloupes were placed in an environmental chamber at 42 °C for 20 h. Then, the fresh produce was immersed in 15 L of chilled water (~4 °C) up to 2 h to simulate immersion hydrocooling. The procedure was conducted in triplicate.

Temperature measurements: Thermal images of fresh produce were taken before, during and after simulated immersion hydrocooling using SBIR cameras ─ Seek Thermal CompactPRO and the FLIR ONE Pro attached to an Android and/or iOS device (iPhone). Thermal images were also taken with handheld cameras FLIR CX5 and Seek Thermal ShotPRO. The surface and internal temperature of the fresh produce was continuously recorded at 10 s intervals using type-K thermocouples connected to a data acquisition system. The experimental setup of simulated hydrocooling experiments is shown in **Fig. 2**.

2.2.2 Storage conditions of fresh produce in walk-in cooler

Walk-in cooler storage: Lettuces and cantaloupes were stored in cardboard boxes at room temperature, and then boxes containing the fresh produce were placed on shelves at different heights in a walk-in cooler (height=7’3”, width= 9’9”) set at ~4 °C (**Fig. 3**).

Temperature measurements: Thermal images of fresh produce were taken before and during walk-in cooler storage using FLIR ONE Pro attached to an Android and/or iOS device (iPhone) and handheld camera FLIR CX5. The surface temperature of five spots of the fresh produce was recorded using thermometers. Also, temperature data loggers were used to record the air temperature at different height positions in the walk-in cooler. The experimental setup of the walk-in cooler storage is shown in Fig. 3.

Three-dimensional model of walk-in cooler: Virtual models of a walk-in cooler were created using a state-of-the-art 360-camera (Matterport Pro2) and the cloud-based software Matterport. The resultant virtual model was manually assembled and assessed based on its precision, accuracy, resolution, and easiness of manipulation. The collected footage was completed in a single take and the resultant virtual model can be accessed online through a computer, smartphone, or with a VR headset.

3 Results

3.1 SBIR cameras

In general, FLIR SBIR cameras were more effective and user-friendly than Seek SBIR cameras regardless of the smartphone type used. FLIR SBIR cameras are easily manipulated with the integrated App FLIR ONE. Also, the collected thermal images can be effectively processed and shared with the smartphones. However, FLIR SBIR cameras have a limited battery life (~45 min) when used continuously. On the other hand, Seek SBIR cameras offer a higher thermal resolution than FLIR SBIR cameras and their power source is the smartphone's battery (this feature is convenient if the thermal camera will be used for extended periods of time). However, Seek SBIR cameras do not have an autofocus feature, which makes them difficult to manipulate for data collection. In addition, the Seek Thermal App is extremely limited and not user-friendly.

Unlike the Seek SBIR cameras and professional grade IR cameras, the FLIR ONE Pro has a lower thermal resolution (results in fewer data points in a thermal image); however, we noticed that the thermal resolution of FLIR SBIR cameras is good enough to monitor surface temperature profiles of fresh produce during simulated hydrocooling and storage. Although excellent quality thermal images were taken with iOS and Android devices, higher quality images were taken when SBIR cameras were connected to Android devices. In addition, the performance of the tested IR thermal imagers was impressive. Overall, they had good thermal resolution and battery life (~4 h). Their construction was robust, and their software was easy to manipulate. Both devices offer Wi-Fi connectivity which facilitates data sharing and storage. The FLIR CX5 model was preferred over the Seek Thermal ShotPRO due to a distinctive feature called MSX (embossed visual details on thermal image). Although the evaluation of the thermal imagers was not initially proposed, our team realized that this type of device can be easily used in packinghouses of fresh produce due to their low cost and effectiveness.

3.2 Simulation of hydrocooling of fresh produce

Surface and internal temperatures (obtained with thermocouples) of lettuce heads during simulated hydrocooling are shown in **Fig. 4**. Simulated hydrocooling of lettuces was conducted for 90 min. Room temperature was kept at ~22 °C; meanwhile chilled water temperature was kept constant (~0.4 °C). As expected, after incubation at ~42 °C for 20 h, the surface and internal temperatures of lettuce heads were >25 °C. Cooling curves of lettuces showed a moderate temperature drop at the beginning of the hydrocooling experiment which corresponds to heat lost (sensible heat) from the product to the chilled water (Fig. 4A–C). After 1 h of hydrocooling, the surface temperature of small romaine lettuce heads approached 5 °C (Fig. 4B). The internal temperature was always higher than the surface temperature of lettuces, and this effect was more evident in iceberg lettuce (Fig. 4C). Furthermore, it was overly concerning that the internal temperature of large lettuce heads never reached 5 °C even after 90 minutes of simulated hydrocooling (Fig. 4C). These results were confirmed with thermal images taken with SBIR cameras (**Figs. 6–8**). Thermal images revealed the higher internal temperatures compared with surface temperatures of lettuce heads during hydrocooling. This result suggests that the hydrocooling conditions were not effective at reducing the temperature of lettuce heads to acceptable levels (~5 °C). This may be a concern if cold surface lettuces with a warm core are further processed for the fresh-cut market.

The cooling curves of warm cantaloupes were also obtained (**Fig. 5**). The surface temperatures of cantaloupes rapidly decreased during the first 30 min of hydrocooling. Internal temperatures were higher than surface temperatures of cantaloupes during the 2 h of simulated hydrocooling. It is important to highlight that the internal temperatures of cantaloupes were ~18 °C after 90 min and did not reach 10 °C even after 2 h of simulated hydrocooling. Thermal images taken with SBIR cameras confirmed those results (**Fig. 9**).

The results suggest that SBIR cameras can be used to obtain surface temperature profiles of fresh produce during hydrocooling. Moreover, thermal images are more effective at supporting quicker informed decisions to correct process deviations compared to conventional single point temperature measurements.

3.3 Storage conditions of fresh produce in walk-in cooler

Refrigerated lettuce heads were left in cardboard boxes at room temperature (~22 °C) for 12 h. Then the surface temperature of lettuce heads was recorded at 20±1 °C (**Fig. 10A**). After 24 h of refrigerated storage, the surface temperature of lettuce heads stored in cardboard boxes decreased ($P<0.05$) (**Fig. 11A**). Mean surface temperatures of lettuce heads stored at higher, middle and lower shelf positions were 3.6±0.27 °C, 3.12±0.13 °C and 2.36±0.1 °C, respectively. After 3 days of storage, the mean surface temperatures of fresh lettuce heads at the higher, middle and lower shelf positions dropped to 2.78±0.21 °C, 2.24±0.16 °C, and 1.71±0.06 °C, respectively. What is more, there is a significant ($P<0.05$) difference in surface temperature between lettuces stored at different height positions during 3 days of storage. Thermal images taken with SBIR cameras confirmed those results (**Fig. 12**).

Similarly, refrigerated cantaloupes were placed in cardboard boxes and left overnight at room temperature (~22 °C) (**Fig. 10B**). The surface temperatures (obtained with thermometers) of fresh cantaloupes during three days of walk-in cooler storage are shown in **Fig. 11B**. After one day of refrigerated storage, the surface temperature of cantaloupes placed at higher, middle and lower shelf positions was 4.32±0.1 °C, 3.78±0.19 °C and 3.31±0.03 °C, respectively. The surface temperature of cantaloupes dropped ~0.3 to 0.4 °C every 24 h and started to plateau after 3 days. After 3 days of refrigerated storage, the surface temperature of cantaloupes at higher, middle and lower shelf position dropped to 3.41±0.09 °C, 3.09±0.06 °C and 2.73±0.09 °C, respectively. A significant ($P<0.05$) difference in surface temperature between cantaloupes stored at different height positions during 3 days of storage was found, and the thermograms obtained from SBIR cameras confirmed those findings (**Fig. 13**).

It is noted that the air temperature obtained from temperature data loggers placed at different height positions in the walk-in cooler constantly fluctuated (**Fig. 14**), which might be caused by human activity in the walk-in cooler and frequent opening and closing of the door during temperature measurements. But there are still differences in air temperature between each height level. High variability and uneven air temperature distributions may be observed inside cold rooms used to store fresh produce. This phenomenon is affected by how the product is stacked, quantities stored and the initial temperature of the products. Temperature abuse inside cold rooms may be observed in areas with poor air circulation and high moisture condensation. If not properly controlled, this may promote a rapid product deterioration and the growth of foodborne pathogens, thus representing a food safety concern. However, critical areas (areas where temperature abuse occurs) may be difficult to identify using conventional tools (Warbick, 2017). Although the experiments carried out in this research were under controlled conditions and adequate air circulation, different results may be obtained in larger commercial walk-in coolers. It is important to mention that our team successfully developed a virtual model of the walk-in cooler (**Fig. 3**) that can be used for workforce training (available at: https://my.matterport.com/show/?m=966gToxUj5D). This model was not planned in the original research, but the team believes that the virtual tour of the walk-in cooler will help to communicate results more effectively.

Presently, there is an opportunity to integrate the use of SBIR cameras to monitor temperature profiles of fresh produce during postharvest handling and storage. SBIR cameras can streamline the acquisition, analysis and reporting of temperature profiles of fresh produce. Moreover, SBIR cameras can be used to improve the effectiveness of the cooling process of fresh produce and assist in identifying faulty equipment in direct contact with produce (e.g., warm conveyor belts and air leakage in insulated cold rooms) that may compromise the temperatures of fresh produce. Thermal images of fresh produce, obtained by produce handlers, can be sent to managers and/or engineers of packinghouses who can remotely evaluate the cooling and storage conditions of fresh produce in "real-time" and at an affordable price.

Outcomes and Accomplishments

Four SBIR and two IR thermal imagers were tested. Our team obtained better results with FLIR SBIR cameras than with Seek SBIR cameras (quality of images, ease of post-processing, etc.) to monitor the temperatures of fresh produce during simulated hydrocooling. These results suggest that SBIR cameras can be effectively used to obtain temperature profiles of hydrocooled fresh produce, and they are comparable to the professional handheld cameras. Moreover, thermal images can be easily read and used to make quicker decisions to correct process deviations compared to conventional contact and single point temperature measurements. During walk-in cooler storage test, the FLIR camaras could still obtain precise results and faster compared to regular thermometers. The research was coordinated and conducted by the PI in collaboration with the Co-PI.

Summary of Findings and Recommendations

Overall, temperature profiles of fresh produce were accurately acquired by SBIR cameras and FLIR SBIR cameras were more effective than Seek SBIR cameras to monitor the temperatures of fresh produce. A main limitation for FLIR SBIR cameras is their short battery life; while for Seek SBIR cameras is their lack of autofocus. IR thermal imagers are effective devices at acquiring surface temperatures of fresh produce with the added benefit of an extended battery life compared to SBIR cameras. The study demonstrated that SBIR cameras can effectively capture temperatures of fresh produce during hydrocooling and refrigerated storage with better effectiveness and convenience than traditional temperature acquisition systems. The approach utilized in this study can be used by the fresh produce to evaluate their current hydrocooling and/or vacuum cooling as well as storing practices. SBIR cameras are a practical, easy-to-use, and cost-effective temperature monitoring alternative that allows a quick response to unexpected process deviations that may compromise the temperature of fresh produce during post-harvest handling and storage.

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APPENDICES

Publications and Presentations

In June 2021, the Principal Investigator presented a poster on interim project results at the CPS Research Symposium (held virtually). Final results of the project will be presented at the CPS Research Symposium in June 2022.

The project was completed in December 2021. A peer-review and/or extension publication is in preparation, and a presentation will be delivered at the Annual Meeting of the Institute of Food Technologists in Chicago, IL in the summer of 2022.

Budget Summary

This project was awarded a total budget of $41,882. We estimate that >80% of the budget has been spent so far. The remaining funds will be spent on travel and publication fees.

Table 1 and Figures 1–14 *(see below)*

Table 1 - Smartphone-based infrared (SBIR) cameras evaluated in the study.

#	Model	Platform	Weight	IR Resolution	Power source	Frame rate	Temp range	Temp accuracy
1	FLIR ONE Pro	Android	1.29 oz	160x120	Battery	8.7 Hz	-20°C ~ 400°C	±3 °C or ±5%
2	FLIR ONE Pro	iOS	1.29 oz	160x120	Battery	8.7 Hz	-20°C ~ 400°C	±3 °C or ±5%
3	Seek Thermal CompactPRO	Android	0.5 oz	320x240	Phone	9 Hz	-40°C ~ 330°C	
4	Seek Thermal CompactPRO	iOS	0.5 oz	320x240	Phone	9 Hz	-40°C ~ 330°C	
5	FLIR CX5*	N/A	6.72 oz	160x120	Battery	8.7 Hz	-20°C ~ 400°C	±3 °C or ±5%
6	Seek Thermal ShotPRO*	N/A	7.2 oz	320x240	Battery	9 Hz	-40°C ~ 330°C	

*Does not require the use of a smartphone.

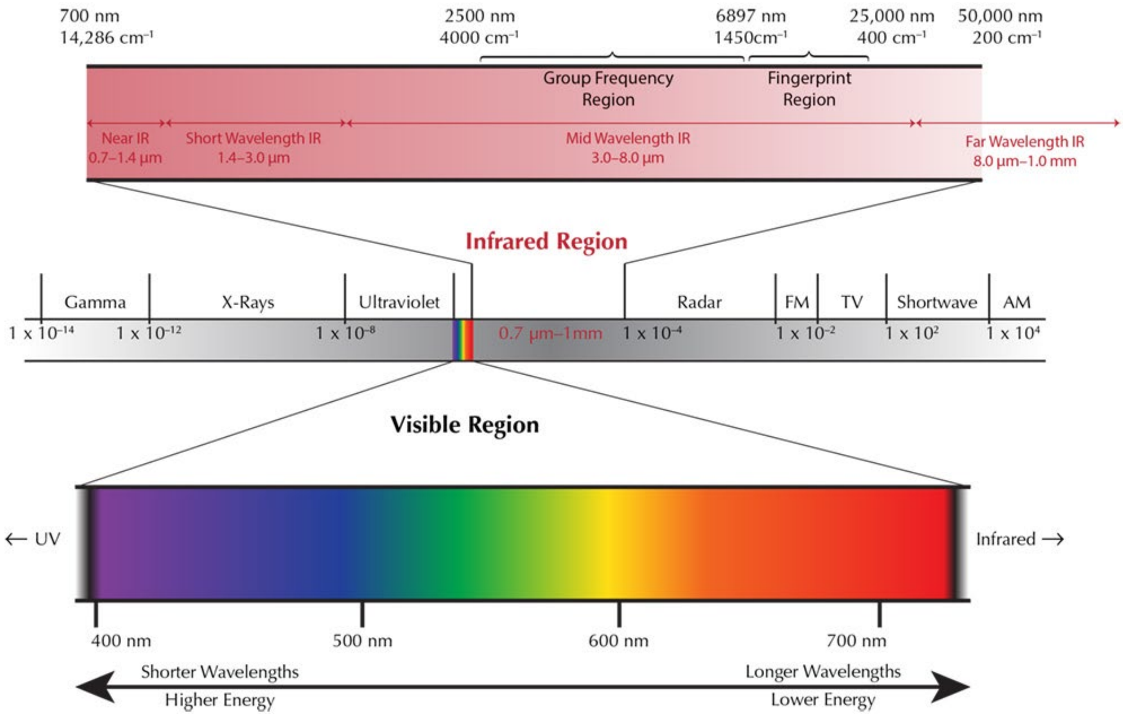


Fig. 1. Electromagnetic spectrum with visible (380−740 nm) and infrared (0.7−1000 μm) spectra magnified (Hughes, Castoro, Nyunt, & Kiefert, 2007).

Fig. 2. Simulated hydrocooling of romaine lettuce, iceberg lettuce and cantaloupes.

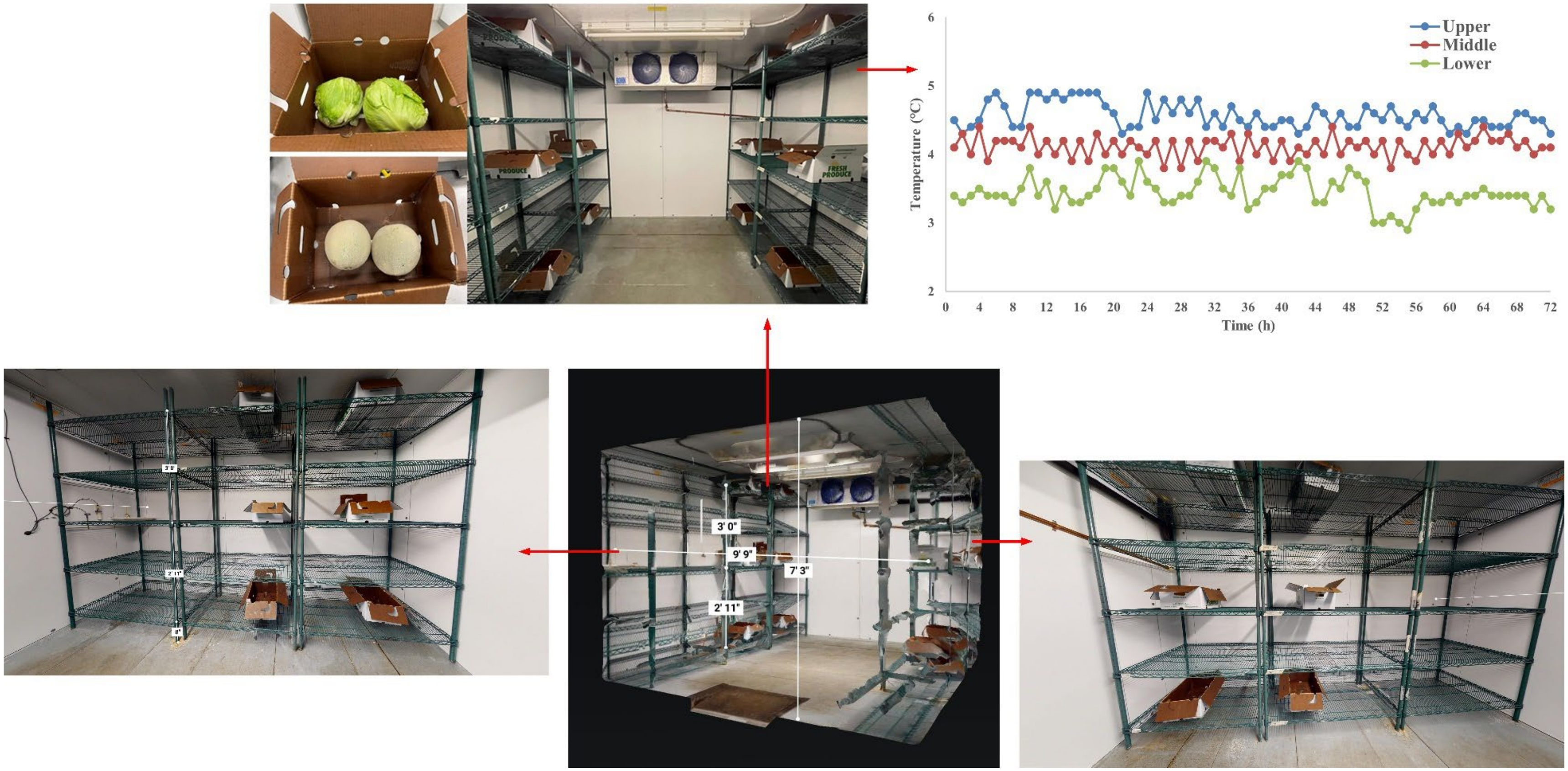


Fig. 3. Walk-in cooler storage of fresh iceberg lettuce and cantaloupes at different height positions (upper, middle, and lower). 3D model of walk-in cooler can be accessed at: https://my.matterport.com/show/?m=966gToxUj5D

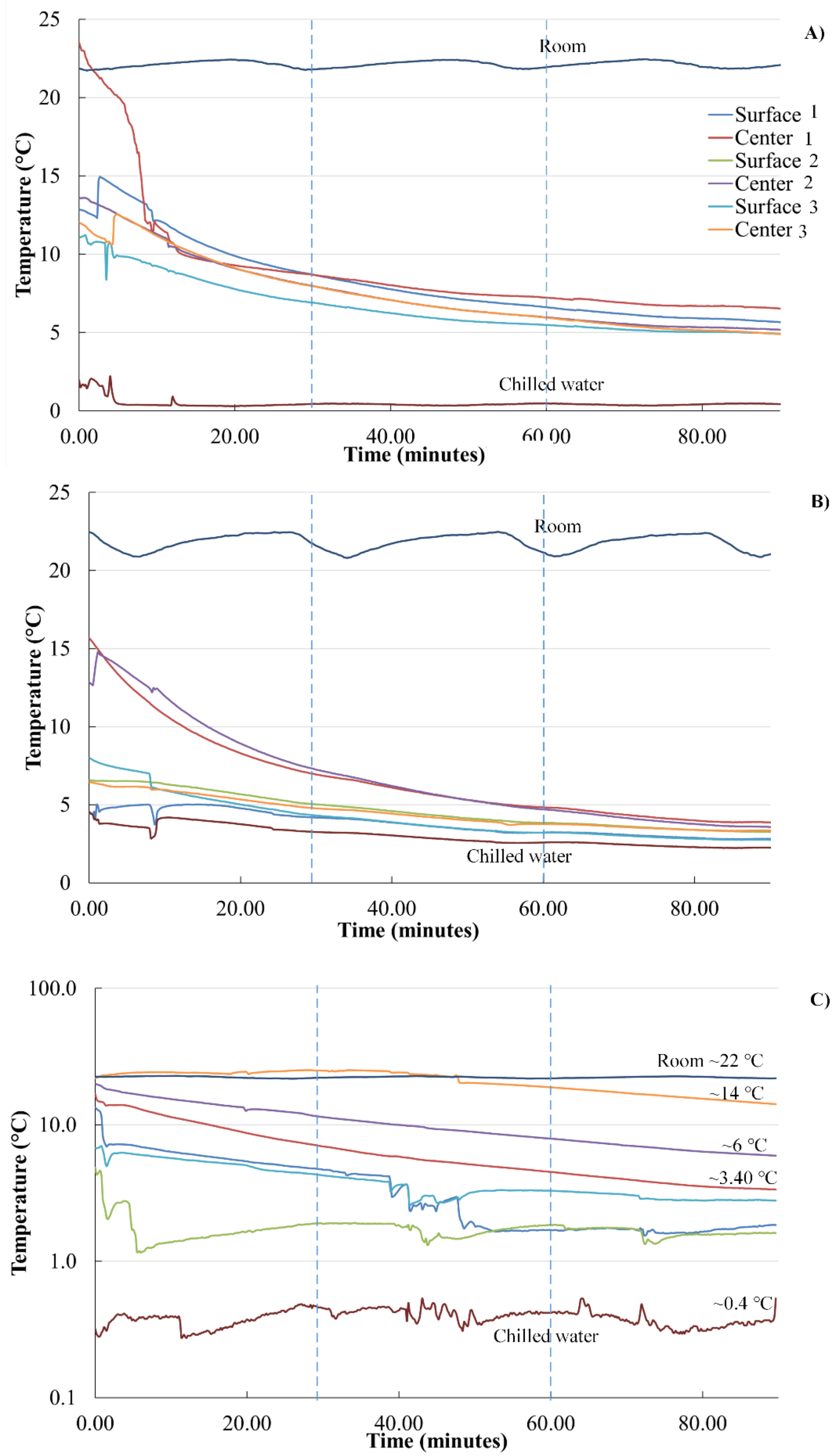


Fig. 4. Surface and internal temperatures (°C) of large romaine lettuce heads (A); small romaine lettuce heads (B); and iceberg lettuce heads (C) during 90 minutes of simulated hydrocooling. The temperature of three lettuce heads were monitored (1, 2, and 3).

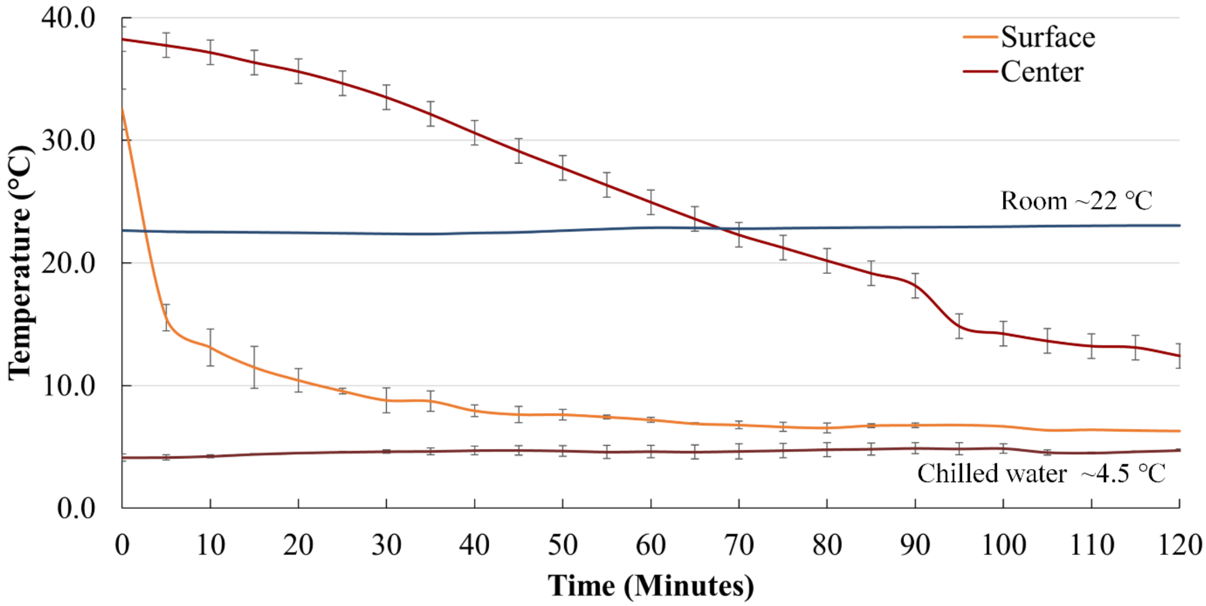


Fig. 5. Surface and internal temperature (°C) of cantaloupes during two hours of simulated hydrocooling.

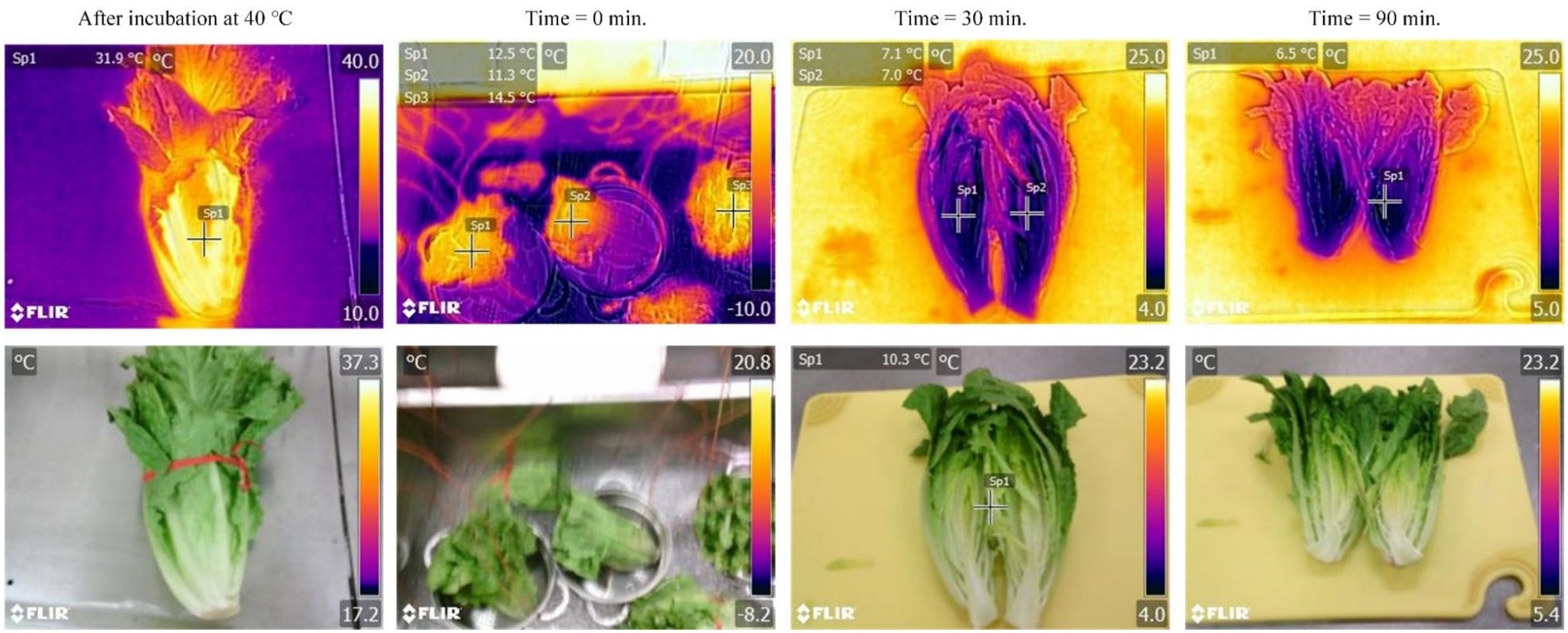


Fig. 6. Thermal images (taken at room temperature of ~22 °C, relative humidity ~55%) of large romaine lettuces stored at 40 °C for 20 h, and during simulated hydrocooling after 0, 30, and 90 min. Thermal images were taken with FLIR CX5 camera.

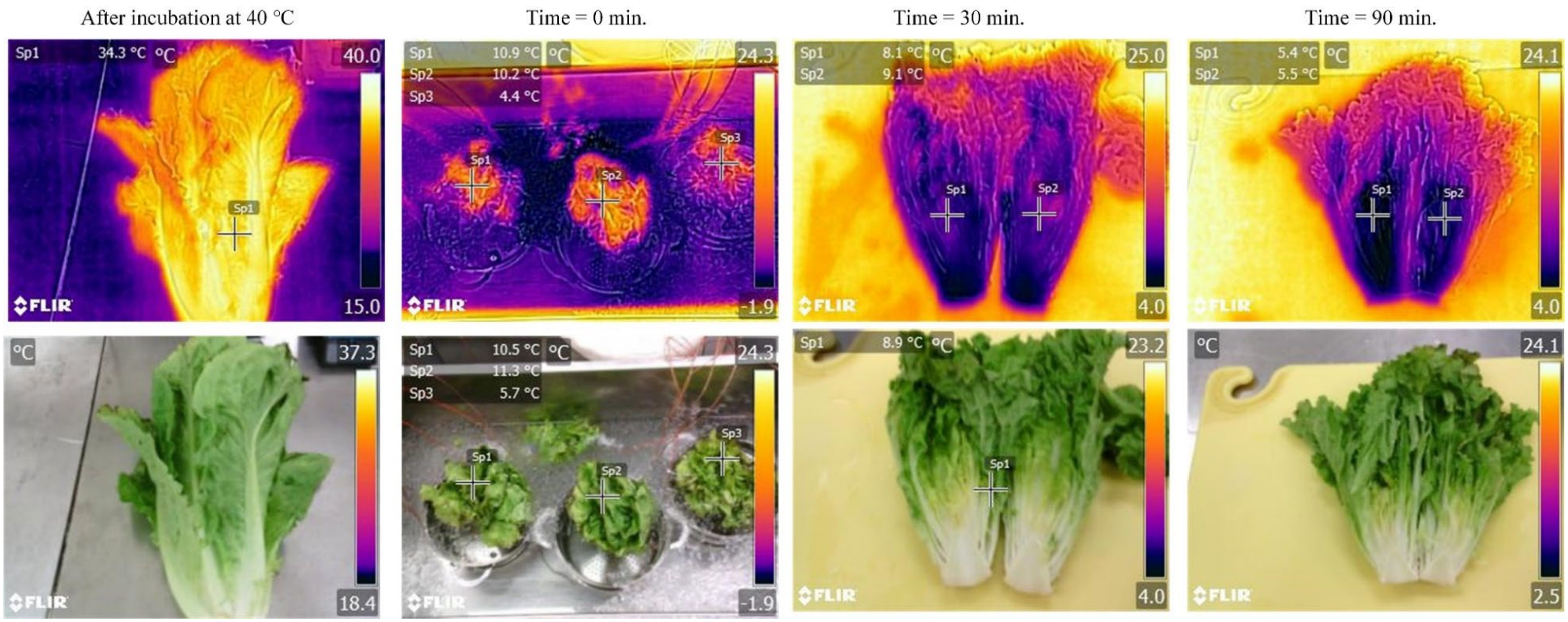


Fig. 7. Thermal images (taken at room temperature of ~22°C, relative humidity ~55%) of small romaine lettuces stored at 40°C for 20 h, and during simulated hydrocooling after 0, 30, and 90 min. Thermal images were taken with FLIR CX5 camera.

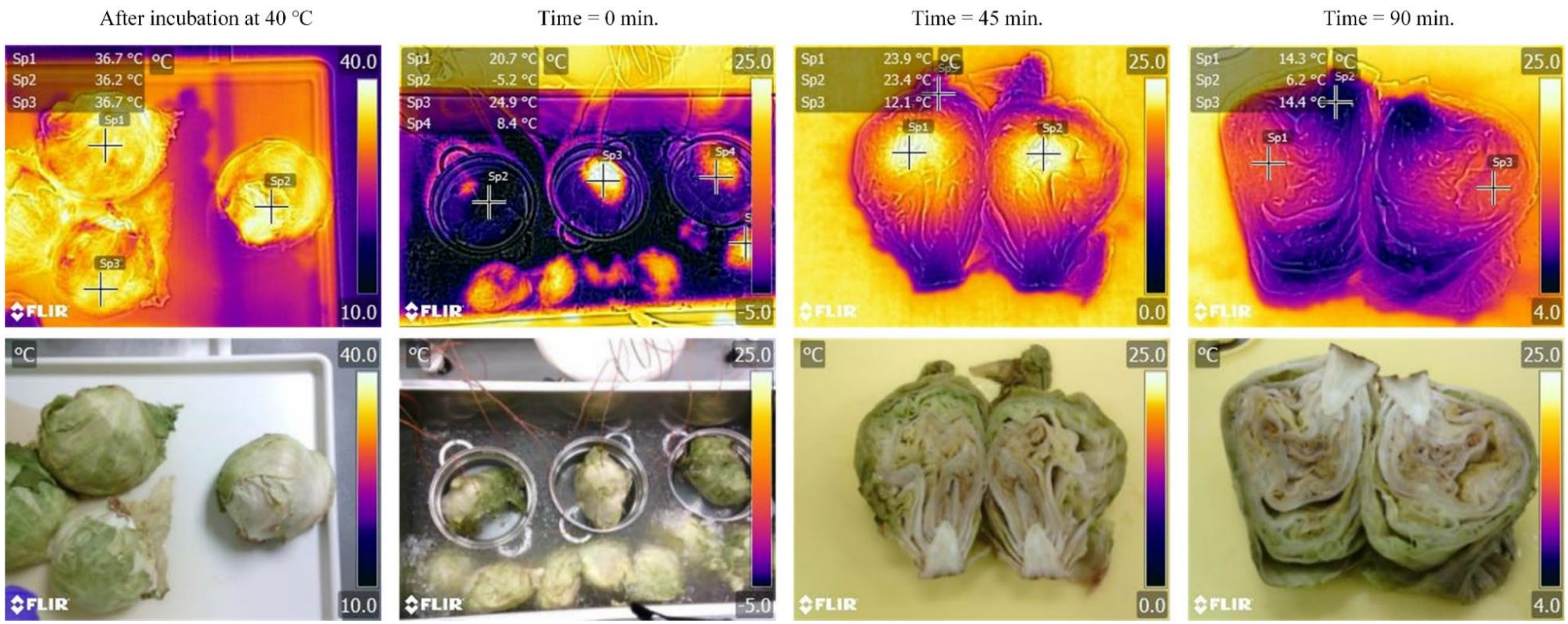


Fig. 8. Thermal images (taken at room temperature of ~22 °C, relative humidity ~55%) of iceberg lettuces stored at 40 °C for 20 h, and during simulated hydrocooling after 0, 30, and 90 min. Thermal images were taken with FLIR CX5 camera.

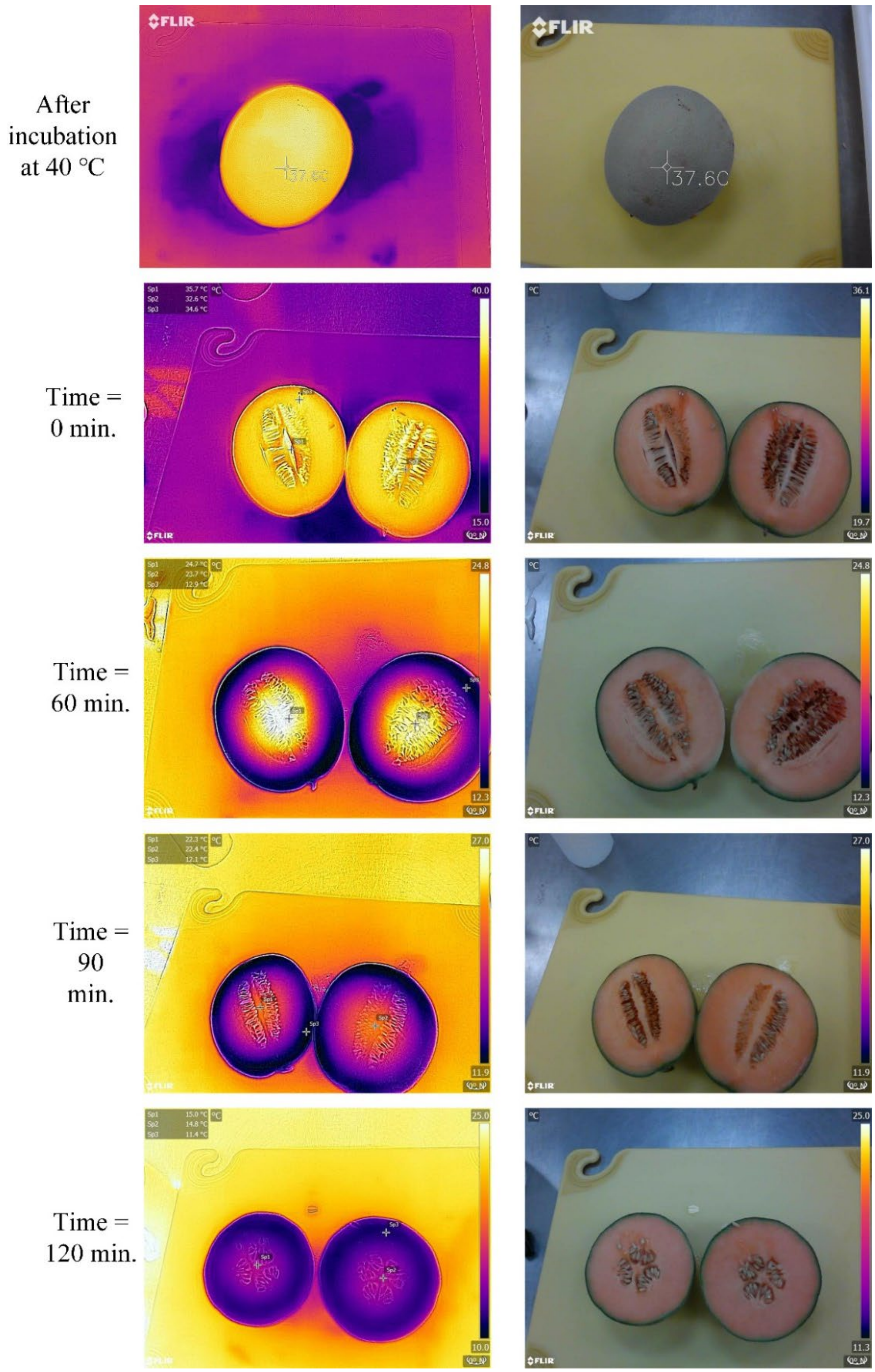


Fig. 9. Thermal images (taken at room temperature of ~22 °C, relative humidity ~55%) of cantaloupes incubated at 42 °C for 20 h, and during simulated hydrocooling after 0, 60, 90 and 120 minutes (about 2 hours). Thermal images were taken with FLIR ONE Pro camera connected to an Android smartphone.

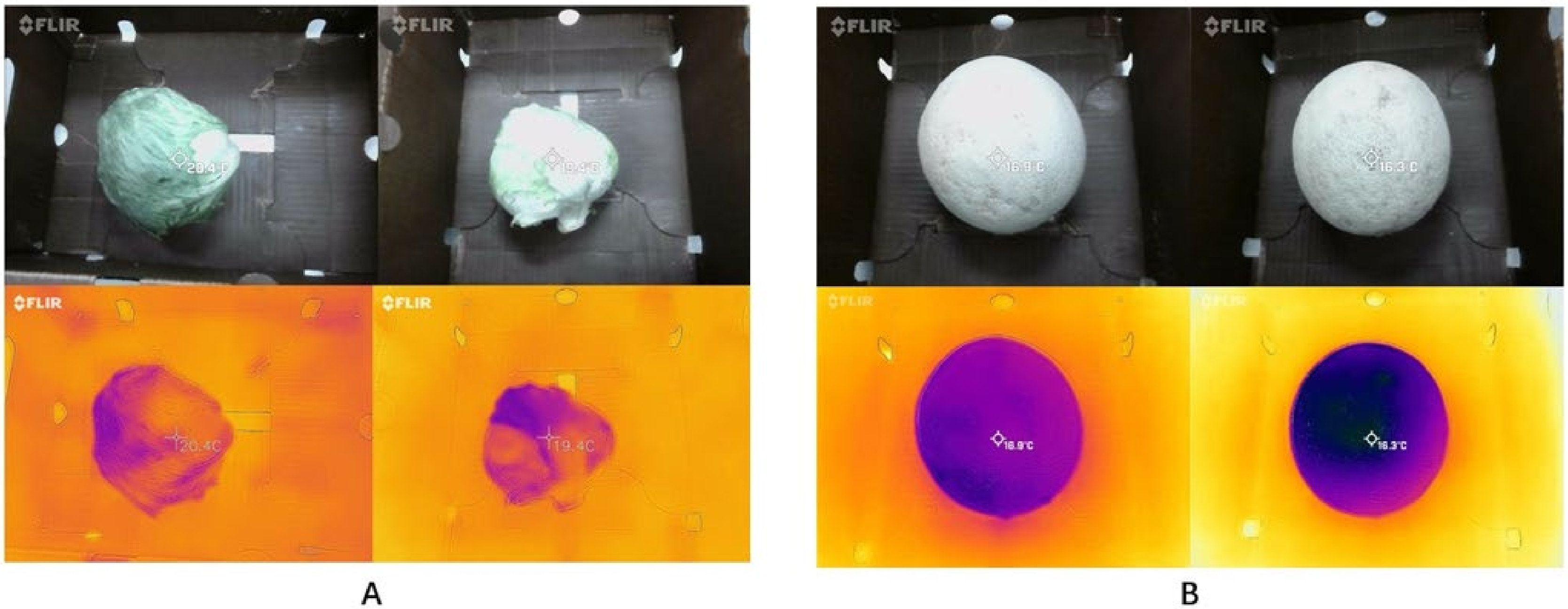
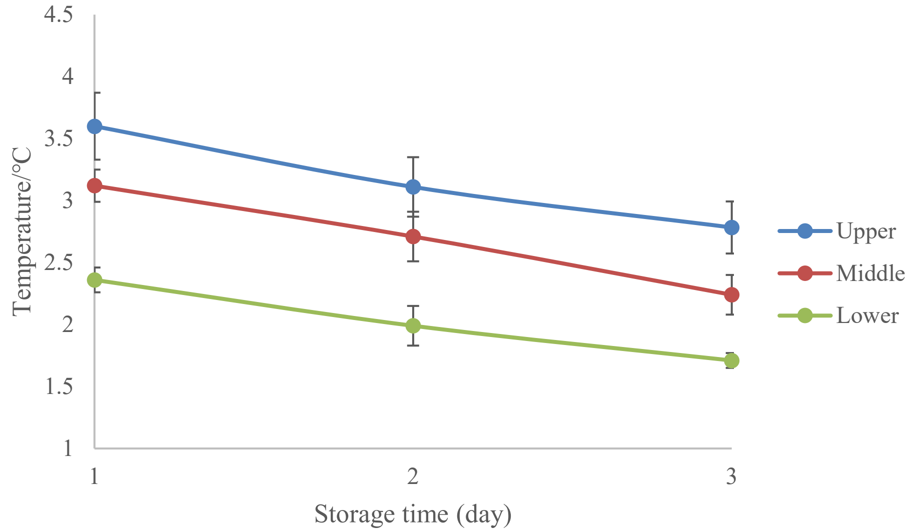


Fig.10. Thermal images of iceberg lettuces and cantaloupes stored at room temperature for 12 h. Thermal images were taken with FLIR ONE Pro camera connected to an Android smartphone.

A)



B)

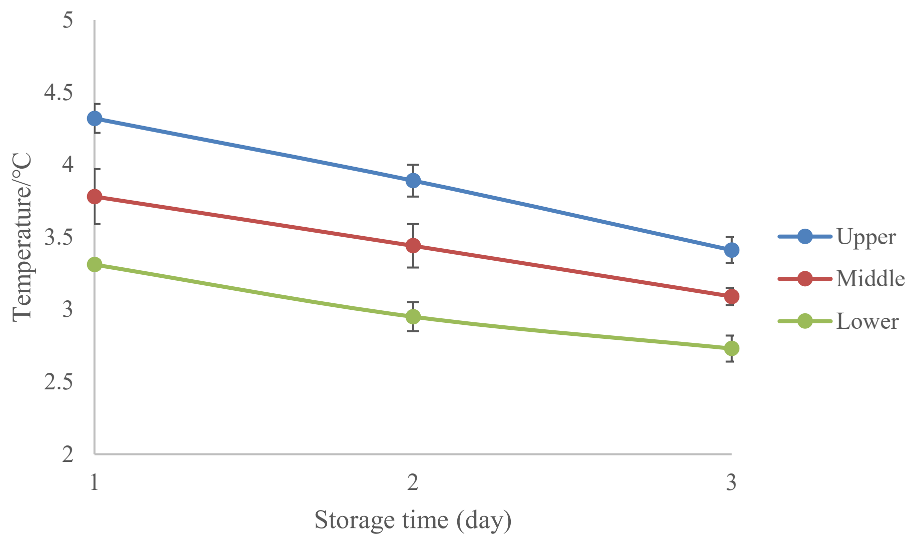


Fig. 11. Surface temperature (°C) of iceberg lettuces (A) and cantaloupes (B) at different heights (upper, middle, and lower) inside a walk-in cooler during three days of refrigerated storage.

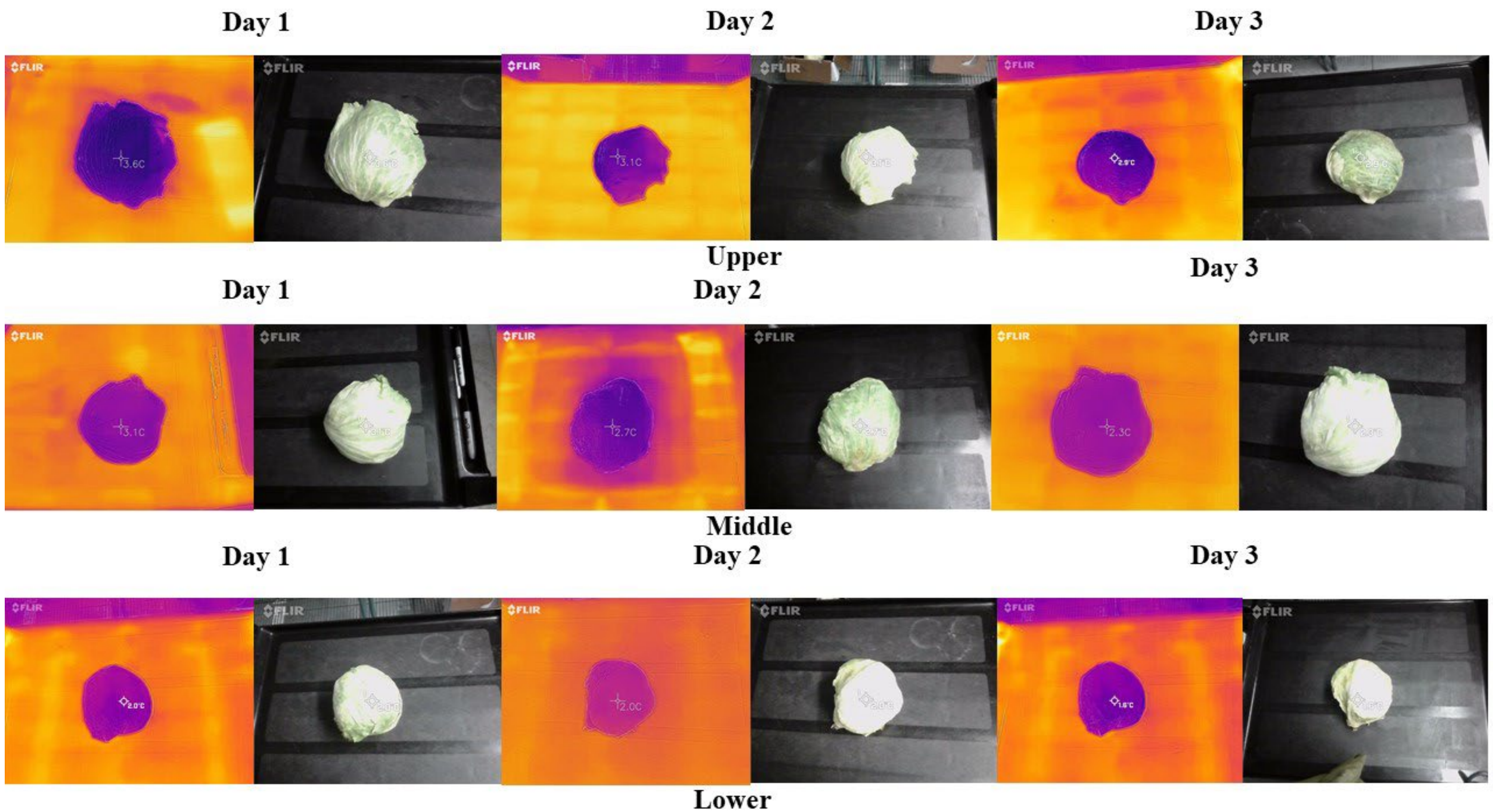


Fig.12. Thermal images of iceberg lettuces at different height positions (upper, middle, and lower) during 3 days of walk-in cooler storage. Thermal images were taken with FLIR One Pro camera connected to an Android smartphone.

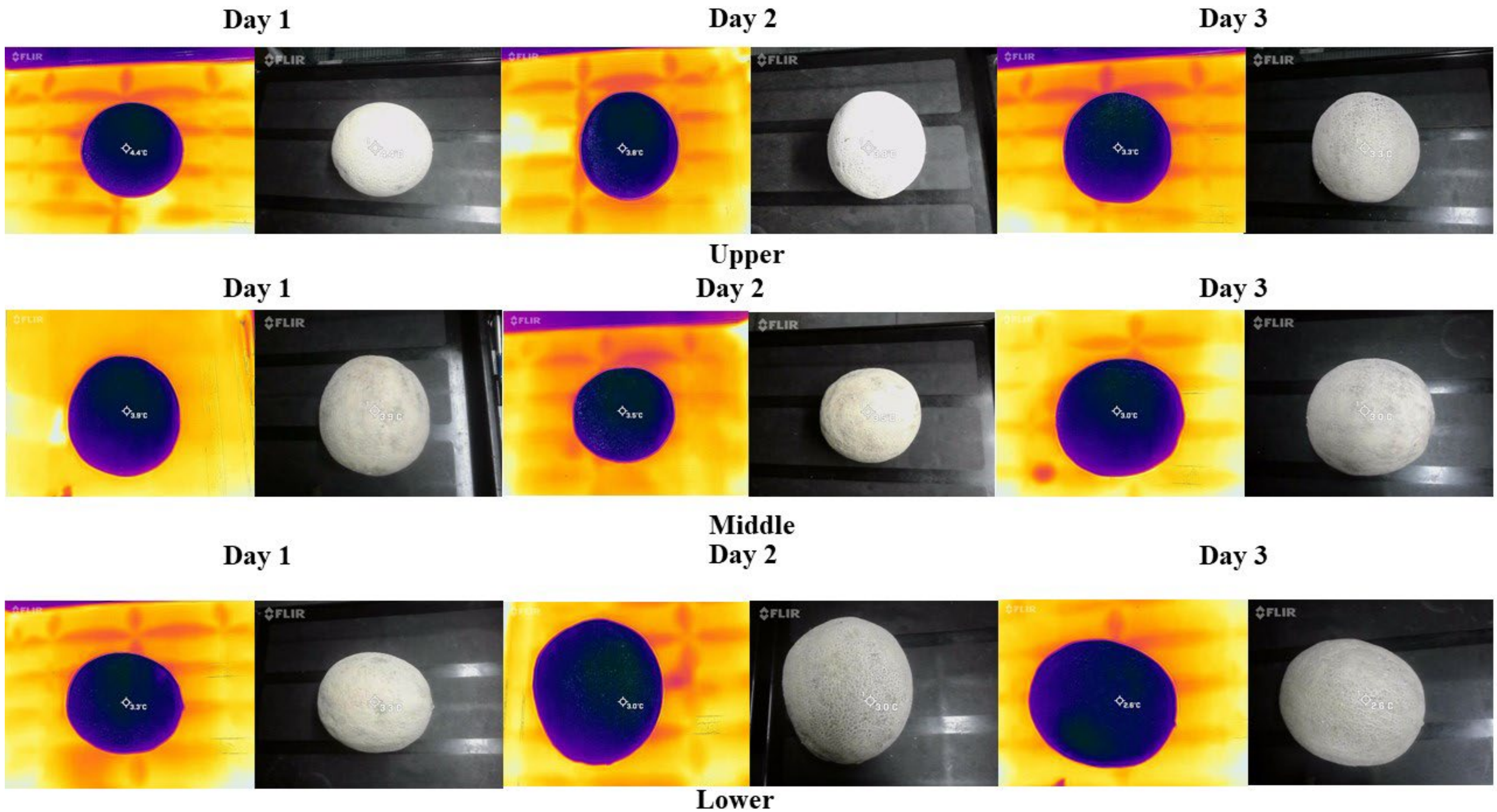


Fig.13. Thermal images of cantaloupes at different height positions (upper, middle, and lower) during 3 days of walk-in cooler storage. Thermal images were taken with FLIR ONEne Pro camera connected to an Android smartphone.

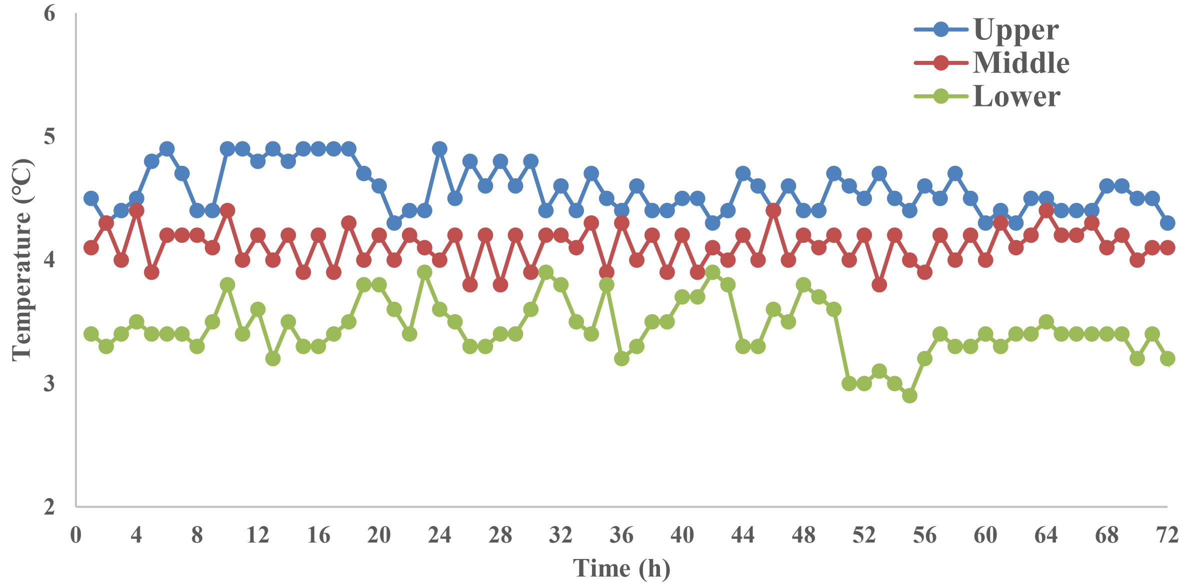


Fig. 14. Air temperature obtained from temperature data loggers placed at different height positions (upper, middle, and lower) in the walk-in cooler.