Hindawi
Journal of Food Processing and Preservation
Volume 2024, Article ID 4004963, 12 pages
https://doi.org/10.1155/2024/4004963

Research Article

Effects of Delayed Precooling on the Postharvest Quality and Anthracnose Incidence of "Irwin" Mangoes

Ying-Che Lee,[1] Zhao-Wei Wei,[1] Meng-Chieh Yu,[1] Jyh-Shyan Tsay,[2] Min-Chi Hsu,[3] Ping-Hsiu Huang,[4] and Yu-Shen Liang[1]

[1]*Department of Plant Industry, National Pingtung University of Science and Technology, Pingtung 912, Taiwan*
[2]*Department of Horticulture and Landscape Architecture, National Taitung Junior College, Taitung 950, Taiwan*
[3]*Taiwan Agricultural Research Institute, Council of Agriculture, Taipei 413008, Taiwan*
[4]*School of Food, Jiangsu Food and Pharmaceutical Science College, No. 4, Meicheng Road, Higher Education Park, Huai'an City, Jiangsu Province 223003, China*

Correspondence should be addressed to Ping-Hsiu Huang; hugh0530@gmail.com
and Yu-Shen Liang; justinliang@mail.npust.edu.tw

Received 23 December 2023; Revised 13 January 2024; Accepted 7 February 2024; Published 28 February 2024

Academic Editor: Ravi Pandiselvam

Copyright © 2024 Ying-Che Lee et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Mangoes are typical climacteric tropical fruits with accelerated metabolism, degradation, and senescence after harvest due to the accumulation of field heat. Thus, removing field heat as soon as possible after harvest is essential. In addition, a severe postharvest disease of mango, anthracnose, has been reported to be caused by *Colletotrichum gloeosporioides*, thus decreasing the shelf life and limiting mango export. This study was performed to investigate the effect of delayed precooling on the quality and incidence of anthracnose during storage of Irwin mango at different operational times after the harvest. Therefore, in this study, Irwin was precooled for 30 min at 3, 6, 12, and 24 h postharvest and immediately stored in a cold room at 5°C. The appearance, anthracnose incidence, respiration rate, ethylene production, firmness, total soluble solids (TSS), titratable acidity (TA), and fruit overripening rate were monitored throughout the shelf life. Early precooling was found to delay anthracnose incidence during the shelf life. Furthermore, the fruit respiration rate during the shelf life was negatively correlated with the precooling delay. The respiration rate of fruits precooled for 3 h after harvest was 8.08 mg CO_2 kg^{-1} h^{-1} and retained a good appearance throughout the shelf life. Their ripening, reduced firmness, and TA were significantly delayed compared with those of fruits with longer precooling delays, which had a firmness of 19 N, TA of 0.29%, and TSS of 12.6°Brix after 30 d of storage at 5°C, while subsequent warming to 20°C for 3 d, the rate of overripening was significantly lower in fruits with precooling delays of 3 and 6 h than in fruits with a precooling delay of 24 h. Thus, precooling mangoes within 3–6 h of harvest will reduce their respiration rate, delay ripening, decrease anthracnose incidence, preserve quality, and prolong storage life.

1. Introduction

Mangoes are climacteric fruits rich in nutrients such as β-carotene and vitamin A, C, and B complexes, while they are sweet and delicate and have a unique aroma [1]. The mango fruit is highly susceptible to accelerated metabolic rates upon harvest, which results in significantly shorter shelf life, while the rapid metabolic activity leads to a consequential loss of quality, deterioration, and senescence [2, 3]. Furthermore, high temperatures exacerbate the situation, and the fruit's short shelf life is further reduced [2, 3]. These limitations mentioned above reduce the quality and shorten the service life of their storage, rendering them unsuitable for long-distance shipping to alternative regions or international markets. Therefore, it is important to remove the field heat from mangoes immediately after harvesting [4].

Mango anthracnose, caused by *Colletotrichum gloeosporioides*, severely reduces the mango's shelf life and export potential, while effective management is crucial for the sustainability of the mango industry [5]. Anthracnose is a disease that causes rot and often shows up during refrigeration or long-distance transportation [6]. Indian mangoes suffer

from postharvest losses of 25–30% due to improper postharvest processing, storage, transportation, environmental conditions, and lack of grading equipment [1]. Therefore, the lack of precooling and delayed cooling in postharvest processing is the leading causes of mango losses, emphasizing the importance of precooling [7].

Temperature control is vital to maintaining agricultural products' postharvest quality and shelf life [8]. The agricultural product undergoes a respiration process involving the oxidation of organic matter, a reaction that releases energy, and a portion of the resulting energy is converted to heat, often called respiratory heat [9]. Typically, fruits and vegetables harvested during daylight carry a lot of field heat since temperatures are high then; simultaneously, these accelerate the metabolic processes, exacerbating microbial growth and water loss [10]. It is imperative to remove excess heat from agricultural products to prevent them from aging prematurely or spoiling; the failure to do so may result in a significant loss of resources. In addition, the presence of bruises on produce can significantly hasten the process of decay, thereby adversely affecting its texture, firmness, color, flavor, appearance, and nutritional value, ultimately leading to a perception of suboptimal freshness [11].

The precooling technique is highly effective for removing heat from the field, which involves lowering the fruit's internal temperature to the appropriate storage level [12] since precooling extends the storage life of fruit by reducing pathogen proliferation and water loss, which is essential for harvesting, packing, and transporting fruit [7]. There are several methods available for precooling mangoes, including forced-air cooling, hydrocooling, vacuum cooling, contact icing, encapsulated icing, and cryogenic cooling, each with advantages and disadvantages [12, 13]. It is crucial to note that the immediate postharvest activities of arranging, sorting, grading, and packing fruits and vegetables can cause significant delays in the precooling process, which can have a detrimental impact on the quality and shelf life of fruits like plums, strawberries, bananas, tomatoes, and grapes [14–16]. It has been reported that delayed precooling of strawberries at 20°C for 16 h-24 h with subsequent storage at 5°C for 3 days resulted in a decrease in ascorbic acid content, thereby implying that strawberries without immediate postharvest precooling suffer from quality loss [17]. The same phenomenon has been reported in the delayed precooling treatment of tomatoes, which can compromise the quality of the fruits, causing rapid weight and firmness loss while increasing the TSS content and skin color change [18]. It is vital to precool the tomatoes immediately after harvesting before transporting them to the processing area or storage to maintain their quality [18].

Therefore, this study evaluated the effects of pressure cooling combined with delayed precooling for different postharvest time points on the incidence of mango anthracnose and the quality of Irwin's mango shelf life.

2. Materials and Methods

2.1. Materials. Irwin mangoes used in this study were harvested within 90–100 days after anthesis, purchased from a local farmer (Pingtung, Taiwan), and confirmed as being of similar size before harvesting. Specifically, the export standard of the Irwin mango mentioned above refers to the ripeness of 80%, where the fruit exhibits the characteristics of having prominent shoulders, fullness, light color of lenticels, and hardness of the fruit; the interior requires hardening of the inner pericarp, and the flesh partially turns yellow. It was delivered to the laboratory within an hour's drive and immediately selected for grading for subsequent processing.

2.2. Methods

2.2.1. Operation of the Side-Suction Precooling Machine. The mangoes were precooled using a side-suction forced-air cooler by being placed in a cold room (6.58 m long, 3.92 m wide, and 2.59 m high) at 10°C, respectively, different times of precooling delay (namely, after postharvest times 3 h, 6 h, 12 h, and 24 h). After cooling the fruits to 7–8°C (after approximately 110 min), they were moved to a 5°C cold room for the storage experiment. During this experiment, quality analyses were performed on five fruits every 5 d, and the analysis was performed in duplicate for each fruit. After 30 d of storage, the fruits were transferred to a cold room for 3 d at 20°C to thaw.

The fruits were loaded into baskets ($47 \times 32 \times 29\,cm^3$) with 3.2 cm × 0.8 cm ($2.56\,cm^2$) holes on all sides; the holes covered 22.5% of the surface area on the widest sides. The baskets were stacked in three layers, with each layer containing 24 fruits. Each basket was wrapped in cling film on its narrowest side (top and bottom) and then placed at the air inlet of the side-suction forced-air cooler. Next, the cooler was turned on to force cold air into the baskets. The wind speed at the inlet was $3.6\,L\,s^{-1}\,kg^{-1}$, and the 11.2 Pa static pressure was for the fruit inside the basket. Thus, the fruits were cooled by horizontally flowing cold air, and heat was conducted to the air outlet of the cooler.

2.3. Physicochemical Analysis

2.3.1. Anthracnose Incidence. During the storage period at 5°C, 20 fruits from each group were monitored and photographed every 2 d to check for black-brown spots, which would indicate anthracnose. Black, abnormal, and pitted lesions characterize anthracnose fruits [19, 20]. Specifically, small water-soaked spots appear at fruit ripening, gradually expanding into round, black, sunken spots that produce pink, sticky spore mounds [20]. Moreover, mycelium's invasion of fruit tissues results in discoloration, softening, and a negative odor, which can accelerate the decay of the fruit. Furthermore, the fusion of most lesions can further exacerbate the deterioration process [20]. Any fruit showing these symptoms was deemed to be infected with anthracnose. Ultimately, the anthracnose incidence in mangoes was calculated by the following equation.

$$\text{Anthracnose incidence}\,(\%) = \frac{\text{number of anthracnose symptoms fruits}}{\text{total number of fruits}} \times 100. \quad (1)$$

2.3.2. Overripening Rate. After storing the fruits at 5°C for 30 d, they were transferred to a cold room at 20°C for 3 d. Twenty fruits were randomly sampled and sliced from each group to check for changes in the color of their flesh. The criteria for determining are based on the fact that the fruit was considered overripe because the flesh was dark yellow, had a macerated appearance, and gave off an unpleasant fermented odor. In contrast, the flesh was bright yellow, and the fruit was considered to be marketable. The overripening rate of mangoes was calculated using the following equation.

$$\text{Overripening rate}\,(\%) = \frac{\text{number of overripened fruits}}{\text{total number of fruits}} \times 100. \quad (2)$$

2.3.3. Weight Loss. Prior to precooling, five fruits from each group were weighed using an electronic balance (UW2200H, Shimadzu Co., Japan). The fruits were weighed again after precooling, and the weight loss was calculated using the following equation:

$$\text{Weight loss rate}\,(\%) = \frac{W0 - W1}{W0} \times 100. \quad (3)$$

where $W0$ is the initial weight of the fruit (prior to precooling) and $W1$ is the weight of the fruit after precooling or cold storage.

2.3.4. Fruit Respiration Rate and Ethylene Production. The gases produced by the mango samples were analyzed using a flow-through system. Precooled fruits were placed in a 1.9 L respiration chamber connected to an airflow controller, which was used to set the airflow of the chamber to 16 mL min^{-1}. Every 2 d, a 1 mL syringe was used to retrieve a 1 mL sample of air from the outlet of the respiration chamber. The sample respiration rate (mg CO_2 kg^{-1} h^{-1}) was determined using the thermal conductivity detector of a GC-8A gas chromatograph (Shimadzu, Kyoto, Japan) equipped with a Porapak Q column (GL Sciences Inc., Torrance, CA, USA) with an injection temperature of 100°C and the column temperature of 90°C. In addition, the ethylene production (μL kg^{-1} h^{-1}) measurement differed from the above by switching to a flame ionization detector, whereas the injection temperature was 100°C and the column temperature was 80°C.

2.3.5. Firmness. Texture analysis was performed using an EZ Test-500N texture analyzer (Shimadzu Co., Tokyo, Japan). The probe had a diameter of 5 mm, and the depth of penetration was set to 10 mm to allow the probe to reach the center of the mangoes (with peels). Firmness (N) measurements were obtained for each fruit on two opposite sides and averaged, and the results were recorded. Five fruits from each group were analyzed, and duplicate measurements were performed on each fruit.

2.3.6. Total Soluble Solids (TSS). To determine the TSS, 30 g of peeled fruit was placed in a polyethylene (PE) bag and crushed to obtain its juice for analysis. Then, 1 mL of the juice was poured into the measuring hole of the pocket refractometer (PAL–1, Atago Co., Ltd., Tokyo, Japan), which calculated the TSS (°Brix). Five fruits from each group were analyzed, and duplicate measurements were performed on each fruit.

2.3.7. Titratable Acidity (TA). First, 30 g of peeled fruit was placed in a PE bag and crushed to obtain its juice. The juice of 5 mL was mixed with 100 mL of reverse osmosis water and then titrated to the endpoint of the titration, pH 8.1, with 0.1 N NaOH by a titrator (Mettler Toledo, Columbus, OH, USA). The TA (g L^{-1} maleic acid) of the mango juice was calculated based on the chemical equation for the reaction between maleic acid and NaOH. Five fruits from each group were analyzed, and duplicate measurements were performed on each fruit.

2.4. Statistical Analysis and Graphing. Statistical Analysis System software suite (V9.0, SAS Institute, Cary, NC, USA) was used to perform analysis of variance (ANOVA) by conducting Fisher's least significant difference (LSD) test; the significance level was $p < 0.05$. SigmaPlot (V10.0, Systat Software, Inc., Chicago, IL, USA) was then used to plot the graphs.

3. Results

3.1. Effects of Delayed Precooling on Anthracnose Incidence and Overripening Rate in Irwin Mangoes

3.1.1. Variations in Anthracnose Incidence. During cold storage at 5°C, the fruits that were precooled 12 h or 24 h after harvest showed anthracnose symptoms by the 4th day of storage. Fruits with a precooling delay of 6 h showed symptoms by the 8th day of storage, and fruits with a precooling delay of 3 h only showed symptoms on the 14th day in storage (Figure 1). The incidence of fruit anthracnose was 15% on the 30th day of storage for 3 h and 6 h precooling delays. Fruits with precooling delays of 12 h and 24 h had anthracnose incidence rates of 35% and 30%, respectively. Figure 2 shows the appearance of these fruits at 5°C for 30 days of storage. This study suggested a positive correlation between the precooling delay's duration and anthracnose's incidence and severity after 30 days in cold storage.

3.1.2. Variations in the Overripening Rate. When mangoes become overripe, they emit a fermented odor, develop brown spots on their flesh, and appear soaked, all of which degrade their quality. Overripening was observed in the sliced fruits stored for 30 d at 5°C and 3 d held at 20°C (Figure 3). The rate of overripening was 65 ± 9.57% in fruits that underwent a precooling delay of 24 h, which was significantly higher than that of fruits with precooling delays of 3 and 6 h. The fruits that underwent a precooling delay of only 3 h had the lowest rate of overripening, that is, 35 ± 5.00% (Figure 4).

3.1.3. Weight Loss Variations. Fruits lose weight during storage because of their intense metabolism and transpiration. As shown in Figure 5, for all groups, the weight loss

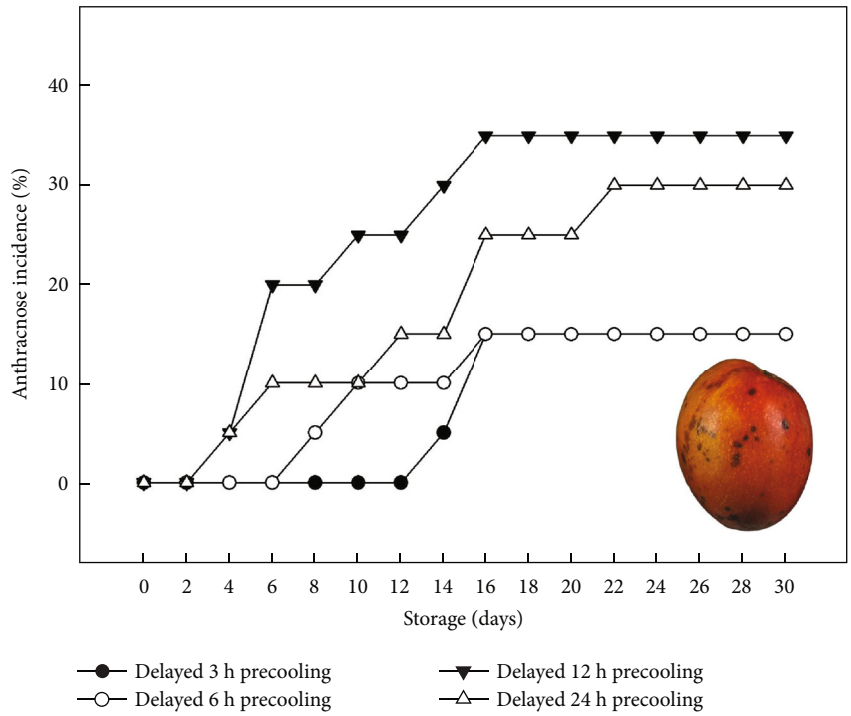


Figure 1: Effect of precooling delay on the anthracnose incidence rate in Irwin mangoes stored at 5°C for different storage periods.

increases as the storage time increases. Fruits with a 24 h precooling delay have significantly higher weight losses during the shelf life than all other groups. However, the weight loss of fruits during shelf life with 3, 6, and 12 h precooling delays does not differ significantly. After 30 d of storage at 5°C, the weight losses of the fruits with precooling delays of 3 h, 6 h, 12 h, and 24 h are 2.47%, 2.37%, 2.99%, and 3.45%, respectively. Therefore, the longer the precooling delay, the greater weight loss of the fruit during the shelf life. Thus, precooling mangoes within 3 h of harvest significantly reduces weight loss during storage.

3.2. Effect of Delayed Precooling of Irwin Mangoes on the Postharvest Physiology

3.2.1. Variations in Respiration Rate and Ethylene Production. The respiration rate is negatively correlated with the storage life and quality of fruits and vegetables; the longer the precooling delay, the higher the fruit respiration rate after precooling. The respiration rate of fruits with a 3 h precooling delay was 8.08 mg CO_2 kg^{-1} h^{-1} (Figure 6(a)); by contrast, the fruits subjected to a 24 h precooling delay had a respiration rate of 30.02 mg CO_2 kg^{-1} h^{-1}, which was the highest among all groups. During cold storage at 5°C, in all groups, the respiration rates decreased during the first 4 d of storage and gradually increased after this point. Nonetheless, the fruits that had only experienced a 3 h precooling delay had relatively low respiration rates, while the fruits with a 24 h precooling delay had higher respiration rates than those of all other groups.

The fruits that were subjected to a 24 h precooling delay produced the most ethylene, that is, 0.14 μL kg^{-1} h^{-1} (Figure 6(b)). During the shelf life, ethylene production was similar among all groups and remained in the range of approximately 0.03–0.09 μL kg^{-1} h^{-1}, except for the brief increase in ethylene production that occurred on the 12th day.

3.3. Effects of Precooling Delay on the Postharvest Quality of Irwin Mangoes

3.3.1. Variations in Firmness, TSS, and TA. Ripening, moisture loss, and senescence soften fruits. Therefore, firmness can be used as an indicator of ripening and quality. During the shelf life, firmness gradually decreases as storage time increases. Fruits whose precooling was delayed by 24 h are significantly less firm than those with precooling delays of 3 h or 6 h (Figure 7(a)). After storage at 5°C for 30 d, the fruits that had undergone precooling delays of 3, 6, 12, and 24 h have firmness of 22.6, 18.5, 18.0, and 15.6 N, respectively. Therefore, early precooling helps delay fruit softening.

As a fruit ripens, the TSS increases rapidly and decreases over time. TSS is an important indicator of sweetness in the mango flesh. Fruits with a precooling delay of 24 h had high TSS values, which gradually decreased during the shelf life (Figure 7(b)). By contrast, fruits with a precooling delay of 3 h maintained a relatively low TSS throughout the shelf life. Therefore, the sooner precooling is performed, the longer one may delay the ripening-induced accumulation of TSS.

The sourness of fruit depends on its TA, while the TA levels decreased over time between all groups in shelf life, but there were no significant differences within the groups (Figure 7(c)).

Table 1 presents the firmness, TSS, and TA values of the fruit in each group for 30 d of storage at 5°C and after thawing at 20°C for 3 d. The fruits with precooling delays of 3 h

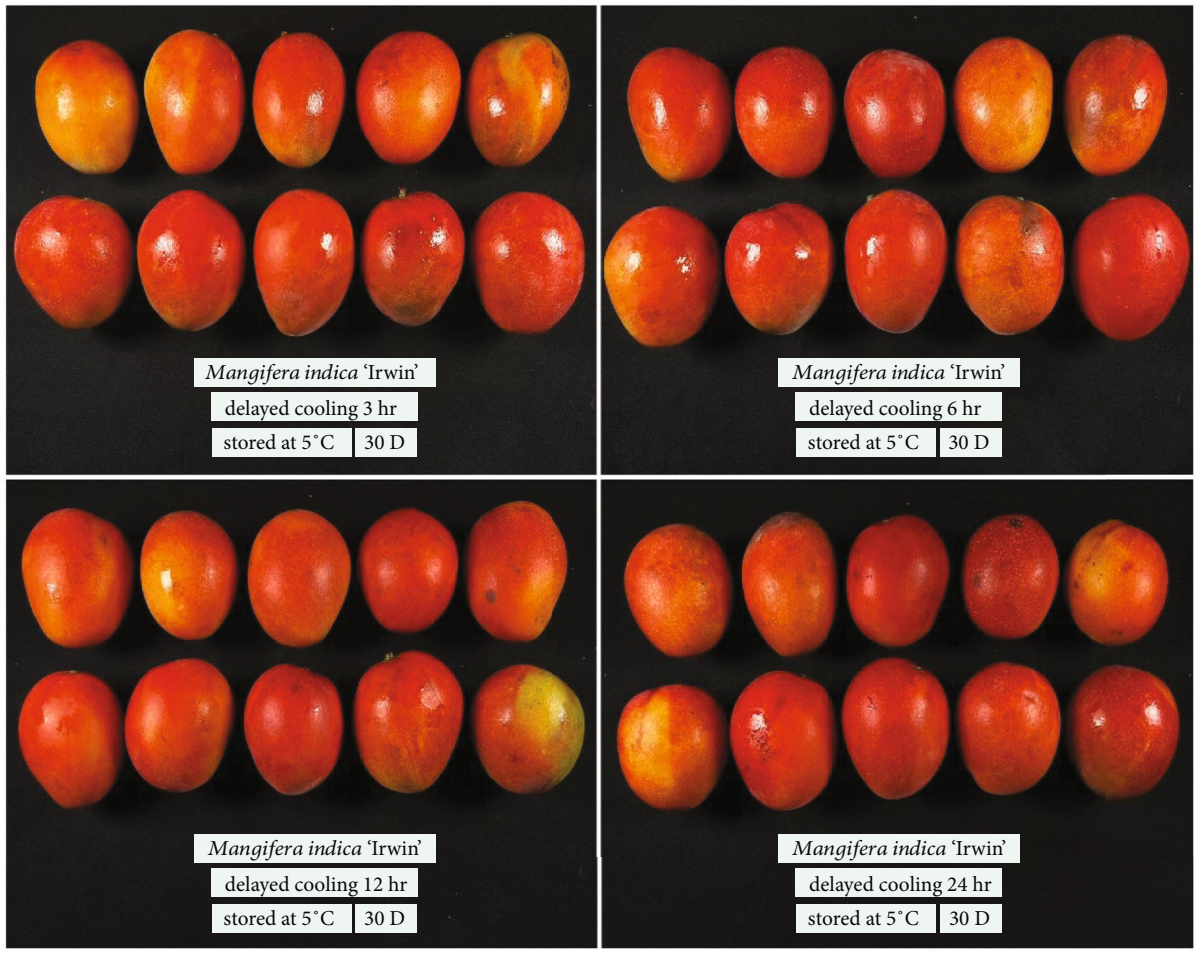


Figure 2: Effect of precooling delay on the appearance of Irwin mangoes after storing at 5°C for 30 days.

and 6 h are significantly firmer than those with a precooling delay of 12 h. However, there were no significant differences in TSS for each group, which generally varies between 13.2°Brix and 15.0°Brix. After thawing for 3 d at 20°C, fruits that have precooling delays of 3 h and 6 h still have significantly higher TA levels than those that have a precooling delay of 24 h. Therefore, early precooling helps to maintain firmness and TA after the thawing period.

4. Discussion

This study investigated the effects of delay between harvest, and precooling affects the quality and rate of anthracnose incidence in Irwin mangoes. Forced-air precooling was performed 3 h, 6 h, 12 h, and 24 h after harvest, and the fruits were then stored at 5°C. The earlier the mangoes were precooled, the longer the time required for anthracnose to occur. The fruits subjected to a precooling delay of only 3 h began to exhibit anthracnose symptoms after a storage period at 5°C for 14 d, whereas the fruits that underwent precooling delays of 12 and 24 h began to show symptoms after the 4th day of storage. Early precooling also decreased the respiration rate, delayed ripening, reduced firmness, and TA and improved the appearance of the mangoes during the shelf life. After storage at 5°C for 30 d and thawing at 20°C for 3 d, the overripening rate was significantly lower in the fruits that had a precooling delay of 3 h than those that had a precooling delay of 24 h.

Postharvest cooling, commonly referred to as precooling, is a critical process for harvested agricultural commodities as it facilitates the rapid dissipation of field heat from the produce immediately after harvesting, which aims to decelerate metabolism and curb degradation, thereby enhancing the quality of the produce before shipping or storage [7]. According to Rudnicki et al. [21], precooling can rapidly cool agricultural produce, which could rapidly cool agricultural products, primarily by decreasing opportunities for bacterial infections, moisture loss, respiration, and ethylene production while significantly minimizing the heat load of cold storage and cold chain transportation [22]. However, postharvest losses resulting from delayed removal of field heat from agricultural products have been estimated to be between 25 and 30%, but promptly precooling can potentially mitigate losses to 5–10% [3].

Mango is a climacteric fruit characterized by ripening and rapid aging despite the absence of exogenous ethylene for ripening. Simultaneously, the failure to promptly remove field heat postharvest may hasten ripening and respiration

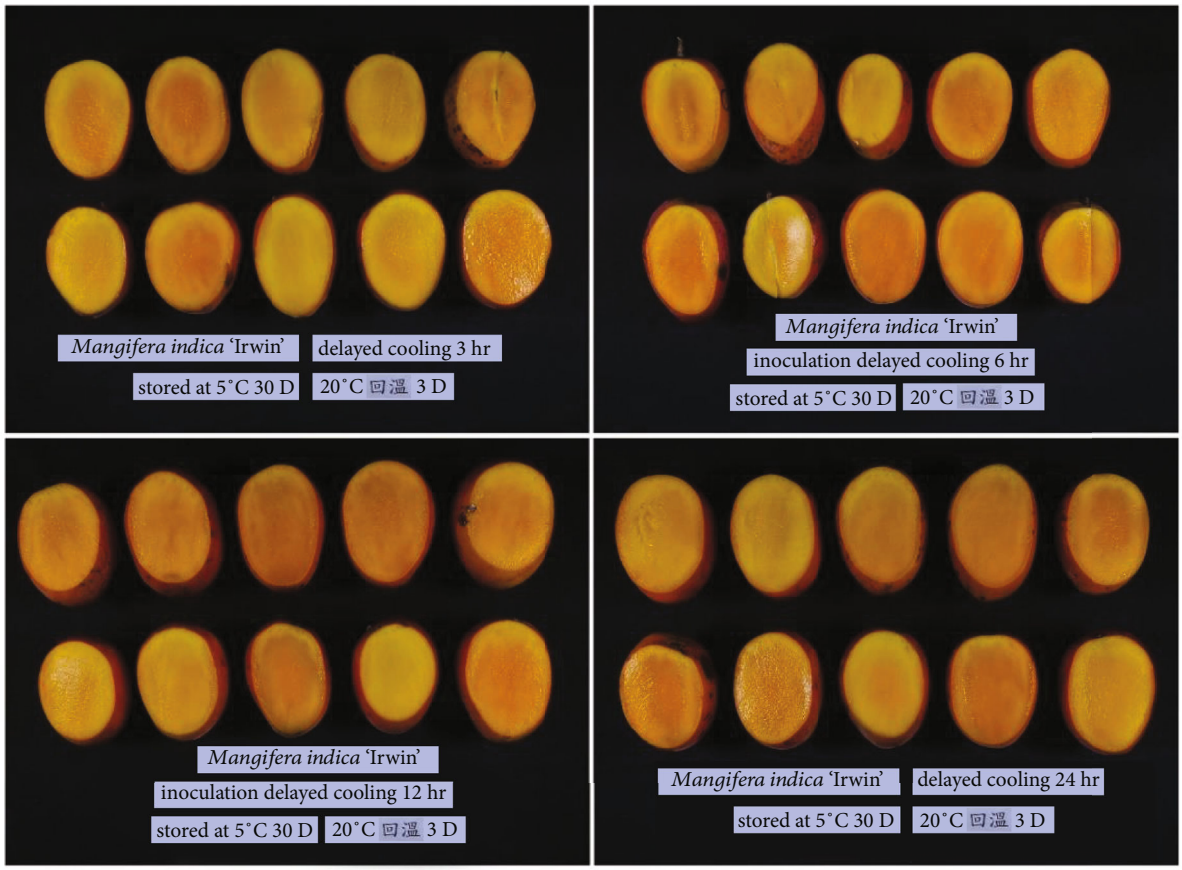


Figure 3: Effect of precooling delay on the appearance of the flesh of Irwin mangoes stored 30 d at 5°C and thawed to 20°C for 3 d.

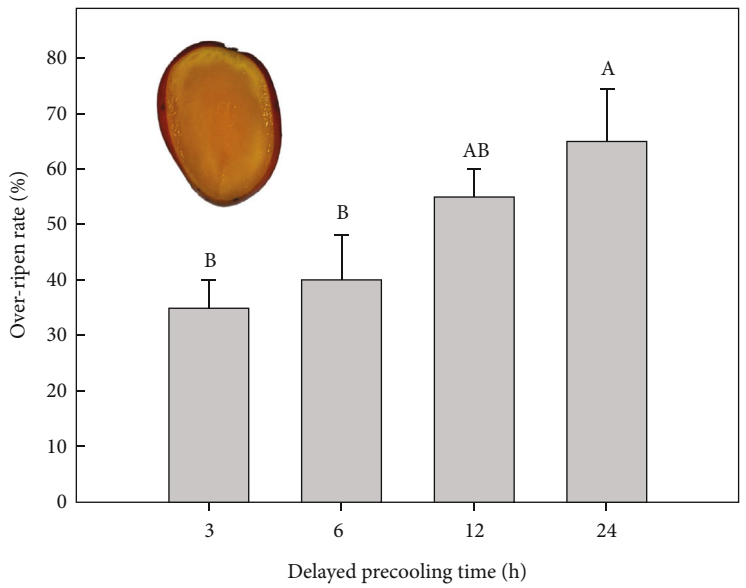


Figure 4: Effect of delayed precooling on the overripening rate of Irwin mangoes stored at 5°C for 30 d and thawed to 20°C for 3 d. The vertical bar indicates the standard errors of the mean, where different uppercase letters indicate a significant difference ($p < 0.05$).

rates, culminating in senescence and consequent loss of commercial value. Therefore, it implies that precooling can effectively delay the occurrence of senescence, namely, the intense metabolic processes caused by the ripening of the fruit, heating due to respiration, and water loss due to transpiration while avoiding spoilage caused by microbial infections [23]. Therefore, precooling represents a critical element of the commercial transportation of mangoes across

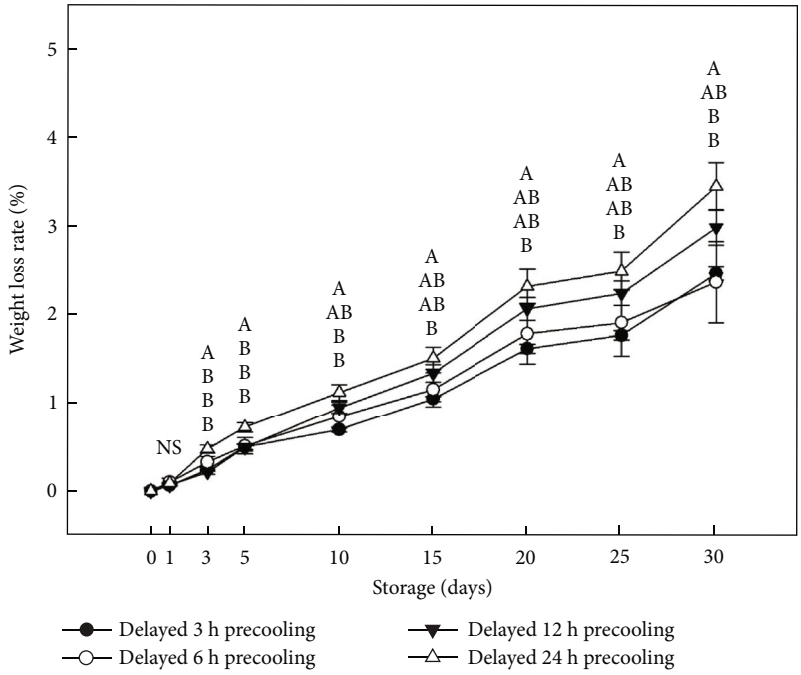


Figure 5: Effects of precooling delay on the weight losses of Irwin mangoes during storage at 5°C. The vertical bar represents the standard errors of the mean, where different uppercase letters indicate a significant difference ($p < 0.05$).

long distances by rapidly lowering the temperature of the fruit, with the primary objective of removing the field heat to avoid the risks mentioned above and to achieve a delayed ripening effect and ultimately prolonging its shelf life [24]. This also means that rapid postharvest removal of field heat is an important part of the cold chain to extend the storage life of mangoes, despite the fact that it has been recommended to keep the air temperature in room cooling and forced-air cooling at 10°C; unfortunately, most mangoes should not be stored below the safety level of 12°C [3].

Mane et al. [25] reported that green-ripening cv. Alphonso mangoes were cooled after harvest using 12°C hydrocooling followed by storage in a 12°C cooler, which was more effective in delaying fruit postripening and minimizing weight loss than storage at ambient temperature or 16°C while effectively maintaining good quality. In this study, the onset of anthracnose was delayed the most in mangoes that were precooled only 3 h after harvest; the longer the precooling delay, the earlier the onset of symptoms. Anthracnose occurred the earliest in fruits with a precooling delay of 24 h. Following the harvest of mangoes, a natural process of ripening and softening occurs, consequently diminishing their pathogenic microorganism resistance and rendering them susceptible to infection or decay [26].

Precooling delays mango ripening by reducing respiration, which maintains fruit resistance to pathogens, minimizing spoilage [27]. In a study focused on Tainong mangoes, Li et al. [26] observed that subjecting the fruit to forced-air precooling at 0°C for 30 min and subsequently storage at 13°C effectively sustained its firmness, subdued skin-color changes, deferred soluble sugar accumulation and ripening, and reduced spoilage rate during storage. Moreover, Kanade et al. [28] explored that the effects of hydrocooling on cv. Alphonso mangoes were precooled with an ice-water mixture at 12°C and then stored at 15°C, indicating that this treatment strategy effectively reduced physiological losses and spoilage. Therefore, it is imperative to expeditiously remove the field heat from mangoes to minimize moisture loss, suppress metabolic and respiratory processes, and curtail ethylene production. These measures serve to prolong the storage life of the mangoes. Interestingly, a physiological disorder of jelly seed has been reported in the frequency of its occurrence concerning mineral nutrients, variety, postripening, and seed maturity, particularly the physiological and respiratory rates causing the development of jelly seed in the fruits [29]. Concurrently, this study was not the case in Irwin mangoes during the overripening rate determination. However, processing in this study confirmed that decreased respiration and physiological and metabolic rates in Irwin mangoes by early precooling without delays may reduce the occurrence of overripening, presumably contributing to the reduction above in the incidence of jelly seed. However, in this study, cv. Irwin mangoes with a precooling delay of 3 h showed the lowest respiration rate among all groups, whereas the fruits precooled 24 h after the harvest had the highest respiration rate. During the shelf life, the fruits that underwent a 3 h precooling delay consistently exhibited low respiration rates, whereas all other groups had highly variable respiration rates. A study reported that precooling prevents deterioration and maintains vitamin C content in cauliflower, whereas delayed postharvest cooling may increase respiration rate and metabolic activity [14]. Moreover, a similar situation was reported for bell peppers, which require rapid precooling within a few hours after harvesting to maintain their quality, and delayed cooling after harvesting accelerates the

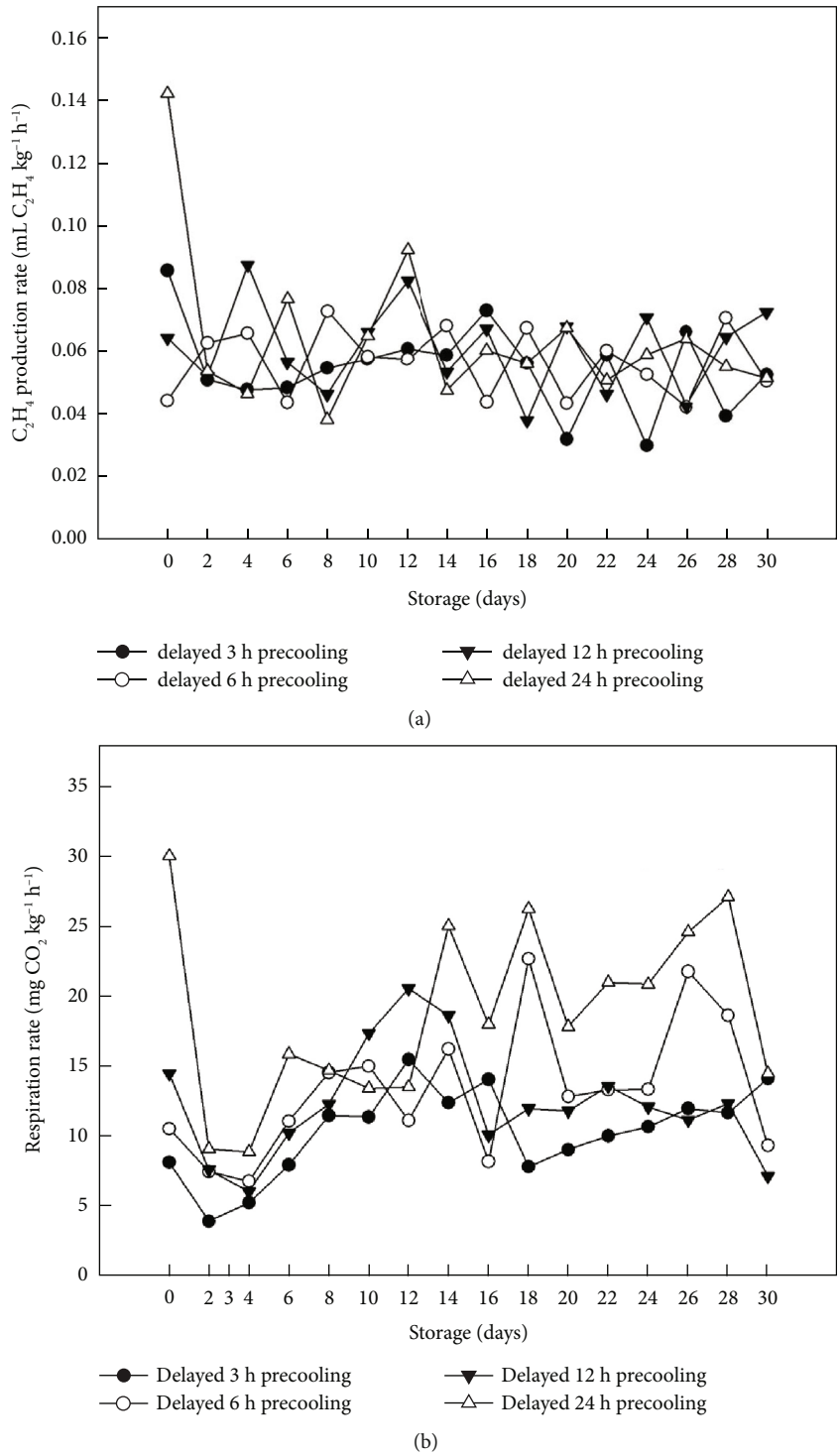
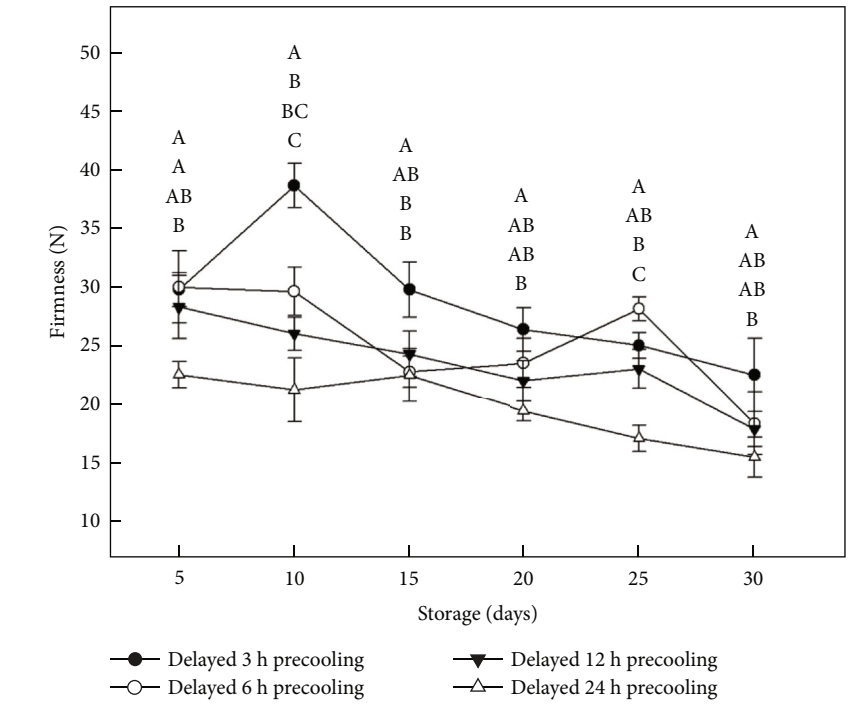
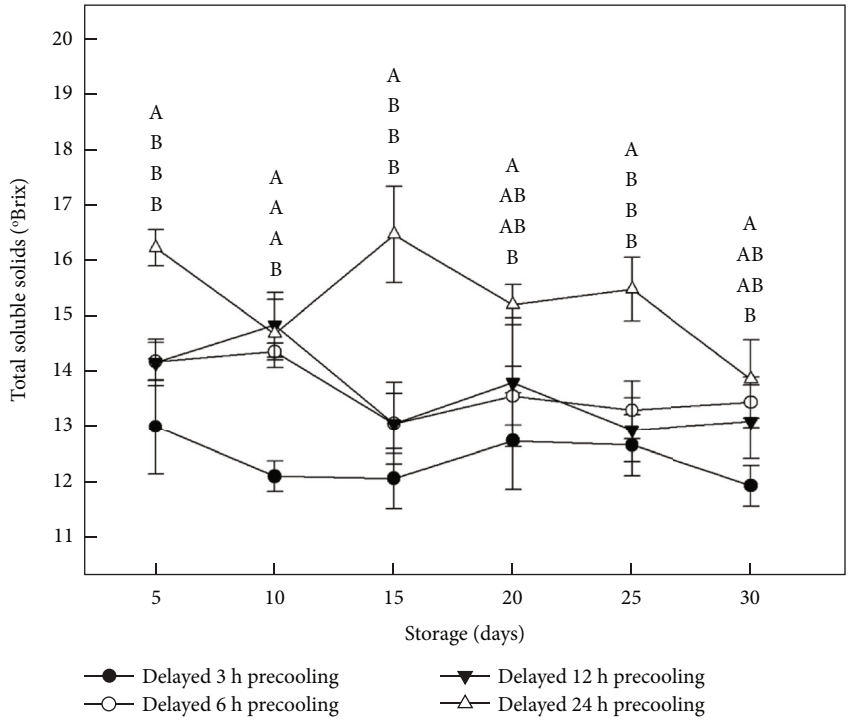


Figure 6: Effects of precooling delay on (a) ethylene production and (b) respiration rate of 5°C stored Irwin mangoes.

deterioration of bell peppers [15]. In addition, it has also been reported that blueberry firmness loss correlates with fruit weight loss, where blueberries delayed storage by up to 6 h at 20°C and up to 8 h at 10°C compared to the most rapid postharvest cooling times, contributing to the retention of blueberry quality, thereby preserving the shelf life of at least 3 weeks [30]. It is noteworthy that low-temperature storage of fruits leads to the development of superior physiological and biochemical properties when compared to storing them at ambient temperature [31]. Mango cv. Kesar has been reported with fewer weight loss and higher sensory scores in refrigerated (available for 35 days at 10°C) and cool chamber storage, and the results showed that they performed better compared to room temperature storage (24 days of storage) [32]. This study showed that the firmness of mangoes decreases as storage time



(a)



(b)

Figure 7: Continued.

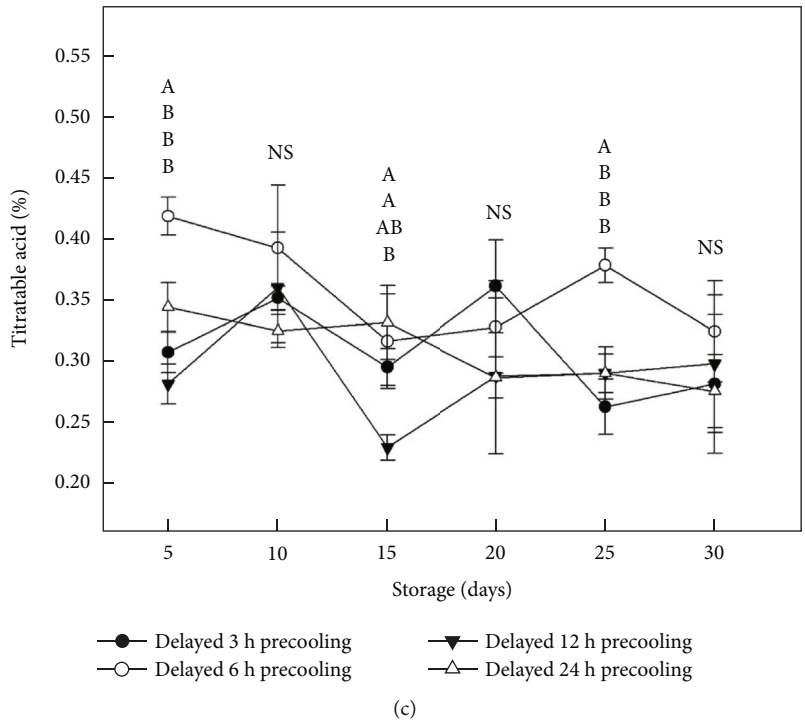


Figure 7: Effects of delayed precooling on the (a) firmness, (b) TSS, and (c) TA of Irwin mangoes during storage at 5°C. The vertical bar represents the standard errors of the mean, where different uppercase letters indicate a significant difference ($p < 0.05$).

Table 1: Effects of delayed precooling on the firmness, TSS, and TA of Irwin mangoes stored for 30 d at 5°C, then allowed to thaw for 3 d at 20°C.

Indicator	Precooling delay				
	3 h	6 h	12 h	24 h	LSD
Firmness (*N*)	$19.1 \pm 2.5^{a*}$	18.3 ± 1.4^{ab}	13.6 ± 0.5^{b}	15.3 ± 2.0^{ab}	5.4082
TSS (°Brix)	14.5 ± 0.7^{a}	15.0 ± 1.1^{a}	14.2 ± 0.7^{a}	13.2 ± 2.3^{a}	1.8692
TA (%)	0.29 ± 0.02^{a}	0.28 ± 0.03^{a}	0.20 ± 0.04^{ab}	0.17 ± 0.01^{b}	0.1161

*Data represent the mean ± standard error of three replicates. Different superscript lowercase letters within the column indicated significantly different values according to one-way ANOVA, followed by the least significant difference test ($p < 0.05$).

progresses. Nonetheless, the firmness remained relatively high in the fruits that had a precooling delay of 3 h, whereas the firmness of fruits that had a precooling delay of 24 h decreased more rapidly. This study's findings agreed with Amwoka et al. [33], who reported that fruits that had undergone proper cold chain processing retained a relatively high level of firmness even after 30 d of storage. Conversely, fruits that were not processed using the cold chain system only retained half of their original firmness at the end of the shelf life. The decrease in fruit firmness is primarily attributed to cellular metabolism and activities of pectinase and hemicellulose [34]. Tigist et al. [35] noted that fruit firmness can be maintained at low temperatures and high humidity levels because the former decreases the activity of ripening-related enzymes, whereas the latter reduces transpiration. In this study, fruits with a precooling delay of 24 h had significantly higher TSS values than all other groups, whereas fruits with a precooling delay of 3 h had relatively low TSS levels throughout the shelf life. The rapid increase in TSS associated with the delay of 24 h could be attributed to their accelerated rates of respiration and metabolism; while this phenomenon has also been reported in the precooling-treated mulberry fruits, the respiration rate affects the metabolic activity, leading to the delayed loss of TSS and TA [36]. In this study, we observed that fruits with precooling delays of 3 h and 6 h retained relatively high levels of TA after 3 d at 20°C, whereas fruits with precooling delays of 12 h and 24 h had lower TA levels. This may be attributed to the elevated rates of respiration after 24 h, which promotes the digestion of organic acids and thus reduces TA levels [37]. It has been observed that the cv. Tainong mangoes demonstrate a noteworthy increase in enzymatic activity of antioxidants coupled with a reduction in reactive oxygen species levels and oxidative stress when subjected to forced-air precooling at 0°C for 30 min [26]. This highlights the importance of precooling, which delays ripening by

reducing the respiration rate, thus preserving fruit quality [38]. Moreover, published literature has reported that a delay of 4 h or more at 25°C–30°C results in a decrease in the quality of nonsutured melons when stored at 2.5°C for 2 weeks and that nature-green bell peppers lose 0.4%–0.75% of their weight per hour during delayed precooling at 25°C and 37°C, respectively, and that 2%–4% reduction in weight reduces, while the color changes at 37°C for 12 h before the cooling; Japanese eggplants lose quality and 3% of their weight after a delay of 3 h at 37°C or 6 h at 25°C [39]. This study revealed that the weight loss of Irwin mangoes during storage decreased with prolonged precooling delay time. In particular, the weight loss was remarkably higher in the 24 h precooling delay group than in the 3 h or 6 h ones. Moreover, these findings suggested that precooling time can substantially impact the postharvest weight loss of mangoes, as this information can be used to optimize the mango's operations and quality. Notably, agricultural produce is a living and respiring product, which maintains an active metabolism postharvest and will also be influenced by the environment (such as high temperature or package) to have more intense respiration and evapotranspiration leading to internal water loss accompanied by the depletion of the accumulated nutrients [40]. Therefore, it is prudent to minimize the delay between harvest and precooling to prevent excessive respiration and transpiration of the product, which contributes to preserving the quality and freshness of the product. This study's emphasis lies in the fact that during the harvesting of Irwin mangoes, the internal temperature of mangoes is raised due to the accumulation of heat from the field and respiratory processes. Therefore, precooling must be executed promptly to ensure that the quality and shelf life of the produce are not compromised.

5. Conclusion

This study showed the effectiveness of pressure cooling on Irwin mango within 3-6 h postharvest in decreasing the respiration rate, delaying ripening, preserving the quality (including firmness, TSS, and TA contents), mitigating anthracnose, providing a favorable appearance, and extending the shelf life of Irwin mango. However, the quality of mangoes is significantly influenced by temperature, and in commercial postharvest processing, delays between harvest and precooling have been observed to have a negative effect on their appearance, nutritional value, and overall consumer acceptability. The mango supply chain stakeholders must prioritize this aspect to optimize the shelf life and market value of mango products. All in all, precooling is the initial step in postharvest temperature management of mangoes, especially in large-scale agricultural production, where opportunities exist to provide extra economic benefits by effectively arranging operations with fewer delays, prolonging shelf life, and minimizing postharvest and financial losses.

Data Availability

Data is contained within the article.

Conflicts of Interest

The authors declare that they have no competing interests.

Authors' Contributions

Ping-Hsiu Huang and Yu-Shen Liang contributed equally to this work.

Acknowledgments

The authors want to acknowledge all the individuals who volunteered for this study. All resources were from Dr. Yu-Shen Liang's laboratory.

References

[1] S. A. Makwana, N. D. Polara, and R. R. Viradia, "Effect of precooling on post harvest life of mango (*Mangifera indica* l.) cv. Kesar," *Food Science and Technology*, vol. 2, pp. 6–13, 2014.

[2] B. Xu and S. Wu, "Preservation of mango fruit quality using fucoidan coatings," *LWT*, vol. 143, article 111150, 2021.

[3] K. K. Patel, "Recent developments in application of precooling of mangoes—an overview," *Journal of Biosystems Engineering*, vol. 47, no. 3, pp. 318–329, 2022.

[4] C.-J. Zhao, J.-W. Han, X.-T. Yang, J.-P. Qian, and B.-L. Fan, "A review of computational fluid dynamics for forced-air cooling process," *Applied Energy*, vol. 168, pp. 314–331, 2016.

[5] A. B. Perumal, P. Sellamuthu, R. Nambiar, and R. Sadiku, "Antifungal activity of five different essential oils in vapour phase for the control of Colletotrichum gloeosporioides and Lasiodiplodia theobromae in vitro and on mango," *International Journal of Food Science & Technology*, vol. 51, pp. 411–418, 2015.

[6] P. K. Bordoh, A. Ali, M. Dickinson, Y. Siddiqui, and G. Romanazzi, "A review on the management of postharvest anthracnose in dragon fruits caused by Colletotrichum spp," *Crop Protection*, vol. 130, p. 105067, 2020.

[7] A. M. Elansari and Y. S. Mostafa, "Vertical forced air precooling of orange fruits on bin: effect of fruit size, air direction, and air velocity," *Journal of the Saudi Society of Agricultural Sciences*, vol. 19, no. 1, pp. 92–98, 2020.

[8] N. Ndraha, H.-I. Hsiao, J. Vlajic, M.-F. Yang, and H.-T. V. Lin, "Time-temperature abuse in the food cold chain: review of issues, challenges, and recommendations," *Food Control*, vol. 89, pp. 12–21, 2018.

[9] A. M. Elansari, D. L. Fenton, and C. W. Callahan, "Precooling," in *In Postharvest technology of perishable horticultural commodities*, E. M. Yahia, Ed., pp. 161–207, Woodhead Publishing, 2019.

[10] Y. S. Liang, O. Wongmetha, P. S. Wu, and L. S. Ke, "Influence of hydrocooling on browning and quality of litchi cultivar feizixiao during storage," *International Journal of Refrigeration*, vol. 36, no. 3, pp. 1173–1179, 2013.

[11] P. B. Pathare and M. Al-Dairi, "Effect of mechanical damage on the quality characteristics of banana fruits during short-term storage," *Discover Food*, vol. 2, no. 1, p. 4, 2022.

[12] G. Wang and X. Zhang, "Evaluation and optimization of air-based precooling for higher postharvest quality: literature review and interdisciplinary perspective," *Food Quality and Safety*, vol. 4, no. 2, pp. 59–68, 2020.

[13] S. Khanbarad, N. Patil, R. Sutar, and D. Joshi, "Studies on precooling of mango for extension of shelf-life," *Journal of Agricultural Engineering*, vol. 50, pp. 23–31, 2012.

[14] L. Li, A. Lichter, D. Kenigsbuch, and R. Porat, "Effects of cooling delays at the wholesale market on the quality of fruit and vegetables after retail marketing," *Journal of Food Processing and Preservation*, vol. 39, no. 6, pp. 2533–2547, 2015.

[15] M. S. Kabir, K. Rasool, W. H. Lee, S. I. Cho, and S. O. Chung, "Influence of delayed cooling on the quality of tomatoes (*Solanum lycopersicum* l.) stored in a controlled chamber," *AIMS Agriculture and Food*, vol. 5, pp. 272–285, 2020.

[16] M. Guerra and P. A. Casquero, "Influence of delayed cooling on storability and postharvest quality of European plums," *Journal of the Science of Food and Agriculture*, vol. 89, no. 6, pp. 1076–1082, 2009.

[17] H. Kitazawa, T. Sato, N. Nakamura, and S. Motoki, "Effects of post-harvest cooling delay on weight loss, soluble solid and ascorbic acid contents of strawberry fruit," *Journal of Food Agriculture and Environment*, vol. 11, pp. 372–376, 2013.

[18] M. S. N. Kabir, M. Ali, W.-H. Lee, S.-I. Cho, and S.-O. Chung, "Physicochemical quality changes in tomatoes during delayed cooling and storage in a controlled chamber," *Agriculture*, vol. 10, no. 6, p. 196, 2020.

[19] A. de Souza-Pollo and A. de Goes, "Mango pathology and diseases," in *In Handbook of Mango Fruit*, pp. 91–104, Wiley, 2017.

[20] Y. Siddiqui and A. Ali, "Chapter 11 - Colletotrichum gloeosporioides (anthracnose)," in *In Postharvest decay. S. Bautista-Baños*, pp. 337–371, Academic Press, San Diego, 2014.

[21] R. M. Rudnicki, J. Nowak, and D. M. Goszczynska, "Cold storage and transportation conditions for cut flowers cuttings and potted plants," in *International Society for Horticultural Science (ISHS)*, pp. 225–236, Leuven, Belgium, 1991.

[22] Y. Duan, G.-B. Wang, O. A. Fawole et al., "Postharvest precooling of fruit and vegetables: a review," *Trends in Food Science & Technology*, vol. 100, pp. 278–291, 2020.

[23] S. Senthilkumar and S. A. Kumar, "Advances in precooling techniques and their implications in horticulture sector: a review," *International Journal of Environmental & Agriculture Research*, vol. 1, no. 1, pp. 24–30, 2015.

[24] M. K. Baloch, F. Bibi, and M. S. Jilani, "Quality and shelf life of mango (*Mangifera indica* l.) fruit: as affected by cooling at harvest time," *Scientia Horticulturae*, vol. 130, no. 3, pp. 642–646, 2011.

[25] S. B. Mane, C. D. Pawar, B. Salvi et al., "Effect of precooling and storage temperature on physical parameters of alphonso mango (*Mangifera indica* l.) fruits," *The Pharma Innovation Journal*, vol. 10, pp. 984–989, 2021.

[26] J. Li, Y. Fu, J. Yan, H. Song, and W. Jiang, "Forced air precooling enhanced storage quality by activating the antioxidant system of mango fruits," *Journal of Food Quality*, vol. 2019, Article ID 1606058, 12 pages, 2019.

[27] X. Wang, S. Gu, and B. Chen, "The mechanism of cholesterol-effect on the quality of green asparagus (*Asparagus officinalis* l.) spears during low temperature storage," *Scientia Horticulturae*, vol. 231, pp. 36–42, 2018.

[28] N. M. Kanade, C. D. Pawar, V. Ghule, R. C. Gajbhiye, and B. Salvi, "Effect of different precooling and storage temperatures on shelf life of mango cv. Alphonso," *International Journal of Current Microbiology and Applied Sciences*, vol. 6, pp. 845–855, 2017.

[29] K. Rama Krishna, R. R. Sharma, and M. Srivastav, "Physiological and biochemical attributes associated with jelly-seed disorder in mango (*Mangifera indica* l.)," *Acta Physiologiae Plantarum*, vol. 42, p. 90, 2020.

[30] A. Paniagua, A. East, and J. Heyes, "Effects of delays in cooling on blueberry quality outcomes," *Acta Horticulturae*, vol. 1012, pp. 1493–1498, 2013.

[31] N. A. Wijewardane, "Effect of pre cooling combined with exogenous oxalic acid application on storage quality of mango (*Mangifera indica*)," *Journal of Postharvest Technology*, vol. 2, no. 1, pp. 45–53, 2014.

[32] D. P. Waskar and R. S. Gaikwad, "Effect of various postharvest treatments on extension of shelf life of Kesar mango fruits," *Indian Journal of Agricultural Research*, vol. 39, no. 2, pp. 95–102, 2005.

[33] E. M. Amwoka, J. L. Ambuko, H. M. Jesang, and W. O. Owino, "Effectiveness of selected cold chain management practices to extend shelf life of mango fruit," *Advances in Agriculture*, vol. 2021, Article ID 8859144, 12 pages, 2021.

[34] K. Ghai, P. K. Gupta, and A. K. Gupta, "Physiochemical behaviour changes during ripening in fruits of Trewia nudiflora Linn," *Perspectives in Science*, vol. 8, pp. 596–598, 2016.

[35] M. Tigist, T. S. Workneh, and K. Woldetsadik, "Effects of variety on the quality of tomato stored under ambient conditions," *Journal of Food Science and Technology*, vol. 50, no. 3, pp. 477–486, 2013.

[36] Q. Han, H. Gao, H. Chen, X. Fang, and W. Wu, "Precooling and ozone treatments affects postharvest quality of black mulberry (*Morus nigra*) fruits," *Food Chemistry*, vol. 221, pp. 1947–1953, 2017.

[37] S. Ali, M. A. Ullah, A. Nawaz et al., "Carboxymethyl cellulose coating regulates cell wall polysaccharides disassembly and delays ripening of harvested banana fruit," *Postharvest Biology and Technology*, vol. 191, article 111978, 2022.

[38] J. Yan, Y. Song, J. Li, and W. Jiang, "Forced-air precooling treatment enhanced antioxidant capacities of apricots," *Journal of Food Processing and Preservation*, vol. 42, no. 1, Article ID e13320, 2018.

[39] M. Cantwell and A. Thangaiah, "Acceptable cooling delays for selected warm season vegetables and melons," *Acta Horticulturae*, vol. 934, pp. 77–84, 2012.

[40] W.-C. Lu, Y.-T. Cheng, C.-J. Lai, B.-H. Chiang, P.-H. Huang, and P.-H. Li, "Mathematical modeling of modified atmosphere package/LDPE film combination and its application to design breathing cylinders for extending the shelf life of green asparagus," *Chemical and Biological Technologies in Agriculture*, vol. 10, no. 1, p. 60, 2023.