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Exploitation of Post-Ripening Treatment for Improving Cold Tolerance and Storage Period of Jin Huang Mango

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Abstract: The limited cold tolerance of the Jin Huang mango represents a significant impediment to its potential for international trade. Therefore, this study evaluated the quality index changes of green maturity Jin Huang mangoes with different post-ripening treatments and then when stored at different storage periods (7, 14, 21, and 28) at 4 °C followed by 6 days at 20 °C. This study showed that the mangoes treated with 500 ppm ethylene were slow to ripen during 4 °C storage, which could be sustainable even under 20 °C storage. In addition, the control (CK) group failed to mature or ripen unevenly after storage at 4 °C. Moreover, the T3 group (ethylene ripening for 1 day and post-ripening at 20 °C for 1 day) minimized the occurrence of CI during storage compared to the CK group while contributing to a 30% decrease in anthracnose incidence and a decrease in firmness and titratable acid (TA), while total soluble solids (TSS) notably increased, yet the ascorbic acid content in this group was lower. Hence, the treatment conditions of Jin Huang mango using T3 helped extend its shelf-life at 20 °C, stocking and minimizing CI and anthracnose, thereby maintaining a certain quality.

Keywords: mango; post-harvest; ripening; chilling injury; shipping; shelf-life

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1. Introduction

Mangifera indica Linn. was successfully hybridized with ♂keitt × ♀white and has long been circulating on the market with the breeder's name (trade name) Jin Huang mango [1]. It has a large size, high sugar content, low acidity, and high fiber content, with flat seeds and a high pulp ratio, and it is appreciated by consumers both for its bright yellow appearance and sweet pulp [2]. However, it is a typical perennial fruit with a short storage period (shelf-life), which will ripen rapidly post-harvest while undergoing drastic physiological changes during the ripening process, with respiration and ethylene peaks occurring. Moreover, anthracnose is a widespread factor that reduces the storage life of mangoes and is characterized by dark brown or black spots, pits, and decay on the mango peel, which results in severe economic losses [3].

Currently, it is common practice to extend the shelf-life of ripe mangoes using low-temperature storage. Yet, Jin Huang mango has poor cold tolerance; more specifically, it

experiences chilling injury (CI), the inability to change peel color period, browning, depression, ripening disorders, poor taste, and sensitivity to spoilage, which are the adverse effects of low-temperature (5 °C–8 °C) storage [4–6]. Additionally, the market receives unripe fruits that are unevenly ripened, necessitating re-ripening treatment and repackaging, while these extra processes result in increased mechanical damage risks and labor costs [7], which are not economically feasible. Consequently, this contributes to the high prices of fruits at the final market end. Unfortunately, the mango faces significant challenges in international distribution due to its inherent difficulty in post-harvest and ripening. This poses a considerable obstacle for the mango industry and limits the potential commercial viability. Therefore, the appropriate mitigation and control of anthracnose, including suitable harvesting techniques, post-harvest handling, and storage practices, are essential. These would effectively prolong the shelf life of mangoes, minimize economic losses, and ensure a steady supply of quality mangoes.

Typically, mango fruits self-ripen on the tree, and most mango varieties can be considered fully ripe on the tree as the standard for harvesting, where the fruits have the best flavor for immediate consumption. In commercial marketing practices, it is generally advised against harvesting fruits when they are fully ripe; however, such fruits are more vulnerable to injury and have a shorter shelf life, which can present significant challenges during transportation and marketing. Since the Jin Huang mango tends to deteriorate in the flesh during ripening, large-scale cultivations commonly harvest at a definite point, such as 100–120 days after anthesis. Yet, the ripening of each fruit differs at the time of harvest, which causes uneven ripening speeds and, hence, variable quality in different fruits. Therefore, the artificial ripening technique involves an exogenous ripening agent, such as exogenous ethylene, which accelerates the ripening time to ensure more uniform ripening of the same batch of fruits and provides consistent quality after ripening [8,9]. Simultaneously, it offers superior quality fruit (appearance, color, smell, and flavor) to satisfy consumers' demands. Moreover, the cold sensitivity of ripened fruits decreases. Zhao et al. [10] reported that the CI index of unripened mangoes was higher than that of light yellow and yellow ones for 12 days of storage at 2 °C and rewarming to 25 °C. In addition, treating tomatoes with ethylene before storage or shipping can be more effective than post-storage treatments, which results in faster and more consistent ripening, leading to a more extended storage period and minimizing the risk of CI during low-temperature storage [7].

In this study, the aim of ripening was combined with refrigerated storage at low temperatures while simulating the transportation conditions of rewarming storage to investigate the different post-ripening treatments (no ripening, ethylene-ripening for 1 day, ethylene-ripening for 1 day + post-ripening for 1 day, and ethylene-ripening for 1 day + post-ripening for 2 days) for green maturity Jin Huang mangoes before low-temperature storage in the refrigerated storage at 4 °C. Simultaneously, we investigated the changes in the anthracnose incidence, CI index, ripening index, respiration rate, ethylene production, color analysis, firmness, total soluble solids (TSS), titratable acid (TA), and ascorbic acid contents of mango during the 28-day storage period and after 20 °C rewarming for 6 days, which could facilitate the evaluation of the feasibility of mango in the actual commercial operation, namely, the long-term low-temperature marine shipping.

2. Materials and Methods

2.1. Materials

The green maturity Jin Huang mangoes used in this study (three batches were harvested from May to July 2023, within 110–120 days after anthesis [11], and the detailed screening color parameters are shown in Figure A1) were purchased from a local fruit farmer (Pingtung, Taiwan). For this study, fruits of commensurate size and free from any signs of disease were selected, while any fruit that displayed signs of bruising was excluded. All mangoes were placed in PVC carriers and transported via a vehicle back to the laboratory (within 1 h of travel time). Afterward, the abraded fruits were excluded, and

similar-sized fruits were selected for subsequent trials. All chemicals were purchased from Sigma-Aldrich® (Merck KGaA, Darmstadt, Germany) and used without any treatment unless otherwise stated.

2.2. Grouping and Pre-Processing

All the experimental mangoes were randomly arranged in sponge-lined baskets and divided into 4 treatment groups (n = 90) as follows: the control group (CK) was without any treatment; the T1 group was ripened with 500 ppm ethylene at 20 °C for 1 day; the T2 group was ripened with 500 ppm ethylene at room temperature for 1 day and ripened at 20 °C for 1 day; the T3 group was ripened with 500 ppm ethylene at 20 °C for 1 day and ripened at 20 °C for 2 days. Then, the mangoes with different treatments were refrigerated at 4 °C, and during the storage period, the chilling injury (CI) index, anthracnose incidence, ripening index, respiration rate, ethylene production color change, and physiological and quality changes were investigated every 7 days, and some of the mangoes were shifted to the 20 °C refrigerators for rewarming investigation on the 14th, 21st, and 28th days. Moreover, the CI index, anthracnose incidence, and color change were investigated daily during the warming period. In addition, peel color analysis was conducted on the 2nd, 4th, and 6th days, while fruit quality was analyzed on the 3rd and 6th days of the warming period.

Group	Treatment method
Control (CK)	Without any treatment
T1	Ripened with 500 ppm ethylene at 20 °C for 1 day
T2	Ripened with 500 ppm ethylene at 20 °C for 1 day and ripened at 20 °C for 1 day
T3	Ripened with 500 ppm ethylene at 20 °C for 1 day and ripened at 20 °C for 2 days

2.3. Chilling Injury (CI) Index

The determination of the CI index of mango in this study was performed as described by Kong et al. [12] with slight modifications. The symptoms of CI were observed with visual inspection for the presence of brown spots, localized browning, and pitting. Specifically, the appearance of scald-like spots (gray) on the epidermis of mangoes also includes browning and discoloration of the pulp [13]. The CI index was categorized into five levels, and the indexes were determined as follows: level 0: Without CI, while the CI area of level 1 is less than 2%; level 2: 2–10%; level 3: 10–20%; and level 4: more than 20%.

2.4. Anthracnose Incidence

The visual observation of the occurrence and determination of anthracnose in mangoes was based on an approach described by Mokgalapa et al. [14] with minor modifications. The symptoms of anthracnose present as black, irregular, and sunken lesions. Affected fruits, especially those of larger size, can undergo a prolonged incubation period, delaying the onset of disease until the final stages of ripening [15]. Prompt diagnosis and treatment are essential to prevent the spread of the disease and minimize losses in yield. Mangoes found to be naturally infected (quiescent) with anthrax at the observation time points during the storage period of this study were immediately removed, and the incidence of anthrax in each group was calculated using the following equation.

$$\text{Anthracnose incidence}(\%) = \frac{\text{Number of anthracnose} - \text{affected fruits}}{\text{total number of fruit}} \times 100 \quad (1)$$

2.5. Ripening Index

The appearance of color change in the mango was observed by the naked eye and determined according to the description in Raghavendra et al. [16], with slight modifications. The color change levels were classified into 5 levels, defined as follows: Level 0: bright green peel color. Level 1: greenish to yellowish peel color area. Level 2: the peel color

area is more yellow than green. Level 3: bright yellow peel color. Level 4: dark yellow peel color.

2.6. Respiration Rate and Ethylene Production

In this study, mango respiration rate and ethylene content were determined according to those described by Cheng et al. [17] and Lawson et al. [18], respectively, with some modifications. Briefly, mangoes were kept in a 6 L breathing tank and then sealed, followed by sampling every 2 days using a 1 mL syringe at the outlet of the breathing tank for analysis. Subsequently, sample analysis was performed using a gas chromatograph (GC-8A, Shimadzu Co., Kyoto, Japan) equipped with a thermal conductivity detector and column of Porapak P (80/100, 2 m, 2 mm ID, GL Sciences Inc., Torrance, CA, USA) under the following conditions: 100 °C at the injection, 90 °C at the column, and respiration rate expressed in mg CO_2 $kg^{-1}h^{-1}$. In addition, the ethylene production measurement was changed to a flame ionization detector with a Porapak Q (100/120, 2 m, 2 mm ID, GL Sciences Inc.) column under the following analytical conditions: 100 °C at the injection, 80 °C at the column, and the ethylene production expressed as μL kg^{-1} h^{-1}.

2.7. Color Analysis

The color appearance of the mango sample was determined following an approach described by Lin et al. [19] and Nkhata, S. G. [20], with minor modifications. The *L*, *a*, and *b* values of the samples were determined by a colorimeter (SD 5000, Nippon Denshoku Ins., Co., Ltd., Tokyo, Japan). The *L* value (brightness) ranges from 0 to 100, with higher values representing brighter colors; *a* value (red, with positive values representing red and negative values representing green); and *b* value (yellow, with positive values representing yellow and negative values representing blue). In addition, the measurements were performed in the middle section on one side of the fruit (2 points were measured randomly and averaged), which was covered with a black cloth to avoid affecting the data results. Then, the total color change (ΔE) was calculated by the following equation.

$$\text{Total color difference}(\Delta E) = \sqrt{\left(\Delta L - CK\right)^2 + (\Delta a - CK)^2 + \left(\Delta b - CK\right)^2} \quad (2)$$

where the Δ*L*, Δ*a*, and Δ*b* are the measured values of the sample (changes in lightness, redness, and yellowness) minus the difference from the CK (control).

Moreover, the hue angle (θ value) and color concentration (C value) determinations and calculations were performed according to the description of Lawson et al. [18], with minor modifications. The θ value was calculated as the absolute values of b/a multiplied by the arctangent function, which was used to indicate the color change of the fruit (0° represents reddish purple, 90° represents yellow, 180° represents blue-green, and 270° represents blue). The C value was calculated by (a value^2 + b value^2)$^{1/2}$, and the higher value indicated that the C value of the mango peel was more intense.

2.8. Firmness

The determination of the firmness of the mango sample was based on the method described by Cheng et al. [17]. The firmness of the mango was measured by using a texture analyzer (EZ-Test 500N, Shimadzu Co., Japan, Tokyo) with the following conditions: use of a No. 5 probe (0.5 cm in diameter and 10 mm deep into the sample). Each mango was measured at a single point at the equator, both the front and back sides were measured, the values were averaged, and the firmness (N) was determined.

2.9. Total Soluble Solid (TSS)

TSS determination in mango was based on the method described by Wu et al. [21]. TSS was determined by taking the juice from the mango pulp and measuring it using a handheld brix meter (N-1E, Atago Co., Ltd., Tokyo, Japan), expressed in terms of °Brix.

2.10. Titratable Acid (TA)

TA determination in mango was based on the method described by Wu et al. [21], with some modifications. A total of 10 g of mango pulp was added to 100 mL of reverse osmosis water and then used a homogenizer (Hsiangtai Machinery Industry Co., Ltd., New Taipei, Taiwan) for homogenization and then filtration. Afterward, 25 mL of the clarified solution was titrated with 0.1 N NaOH to pH 8.1 titration endpoint using an automatic titrator (T5, Mettler Toledo, Columbus, OH, USA). The titration result was determined by the equivalence of malic acid and NaOH to determine the TA content.

2.11. Ascorbic Acid

The determination of the ascorbic acid of the mango sample was based on the method described by Cheng et al. [17]. Mango pulp (5 g) was added to 50 mL of 3% metaphosphoric acid (HPO_3), mixed evenly, and filtered. Then, 5 mL of the filtrate was added with 5 mL of HPO_3, which was titrated with indophenol until the color of the solution turned pink. The above process was repeated for the standard of 1 mM ascorbic acid. Finally, it was calculated by the following equation:

$$\text{Ascorbic acid content}(\text{mg}/100\ \text{g}) = \frac{\text{Volume of indophenol used for sample titration (mL)}}{\text{Volume of indophenol used for titration of ascorbic acid standard (mL)}} \times \frac{50\ \text{mL}}{5\ \text{mL}} \times \frac{1\ \text{g}}{5\ \text{g}} \quad (3)$$

2.12. Statistical Analysis

All data in this study were analyzed with Statistical Analysis System (V9.0, SAS Institute, Cary, NC, USA) for one-way analysis of variance (ANOVA), followed by Fisher's Least Significant Difference (LSD) to analyze the differences at the significance level of $p < 0.05$. Each treatment was observed for thirty fruits, with every ten fruits as one repetition ($n = 1$), while all assays used six fruits per group and performed triplicate trials ($n = 3$). All the data in the figures were expressed as mean ± standard deviation (SD), and the figures were plotted with SigmaPlot (V10.0, Systat Software, Inc., Chicago, IL, USA).

3. Results

3.1. Changes in Different Treatments on the Appearance of Mango Fruits

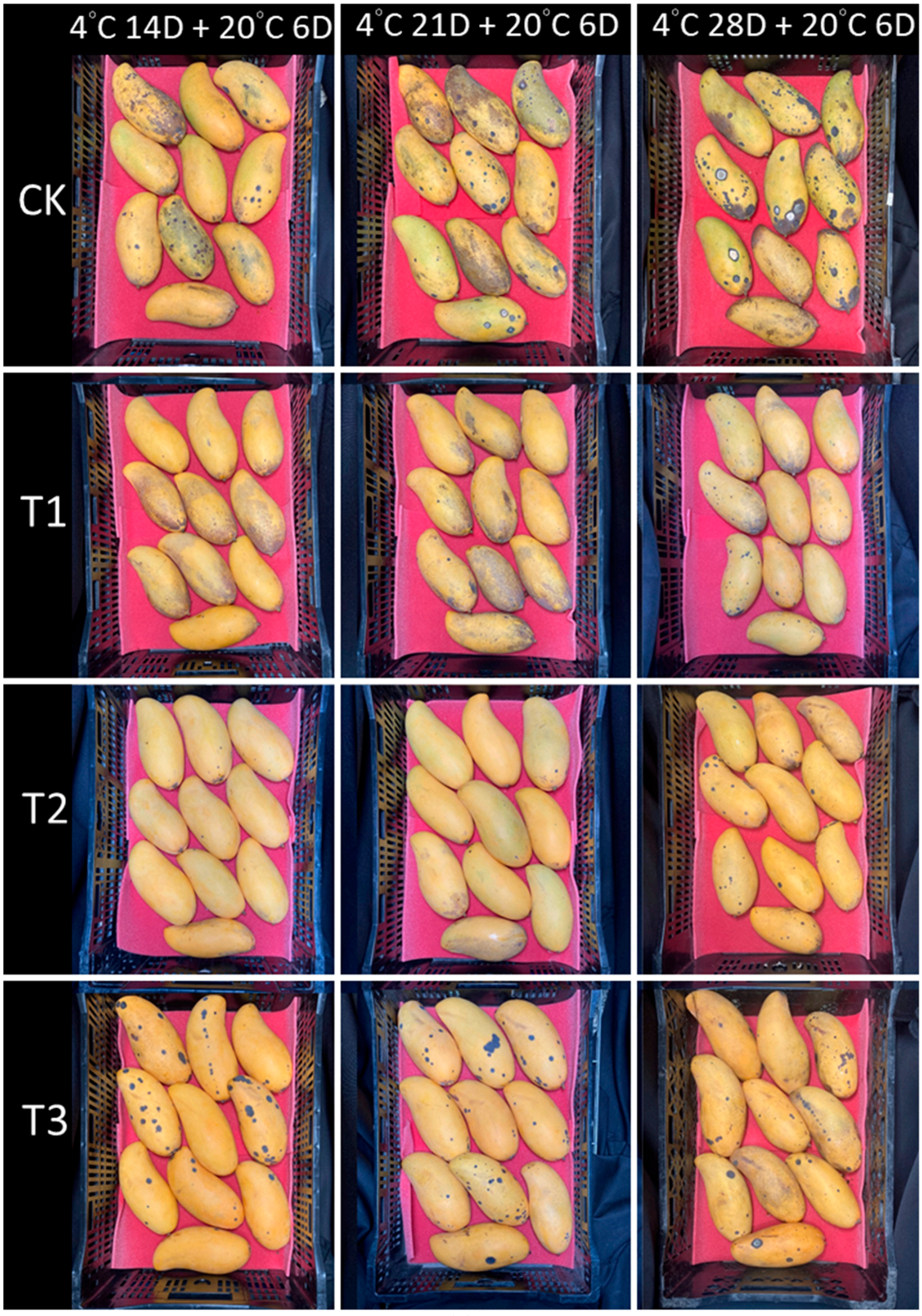
This study showed the peel of CK and T1 remained green and yellowish during storage, while the peel of T2 and T3 turned yellow (Figure 1A). However, CI occurred in CK and T1 during storage and was most severe in CK, whereas it occurred to a lesser extent in T2 and T3. This was attributed to the increased post-ripening period before storage, which assisted in minimizing the occurrence of CI in the mango fruit. Afterward, all mango fruits were stored at 4 °C for 14, 21, and 28 days, respectively. A portion of the mangoes was removed and kept at 20 °C for 6 days. The results indicated that both CK and T1 peels showed visible signs of CI and a change in the color of the peels (Figure 1B). Moreover, the peels on T2 showed a bright yellow color and some anthracnose symptoms, while the peels of CK and T3 showed more severe anthracnose symptoms.

3.2. Effect of the Post-Ripening Period on the Incidence of Anthracnose in Post-Harvest Mangoes

This study revealed that the incidence of anthracnose was significantly higher in T3 compared to others during storage; in particular, there were 23% and 47% incidences of anthracnose at 14 and 21 days of storage, respectively, whereas there was significant anthracnose incidence in CK at 28 days of storage, while T1 exhibited no anthracnose incidence during the storage period (Figure 2A). Next, all fruits after 14, 21, and 28 days of storage were rewarmed (20 °C) and stored for 6 days. In this study, the anthracnose incidence of all fruits was positively correlated with the subsequent storage time, while T3 was the highest and T1 was the lowest. (Figure 2B–D). Notably, CK showed a rapid expression of anthracnose symptoms after 21 and 28 days of storage and rewarming.

(**A**)

Figure 1. *Cont*.



(**B**)

Figure 1. Effects of the post-ripening period on the appearance of Jin Huang mango (**A**) stored at 4 °C for 7, 14, 21, and 28 days; (**B**) followed by those stored at 20 °C for 6 days. The control group (CK) was without any treatment; the T1 group was ripened with 500 ppm ethylene at 20 °C for 1 day; the T2 group was ripened with 500 ppm ethylene at 20 °C for 1 day and ripened at 20 °C for 1 day; the T3 group was ripened with 500 ppm ethylene at 20 °C for 1 day and ripened at 20 °C for 2 days.

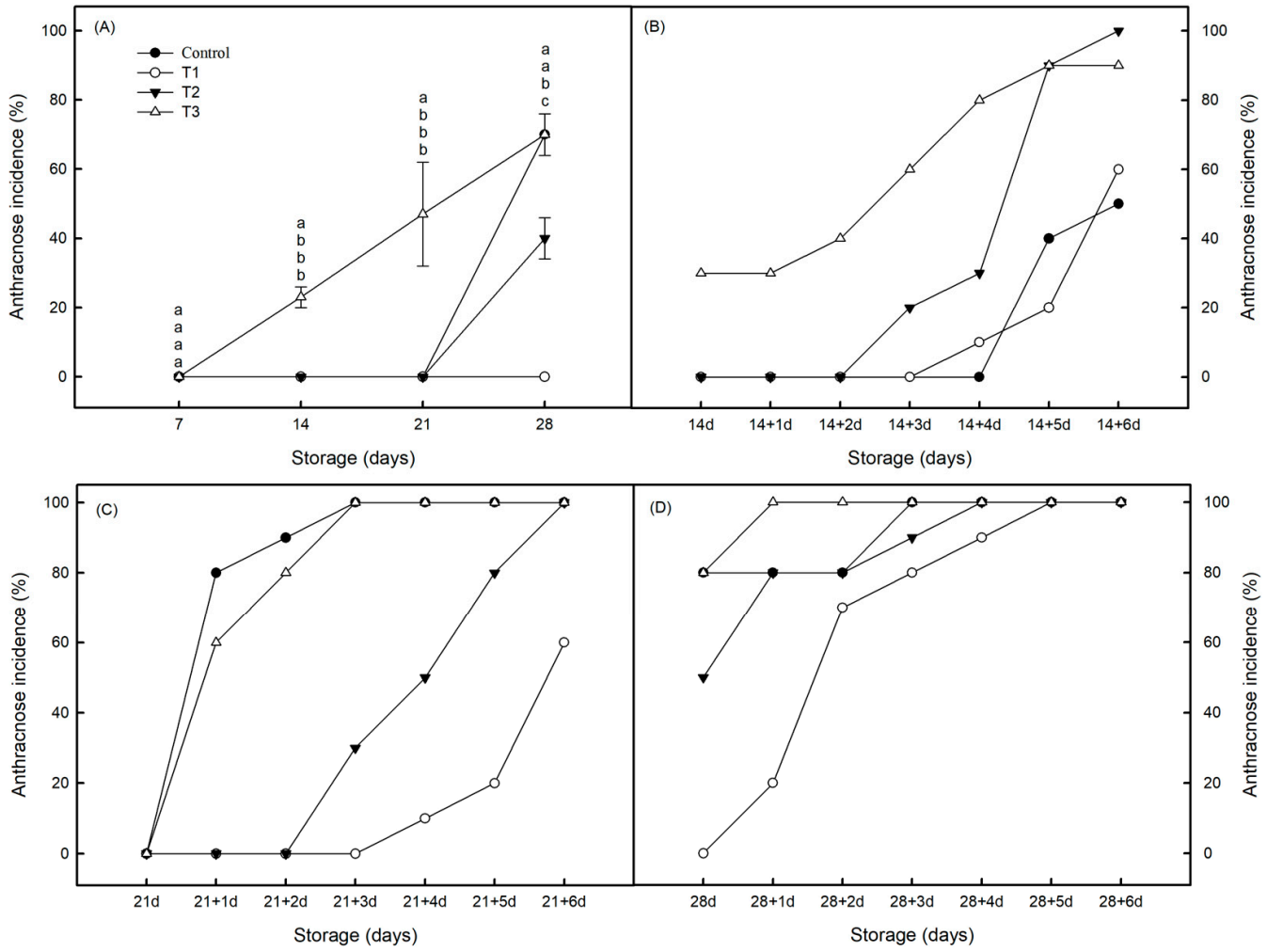


Figure 2. Effects of post-ripening time on the anthracnose incidence of post-harvest Jin Huang mango. (**A**) Storage at 4 °C; (**B**) storage at 4 °C for 14 days with rewarming (20 °C) for 6 days; (**C**) storage at 4 °C for 21 days with rewarming (20 °C) for 6 days; (**D**) storage at 4 °C for 28 days with rewarming (20 °C) for 6 days. The control group (CK; •) was without any treatment; the T1 group (○) was ripened with 500 ppm ethylene at 20 °C for 1 day; the T2 group (▼) was ripened with 500 ppm ethylene at 20 °C for 1 day and ripened at 20 °C for 1 day; the T3 group (△) was ripened with 500 ppm ethylene at 20 °C for 1 day and ripened at 20 °C for 2 days. The vertical bar represents the standard errors of the mean. Values with different letters indicate significant differences ($p < 0.05$).

3.3. Effects of the Post-Ripening Period on Chilling Injury (CI) Index of Post-Harvest Mangoes

This study showed that the CI index increased rapidly in both the CK and T1 groups during storage, while CK (3.5) was higher than the others during the 28-day storage period, and T3 was the lowest ($p < 0.05$) (Figure 3A). In addition, the CI index of CK and T1 were significantly higher ($p < 0.05$) for 14 and 21 days of storage at 4 °C with rewarming. This also indicated that the T2 and T3 treatments significantly minimized the CI index of mango, where the T3 treatment was the most effective, practically without any CI (Figure 3B,C). However, the CI index at 4 °C for 28 days of storage and rewarming in the CK and T3 groups was significantly higher than others ($p < 0.05$), whereas the T2 treatment was effective in minimizing ones (Figure 3D).

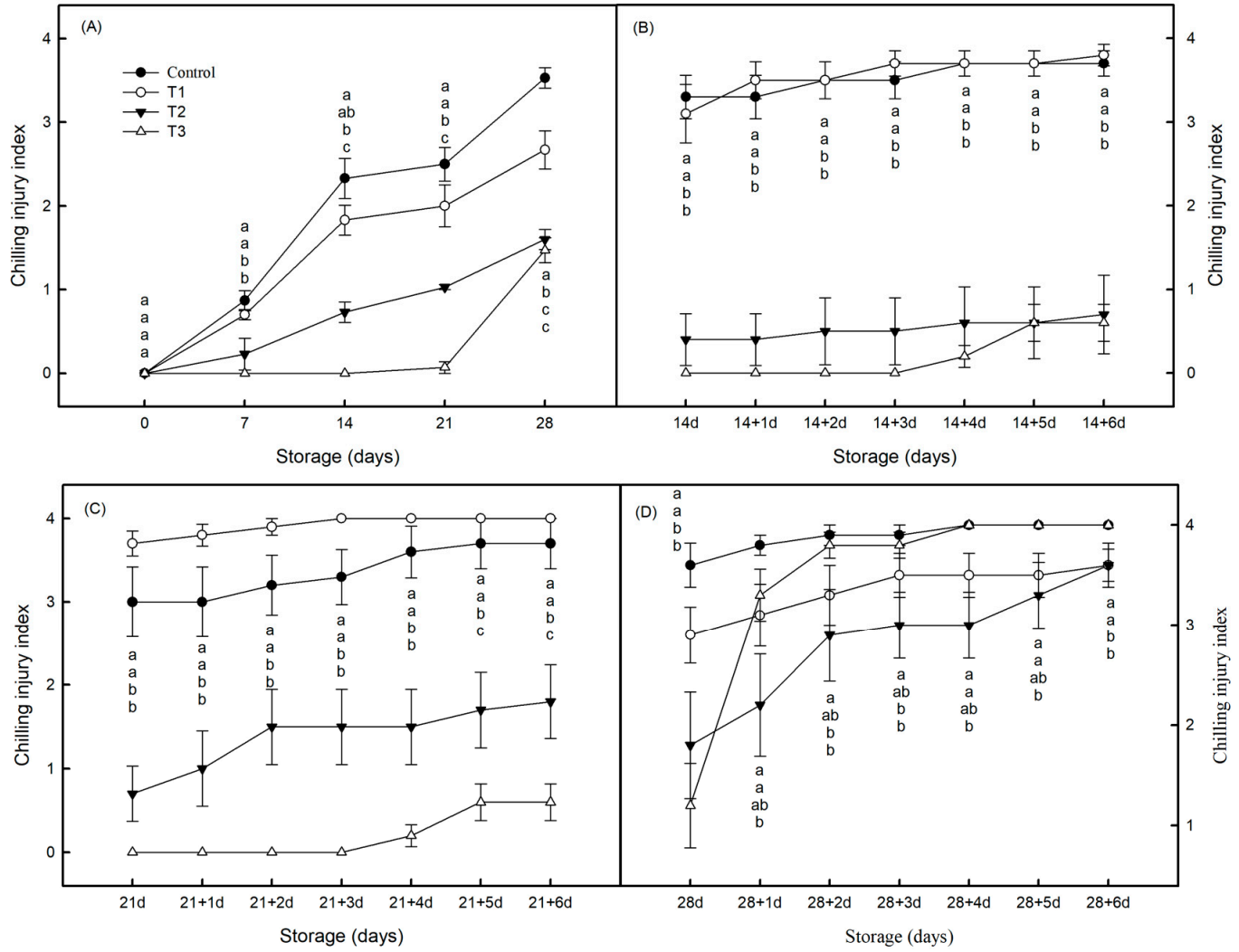


Figure 3. Effects of post-ripening time on the chilling injury index of post-harvest Jin Huang mango. (**A**) Storage at 4 °C; (**B**) storage at 4 °C for 14 days with rewarming (20 °C) for 6 days; (**C**) storage at 4 °C for 21 days with rewarming (20 °C) for 6 days; (**D**) storage at 4 °C for 28 days with rewarming (20 °C) for 6 days. The control group (CK; ●) was without any treatment; the T1 group (○) was ripened with 500 ppm ethylene at 20 °C for 1 day; the T2 group (▼) was ripened with 500 ppm ethylene at 20 °C for 1 day and ripened at 20 °C for 1 day; the T3 group (△) was ripened with 500 ppm ethylene at 20 °C for 1 day and ripened at 20 °C for 2 days. The vertical bar represents the standard errors of the mean. Values with different letters indicate significant differences ($p < 0.05$).

3.4. Effects of the Post-Ripening Period on Ripening Index of Post-Harvest Mangoes

This study revealed the same trend of peel color change in mango during storage at 4 °C and rewarming (20 °C) at storage. However, CK without ripening treatment showed almost no discoloration, while the ripening index was lower than the ripened mango during the entire storage period (Figure A2A–D). Notably, the CK showed an abnormal post-ripening phenomenon after rewarming at storage. Moreover, the ripening index of fruits was higher and quicker as the duration of ripening treatment increased, where T3 exhibited the highest ripening index during the storage period, followed by T2, while T1 was slower ($p < 0.05$).

3.5. Effects of the Post-Ripening Period on Respiration Rate and Ethylene Production of Post-Harvest Mangoes

This study showed no noticeable change in the respiration rate of all groups during storage. In contrast, the respiration rate of the treatments with different ripening times

was significantly higher than that of CK on the 7th day of storage ($p < 0.05$). In contrast, the T2 and T3 groups exhibited higher respiration rates of 12.6 and 13.9 mg CO_2 kg^{-1} h^{-1}, respectively (Figure 4A). In addition, the respiratory peak was reached in the T3 group at 14 days of storage (24.5 mg CO_2 kg^{-1} h^{-1}), whereas in the T1 group at 21 days of storage (16.6 mg CO_2 kg^{-1} h^{-1}), which was higher than others. Regarding ethylene production, CK showed a higher ethylene production of 1.1 μL kg^{-1} h^{-1} at 14 days of storage, whereas there was no significant difference between the groups, which were less than 1.0 μL kg^{-1} h^{-1} (Figure 4B).

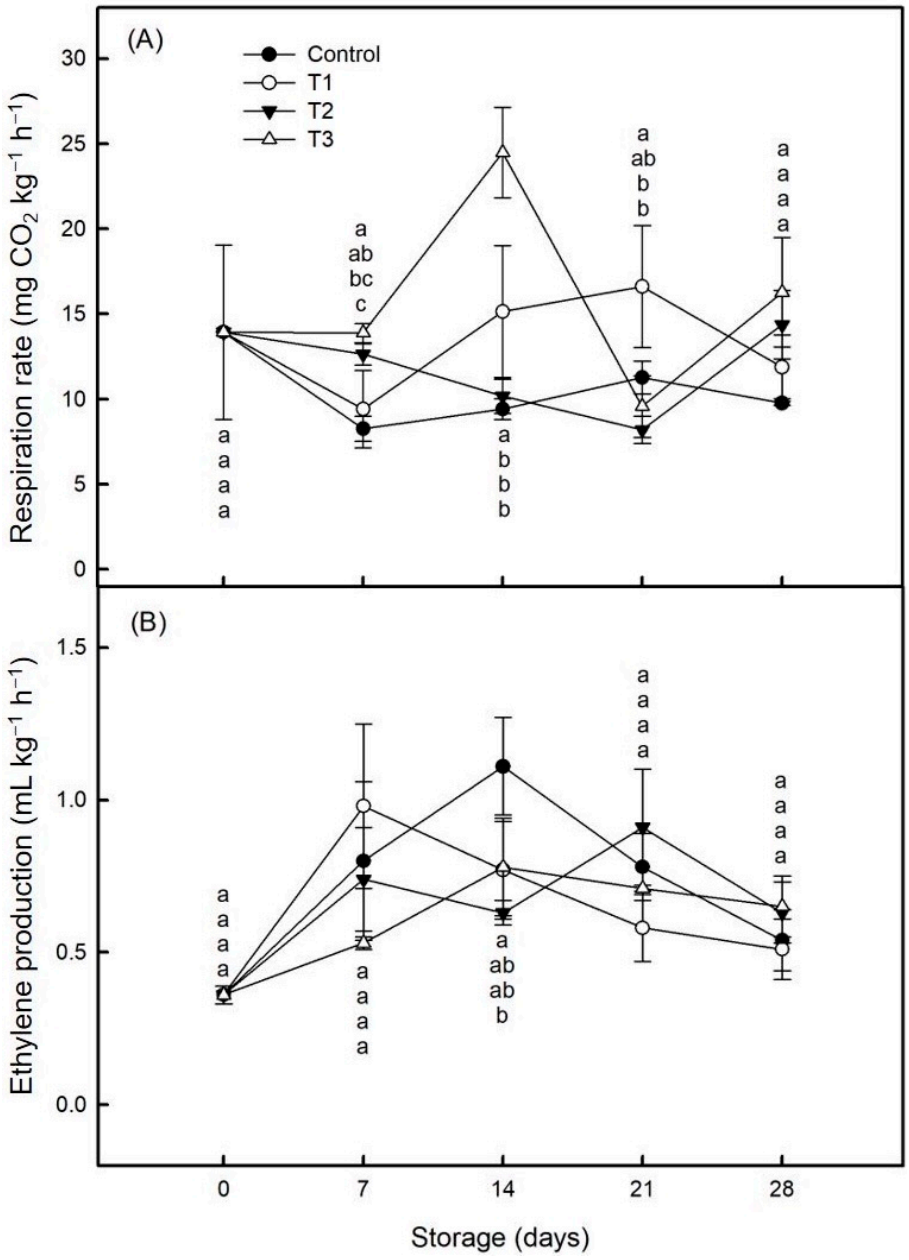


Figure 4. Effects of the post-ripening period on (**A**) respiration rate and (**B**) ethylene production of Jin Huang mango during storage at 4 °C. The control group (CK; ●) was without any treatment; the T1 group (○) was ripened with 500 ppm ethylene at 20 °C for 1 day; the T2 group (▼) was ripened with 500 ppm ethylene at 20 °C for 1 day and ripened at 20 °C for 1 day; the T3 group (△) was ripened with 500 ppm ethylene at 20 °C for 1 day and ripened at 20 °C for 2 days. The vertical bar represents the standard errors of the mean. Values with different letters indicate significant differences ($p < 0.05$).

3.6. Effects of the Post-Ripening Period on the Post-Harvest Quality of Jin Huang Mangoes

3.6.1. Change in ΔE of the Peel

During the initial stage of treatment with varying post-ripening periods, the color parameters changed in all groups (Figure A3), which were significantly different from each other ($p < 0.05$). These implied that values increased over storage time, where the appearance of color in the T2 and T3 groups significantly differed from that of the CK group. In addition, the L^* and a^* values of all fruits under each treatment decreased compared to the initial values of each, which were reflected in the presentation of ΔE, meaning that the fruits tended to over-ripen; these results were also validated in the subsequent analysis (Section 3.7). However, during storage at 4 °C, the peel L^* value of the CK group was observed to have undergone a considerable decline, which was significantly more pronounced than that of the other groups, while this was also reflected in the value of ΔE. Regarding the storage in the warmed (20 °C) condition, the lowest peel L^* value was determined in the CK group, while the T1, T2, and T3 groups were significantly higher, which also leads to differences in the ΔE (Figure A3B–D). This was attributed to the lack of post-ripening treatment in the CK group, thereby contributing to CI during storage. In contrast, the other groups showed relatively slight CI due to the post-ripening treatment, which enhanced the tolerance to low temperatures. It was recommended that further investigations be conducted to elucidate the underlying mechanisms responsible for these observations.

3.6.2. Changes in the Hue Angle (θ Value) of the Peel

This study showed that during storage at 4 °C, the CK group had the highest peel θ value, which ranged from 99.6 ± 0.9 to 103.9 ± 0.6 ($p < 0.05$), as indicated in Figure A4A. However, the three ripening treatment groups showed a significantly lower peel θ value, while the T3 group exhibited the lowest value, ranging from 85.9 ± 0.8 to 86.7 ± 1.0 during storage. In contrast, the T2 group consistently declined the peel θ value throughout storage, starting from day 14 and persisting until day 28. This trend suggested a gradual deterioration in the mango quality of those that were stored. Moreover, a similar trend occurred for the 4 °C stored fruits, which were changed to the rewarming (20 °C) storage, and the peel θ value gradually decreased in all groups with increasing rewarming time (Figure A4B–D).

3.6.3. Changes in the Color Concentration (C Value) of the Peel

This study showed that the peel C value of mango with different ripening treatments during storage at 4 °C ranged from high to low in T3, T2, T1, and CK groups, respectively. This indicated that the peel C values of mango were significantly increased ($p < 0.05$) by ripening treatments (Figure A5). During storage at rewarming (20 °C), the C values of the ripening treatment groups were also significantly higher than that of the CK group (Figure A5B–D), which suggested that there were no significant differences in the effects of the two storage conditions on the C value of the mango peel.

3.6.4. Changes in the Firmness of the Mango

This study showed that the firmness of the ripened mango groups was significantly lower than that of the CK group during storage at 4 °C ($p < 0.05$) (Figure 5A), which was negatively correlated with the storage time. However, the firmness of mango fruits of each group in descending order was CK, T1, T2, and T3. Similar trends were also observed after rewarming, where increased post-ripening contributed to a decrease in firmness during storage, which also decreased with increased storage time (Figure 5B–D).

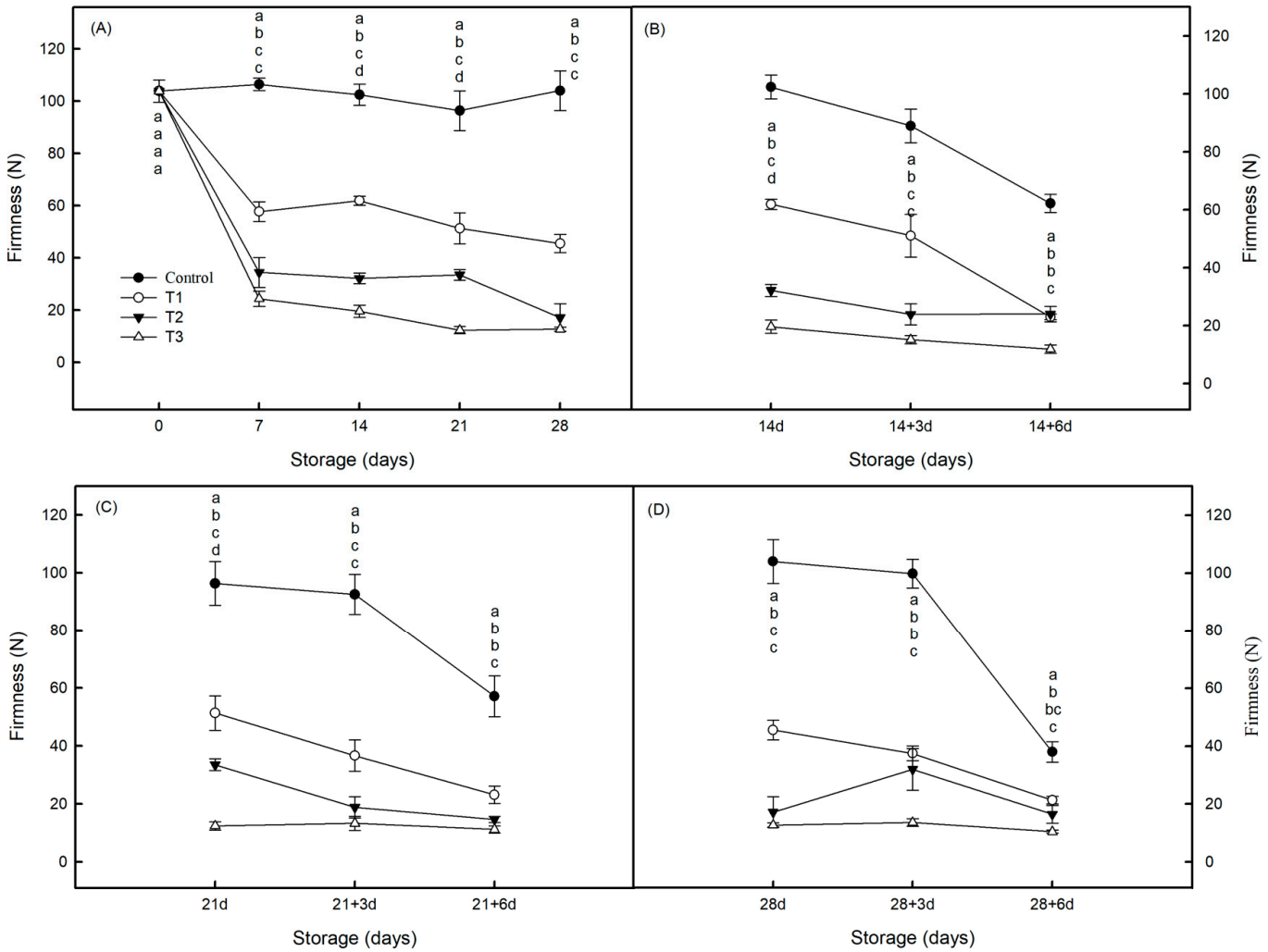


Figure 5. Effects of post-ripening time on the firmness of post-harvest Jin Huang mango. (**A**) Storage at 4 °C; (**B**) storage at 4 °C for 14 days with rewarming (20 °C) for 6 days; (**C**) storage at 4 °C for 21 days with rewarming (20 °C) for 6 days; (**D**) storage at 4 °C for 28 days with rewarming (20 °C) for 6 days. The control group (CK; ●) was without any treatment; the T1 group (○) was ripened with 500 ppm ethylene at 20 °C for 1 day; the T2 group (▼) was ripened with 500 ppm ethylene at 20 °C for 1 day and ripened at 20 °C for 1 day; the T3 group (△) was ripened with 500 ppm ethylene at 20 °C for 1 day and ripened at 20 °C for 2 days. The vertical bar represents the standard errors of the mean. Values with different letters indicate significant differences ($p < 0.05$).

3.6.5. Changes in the Total Soluble Solids (TSS) Content of the Mango

This study showed that the CK group exhibited the lowest TSS content (ranging from 5.8 ± 0.7. Brix to 7.6 ± 1.4. Brix) during storage at 4 °C (Table 1). However, the TSS contents increased with post-ripening treatment time, particularly in the T2 and T3 groups, which exhibited higher TSS contents. In contrast, it was discovered that the TSS content of the post-ripening treatment groups was significantly greater than that of the CK group during the rewarming storage period (20 °C) ($p < 0.05$). However, no significant differences were observed among the treatment groups. Notably, the TSS content of the CK group tended to increase as the rewarming period of storage increased (14–28 days).

The control group (CK) was without any treatment; the T1 group was ripened with 500 ppm ethylene at 20 °C for 1 day; the T2 group was ripened with 500 ppm ethylene at 20 °C for 1 day and ripened at 20 °C for 1 day; the T3 group was ripened with 500 ppm ethylene at 20 °C for 1 day and ripened at 20 °C for 2 days.

Table 1. Effects of post-ripening time on the total soluble solids (TSS), titratable acid (TA), and ascorbic acid contents of post-harvest Jin Huang mango.

Treatment	Group/Measurement Item											
	CK	T1	T2	T3	CK	T1	T2	T3	CK	T1	T2	T3
	Total Soluble Solids (°Brix)				Titratable Acid (%)				Ascorbic Acid (mg/100 g)			
0 Day (D)	6.20 ± 0.32a				0.56 ± 0.03a				24.10 ± 1.14a			
4 °C, 7D	5.90 ± 0.32b	8.47 ± 1.26b	12.80 ± 0.65a	14.30 ± 0.76a	0.46 ± 0.00b	0.48 ± 0.05b	0.52 ± 0.02ab	0.59 ± 0.03a	20.91 ± 0.07b	23.40 ± 0.07a	21.08 ± 0.33b	18.82 ± 1.19c
4 °C,14D	7.57 ± 1.39c	10.73 ± 0.52b	12.87 ± 0.64ab	14.63 ± 0.37a	0.68 ± 0.01b	0.82 ± 0.03a	0.52 ± 0.07c	0.77 ± 0.03ab	20.69 ± 0.33c	25.8 ± 0.79a	22.42 ± 0.46b	21.88 ± 0.09bc
4 °C, 21D	6.50 ± 0.67c	11.7 ± 0.61b	12.8 ± 0.25ab	14.23 ± 0.12a	0.52 ± 0.08b	0.63 ± 0.09ab	0.87 ± 0.05a	0.68 ± 0.14ab	20.68 ± 0.82a	18.44 ± 0.62ab	19.80 ± 0.39ab	16.83 ± 1.74b
4 °C, 28D	5.77 ± 0.69c	13.50 ± 0.51b	15.77 ± 0.61a	15.3 ± 0.71ab	0.68 ± 0.03a	0.68 ± 0.11a	0.67 ± 0.04a	0.63 ± 0.01a	15.36 ± 0.30c	18.84 ± 0.60bc	25.19 ± 1.78a	20.12 ± 1.37b
4 °C, 7D	5.90 ± 0.32b	8.47 ± 1.26b	12.80 ± 0.65a	14.30 ± 0.76a	0.46 ± 0.00b	0.48 ± 0.05b	0.52 ± 0.02ab	0.56 ± 0.27a	20.91 ± 0.07b	23.40 ± 0.07a	21.08 ± 0.33b	18.82 ± 1.19c
4 °C, 7D + 20 °C, 3D	9.37 ± 0.26c	14.53 ± 0.67b	16.80 ± 1.01ab	17.73 ± 1.27a	0.54 ± 0.03c	0.67 ± 0.03b	0.78 ± 0.02a	0.63 ± 0.02b	17.61 ± 0.26a	17.97 ± 0.57a	17.13 ± 0.79a	16.93 ± 1.30a
4 °C, 7D + 20 °C, 6D	16.67 ± 0.86a	15.93 ± 1.34a	16.10 ± 0.61a	15.43 ± 1.23a	0.88 ± 0.12a	0.57 ± 0.02b	0.51 ± 0.02b	0.38 ± 0.02b	30.96 ± 3.39a	10.53 ± 0.96c	16.50 ± 0.52b	16.83 ± 0.74b
4 °C,14D	7.57 ± 1.39c	10.73 ± 0.52b	12.87 ± 0.64ab	14.63 ± 0.37a	0.69 ± 0.01b	0.82 ± 0.03a	0.52 ± 0.07c	0.77 ± 0.03ab	20.69 ± 0.33c	25.8 ± 0.79a	22.42 ± 0.46b	21.88 ± 0.09bc
4 °C,14D + 20 °C, 3D	10.70 ± 1.06c	13.70 ± 0.29ab	12.30 ± 0.23bc	14.93 ± 0.22a	0.83 ± 0.05a	0.72 ± 0.09a	0.87 ± 0.10a	0.79 ± 0.12a	21.27 ± 0.40a	23.52 ± 0.46a	24.73 ± 2.83a	20.41 ± 0.61a
4 °C, 14D + 20 °C, 6D	12.23 ± 0.67c	16.76 ± 0.35a	15.37 ± 0.26b	14.50 ± 0.26b	0.83 ± 0.06a	0.64 ± 0.00b	0.86 ± 0.04a	0.35 ± 0.02c	21.08 ± 0.95a	9.96 ± 0.80c	15.36 ± 0.54b	16.46 ± 0.68b
4 °C, 21D	6.50 ± 0.67c	11.7 ± 0.61b	12.8 ± 0.25a	14.23 ± 0.12ab	0.52 ± 0.08b	0.63 ± 0.09ab	0.87 ± 0.05a	0.68 ± 0.14ab	20.68 ± 0.82a	18.44 ± 0.62ab	19.80 ± 0.39ab	16.83 ± 1.74b
4 °C, 21D + 20 °C, 3D	8.53 ± 2.11b	16.00 ± 0.35a	16.97 ± 0.89a	16.27 ± 1.50a	0.76 ± 0.05a	0.74 ± 0.01ab	0.65 ± 0.04b	0.69 ± 0.01ab	22.91 ± 0.78a	13.65 ± 0.62c	22.24 ± 1.76ab	18.74 ± 0.83b
4 °C, 21D + 20 °C, 6D	15.70 ± 0.52a	16.57 ± 0.33a	16.80 ± 0.26a	15.7 ± 0.23a	0.71 ± 0.06a	0.53 ± 0.03bc	0.65 ± 0.05ab	0.42 ± 0.02c	18.56 ± 0.80a	17.36 ± 0.98a	18.31 ± 0.46a	19.98 ± 1.01a
4 °C, 28D	5.77 ± 0.69c	13.50 ± 0.51b	15.77 ± 0.61a	15.3 ± 0.71ab	0.68 ± 0.03a	0.69 ± 0.11a	0.67 ± 0.04a	0.63 ± 0.01a	15.36 ± 0.3c	18.84 ± 0.6bc	25.19 ± 1.78a	20.12 ± 1.37b
4 °C, 28D + 20 °C, 3D	7.67 ± 0.67b	15.60 ± 0.38a	14.60 ± 0.51a	16.67 ± 0.95a	0.87 ± 0.02a	0.61 ± 0.02b	0.63 ± 0.04b	0.44 ± 0.01c	26.80 ± 1.97a	18.33 ± 0.46c	23.34 ± 0.52ab	21.06 ± 1.98bc
4 °C, 28D + 20 °C, 6D	13.17 ± 0.64b	16.47 ± 0.65a	15.60 ± 0.89a	16.03 ± 0.33a	0.58 ± 0.06ab	0.61 ± 0.04a	0.43 ± 0.05b	0.47 ± 0.06ab	23.30 ± 1.45a	10.80 ± 0.95c	10.76 ± 0.33c	16.25 ± 0.76b

Different letters in lowercase in the same column represent significant differences ($p < 0.05$).

3.6.6. Changes in the Titratable Acid (TA) Content of the Mango

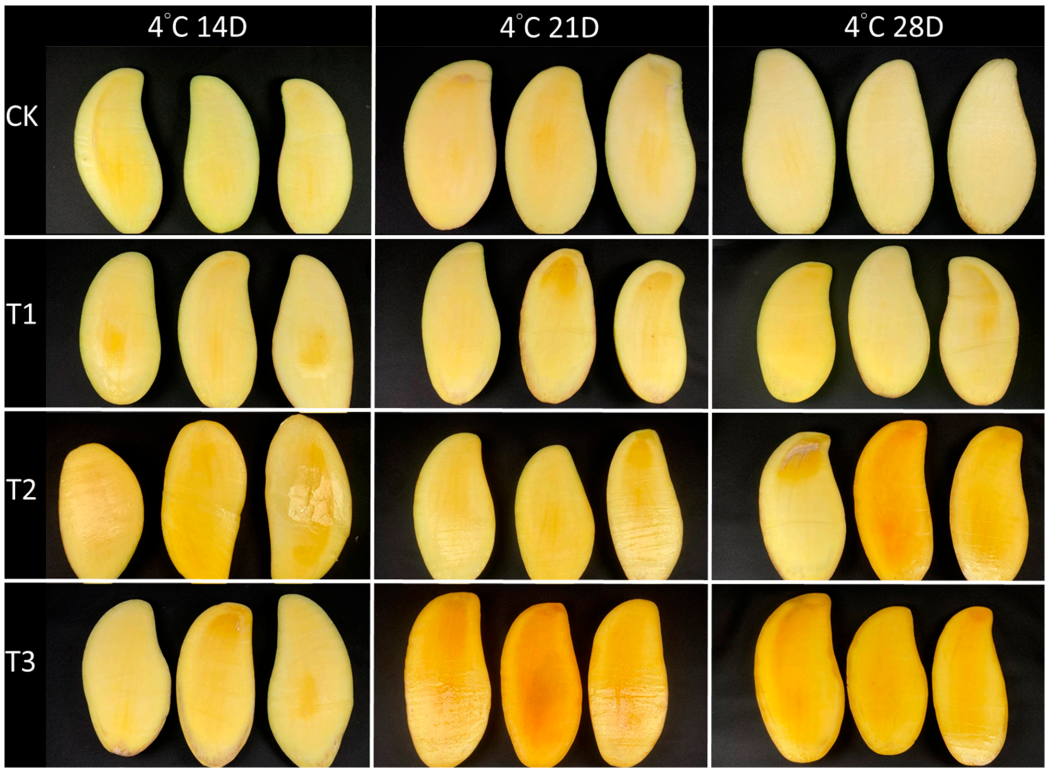
This study showed that the TA content of each group during 4 °C storage initially increased with the storage time, then decreased slightly until stabilized (Table 1). These results indicate that the storage time influenced the TA content of the mangoes. However, after 14 and 21 days of storage at 4 °C then storage at a rewarming temperature (20 °C) for 6 days, the TA contents of the T1 and T3 groups were significantly lower, whereas the CK and T2 groups exhibited higher TA contents. In addition, the lower TA contents of the T2 and T3 groups were detected after 28 days at 4 °C and then 6 days of storage at 20 °C. However, the TA contents of mangoes in all treatment groups tended to decrease significantly during the rewarming storage period.

3.6.7. Changes in the Ascorbic Acid Content of the Mango

In this study, except for the T2 group, which showed a higher ascorbic acid content after storage at 4 °C, other groups showed a gradual decrease in ascorbic acid contents as storage time increased; from highest to lowest, they are ranked as T2, T3, T1, and CK, which were significantly different from each other ($p < 0.05$) (Table 1). However, after 14 and 28 days of storage at 4 °C and then 6 days of rewarming (20 °C), the ascorbic acid contents tended to decrease in all groups. Interestingly, after 21 days of storage at 4 °C followed by rewarming, there was a decreasing trend in CK and T2, whereas there was an increasing trend in T1 and T3. Yet, there were no significant differences for all groups.

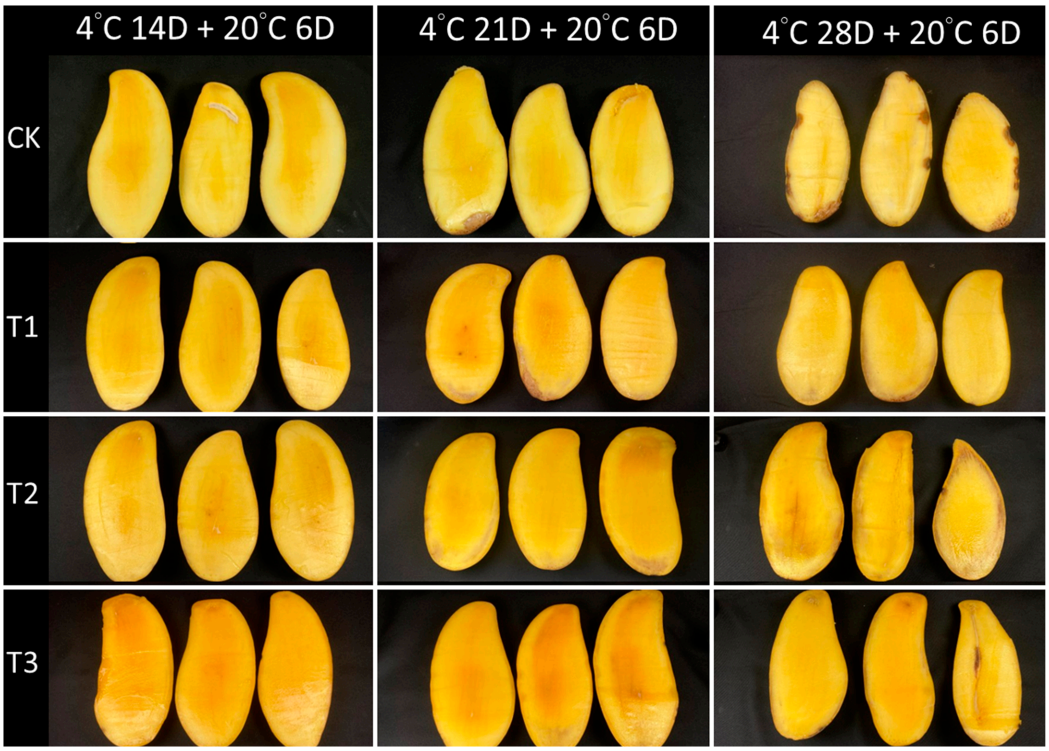
3.7. Changes in the Appearance of Mango Pulp

This study showed that the pulps of CK and T groups were light yellow, and there were no significant changes during storage at 4 °C, whereas the pulps of T2 and T3 groups were markedly yellow and turned more yellow as storage time increased (Figure 6A). Subsequently, in the 6 days of storage at a rewarming temperature (20 °C), the pulp of the CK group showed uneven ripening and was waterlogged, as opposed to the fully ripened and dark yellow pulps of the ripened groups (Figure 6B).



(**A**)

Figure 6. *Cont.*



(**B**)

Figure 6. The effects of the post-ripening period on pulps appearance of post-harvest Jin Huang mangoes (**A**) stored at 4 °C for 14, 21, and 28 days; (**B**) followed by stored at 20 °C for 6 days. The control group (CK) was without any treatment; the T1 group was ripened with 500 ppm ethylene at 20 °C for 1 day; the T2 group was ripened with 500 ppm ethylene at 20 °C for 1 day and ripened at 20 °C for 1 day; the T3 group was ripened with 500 ppm ethylene at 20 °C for 1 day and ripened at 20 °C for 2 days.

4. Discussion

Anthracnose pathogens are known to form wounds on the fruit surface, whereas ethylene improves the permeability of the wounds and releases nutrients to facilitate the bioviability of the attached pathogens, thus enhancing the probability of the fruit being infected by the pathogens [3,14,22]. Moreover, anthracnose is no longer a minor issue but a major concern for exporters, given the crucial demand for top-notch produce in international markets [23]. It was reported that the most common fungal isolates currently associated with mangoes involve 13 species, mainly *C. asianum* and *C. siamense*, which accounted for 60% of the germination [24]. It is worth mentioning that anthracnose has asexual spores (conidia) that can be transmitted, while spores contacting the susceptible tissues of the host begin to infect the host. The pathogen reproduces, culminating in developing the disease in the fruit [25]. More specifically, *Colletotrichum* spp. utilizes a semi-biotrophic mode of infection to penetrate, colonize, and spread within susceptible host plants; i.e., black adherent cysts are formed that penetrate the host and form harmless primary mycelium during the biotrophic stage of infection. Secondary hyphae are then formed during the necrotic stage, leading to spore colonization on the surface of infected tissues of the host, resulting in continuous repetitive pathogen transmission and infection [26]. However, this study showed that storage at 4 °C for 28 days in the T1 group and storage at 4 °C for 21 days in the T3 group effectively minimized anthracnose incidence development (Figure 2A). It is worth mentioning that the CK and T1 groups storage at 4 °C for 14–21 days before switching to rewarming storage for 2–4 days also effectively decreases the incidence of anthracnose (Figure 2B,C). As fruits ripened, anthracnose incidence increased [27–29]. Furthermore, it was suggested that fruit stored at 20 °C ripens faster and is more susceptible to disease than fruit stored at 10 °C and 15 °C, with a faster increase in disease severity [30].

The invasion of fruit pathogens will not show symptoms immediately and only show red pinpoints on the fruit surfaces, indicating latent infection. Rain or dew will also assist in spreading the infection, namely, the appearance of reddish-colored tear spots on the surface of the fruit [31]. The needle-like spots of latent infection expand after ripening, and black, sunken, irregularly shaped spots appear. However, the spots expand rapidly when the fruits are ripe, eventually becoming water-soaked and rotted, making it a severe storage disease [22,31].

Previously, this study confirmed that the T1 group treatment (ripened with 500 ppm ethylene at 20 °C for 1 day) and the modification of storage temperature contributed to the prolonged shelf-life and incidence of anthracnose during the post-ripening mango storage.

Moreover, CI is the primary limiting factor in mango quality maintenance during long-term refrigeration and ambient temperature shelf-life, where the typical symptom of CI was incomplete post-ripening [32]. In particular, exogenous ethylene supplementation during the storage of tomatoes [33] and mangoes [34–36] provided excellent relief of fruit CI symptoms. This was attributed to ethylene being a gaseous hormone that regulates fruit post-ripening, aging, and response to adversity [8,36], and the blockade of ethylene biosynthesis under low-temperature adversity was shown to be a key factor contributing to the CI of some fruits. Therefore, the high-maturity fruits were less susceptible to CI than poorly matured ones [33]. Simultaneously, ethylene treatment promotes mango peel color change during storage, associated with pigment metabolism in the peel involved in the endogenous enzyme activities, anthocyanin, and carotenoid accumulation [35].

However, this study confirmed that T2 and T3 treatments were significantly associated with decreased CI index (Figure 3A–C), where T3 treatment was the most effective (Figure 3B). Unfortunately, the CI symptoms were evident after rewarming the fruits from low-temperature storage to high, as observed in this study for 28 days of storage at 4 °C and subsequently storage at 20 °C of mangoes (Figure 3D). Similarly, Jiang et al. [37] reported that CI symptoms of 'Guifei' mango during storage at 5 °C were minor and exhibited a gradual darkening of the peel color with the appearance of small black spots while chilling symptoms of mango turned poorer rapidly after rewarming to 20 °C as severe browning, enlargement of the black spots, depression, and unripeness were observed. In terms of color appearance, this study found that in the CK group, which was severely chilled after 14 days of storage at 4 °C and then at 20 °C for another 6 days, there were still some green coloration, which might result from the chloroplast damage of CI [6,38–40].

Ethylene production and respiration rate serve as important indicators of mango physiological metabolism, whereas peaks of ethylene and respiration were characterized in the post-ripening process of mango [41]. Therefore, all groups in this study peaked in respiration rate and ethylene production during storage at 4 °C for 14–21 days (Figure 5A,B), despite a study by Jiang et al. [37], which reported that ethylene production in mango fruit was inhibited by storage at a low temperature of 5 °C. It was hypothesized that the possible explanation was caused by cultivar differences and differences associated with the ripening treatments before storage. Fruit softening is one of the annual ripening characteristics, significantly affecting shelf life and market value [42]. The softening process of fruits is caused by the degradation of polysaccharides such as starch, cellulose, and pectin by amylase, polygalacturonase, and pectin esterase enzymes, which leads to the structural degradation of the cell wall, thus contributing to the reduction of fruit firmness [21,43–45]. Therefore, the loss of cell expansion pressure and cell wall relaxation with fruit ripening and senescence resulted in a decrease in firmness [46], which agreed with the results of this study. Moreover, ethylene plays a crucial role in inducing gene expression, associated with starch conversion to sugar, with changes in the cell wall structure contributing to decreased fruit firmness [47]. However, in this study, treatment with ethylene prior to storage enhanced fruit ripening, leading to the gradual softening of fruits, presumably due to pectin hydrolysis [48,49].

Regarding TA and TSS, both influence the flavor of fruits and are indicators of their quality. In mango fruits, TSS content tends to increase with storage time due to the

decomposition of large molecules such as starch and pectin into smaller ones, namely, the accumulation of sugar during respiration and the decrease in water content, thus leading to an increase in TSS content [43,50]. Therefore, this study confirmed that the TSS contents of mangoes treated with ripening agents were considerably higher than those of the CK group. The TSS contents kept increasing with ripening during storage. A similar study reported that the post-harvest application of exogenous ethylene increased TSS levels in Keitt mangoes [51]. Unfortunately, the TA content of mangoes is observed to decrease with prolonged storage time. This phenomenon is supported by previous research conducted by Montalvo et al. [36], who reported that the application of exogenous ethylene can cause a decrease in the TA of fruits. Moreover, Wang et al. [52] documented a rapid decline in the citric acid content of mangoes subjected to ethylene treatment. These findings highlight the significance of storage duration and ethylene treatment in preserving fruit quality.

Furthermore, ascorbic acid is one of the critical antioxidant components in the plant defense system, which can be minimized by producing free radicals during fruit ripening [53]. In this study, we observed that the ascorbic acid content of mango was significantly higher in the T1 and T2 groups during storage at 4 °C as the minimum CI, which was consistent with the findings of Taghipour et al. [54]. However, the occurrence of CI and lower ascorbic acid content in the CK group agreed with the findings of Ribeiro, B. S. and S. T. de Freitas [55], as CI is associated with the production of excessive reactive oxygen species (ROS) related to chloroplasts and mitochondria, such as hydrogen peroxide, superoxide radicals, and hydroxyl radicals, thereby leading to oxidative damage [12,27,37,38].

Taken together, the conditions of the T3 treatment in this study led to a positive effect on quality-related indicators, namely decreased TA content and increased TSS. This implies that mangoes improve overall quality (including flavor, color, texture, and nutrition) during post-harvest storage. Therefore, the results of this study may contribute to the improvement and control of the ripening of mangoes during storage and transportation operations with other potential practical applications.

5. Conclusions

This study confirmed that the pre-ripening treatment at 20 °C for 1 day and post-ripening for 1 day of Jin Huang mangoes with ethylene before storage was sustainable during storage (4 °C), while the accompanying change in temperature effectively mitigated the CI index of mangoes and provided the benefit of decreasing the anthracnose incidence. Moreover, maintaining fruit quality storage at 20 °C proved to be a practical approach to enhancing the storage and transportation of Jin Huang mangoes, which also contributed to the maintenance of the mango availability for consumption despite the decreased firmness, TA, and ascorbic acid content but increased TSS and favorable appearance. Additionally, this information could be highly beneficial for researchers and suppliers of Jin Huang mango, facilitating further development opportunities. However, it is necessary to conduct further exploration to comprehensively understand the underlying intricacies and develop a more effective combined approach for mitigating various effects on mango quality during storage.

Author Contributions: Conceptualization, Y.-C.L. and M.-C.Y.; methodology, Y.-C.L. and C.-Y.Y.; software, M.-C.Y., C.-Y.Y. and J.-S.T.; validation, J.-S.T., C.-Y.H. and P.-H.L.; formal analysis, Y.-C.L. and C.-Y.Y.; investigation, Y.-C.L., M.-C.Y., C.-Y.Y. and J.-S.T.; resources, Y.-S.L.; data curation, Y.-C.L., C.-Y.Y. and M.-C.Y.; writing—original draft preparation, Y.-C.L. and P.-H.H.; writing—review and editing, P.-H.H. and Y.-S.L.; visualization, Y.-C.L., M.-C.Y., C.-Y.Y. and J.-S.T.; supervision, C.-Y.H., P.-H.L. and Y.-S.L.; project administration, Y.-C.L. and Y.-S.L. All authors have read and agreed to the published version of the manuscript.

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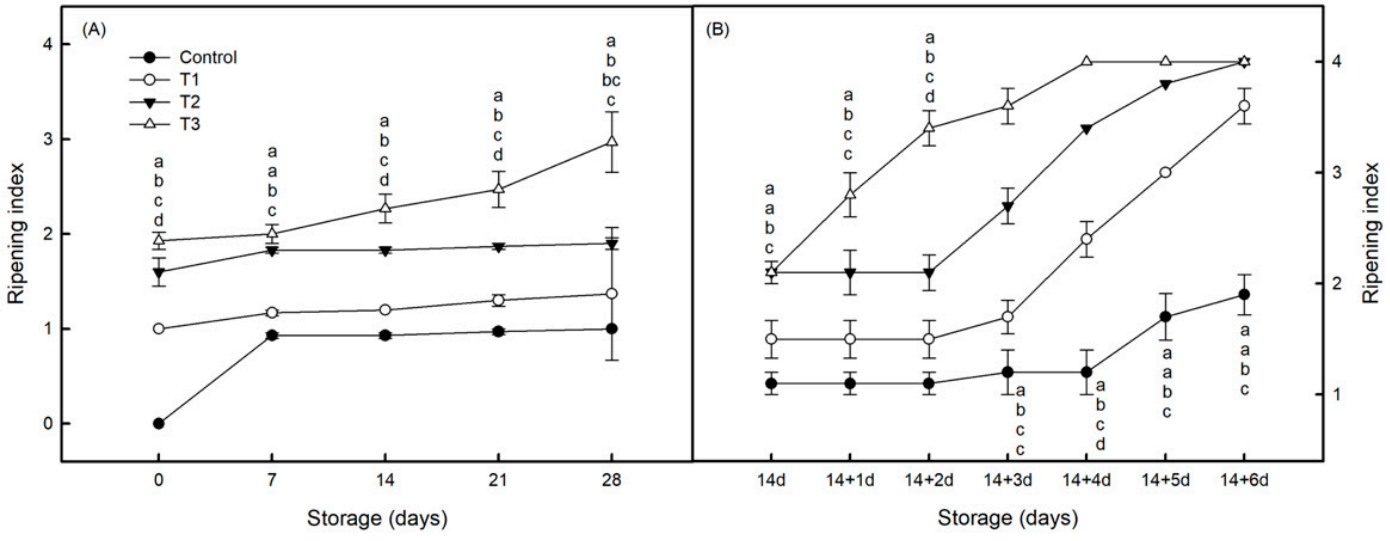
Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Figure A1. The color of Jin Huang mango (harvested within 110–120 days after anthesis) on day 0 of each batch in this study. The specific conditions are as follows: (1) *L* value: 64.96 (average), 69.43 (maximum), 52.34 (minimum); (2) Hue angle (θ value): 103.89 (average), 107.91 (maximum), 98.99 (minimum); (3) Chroma (C value): 44.79 (average), 49.31 (maximum), 39.19 (minimum).



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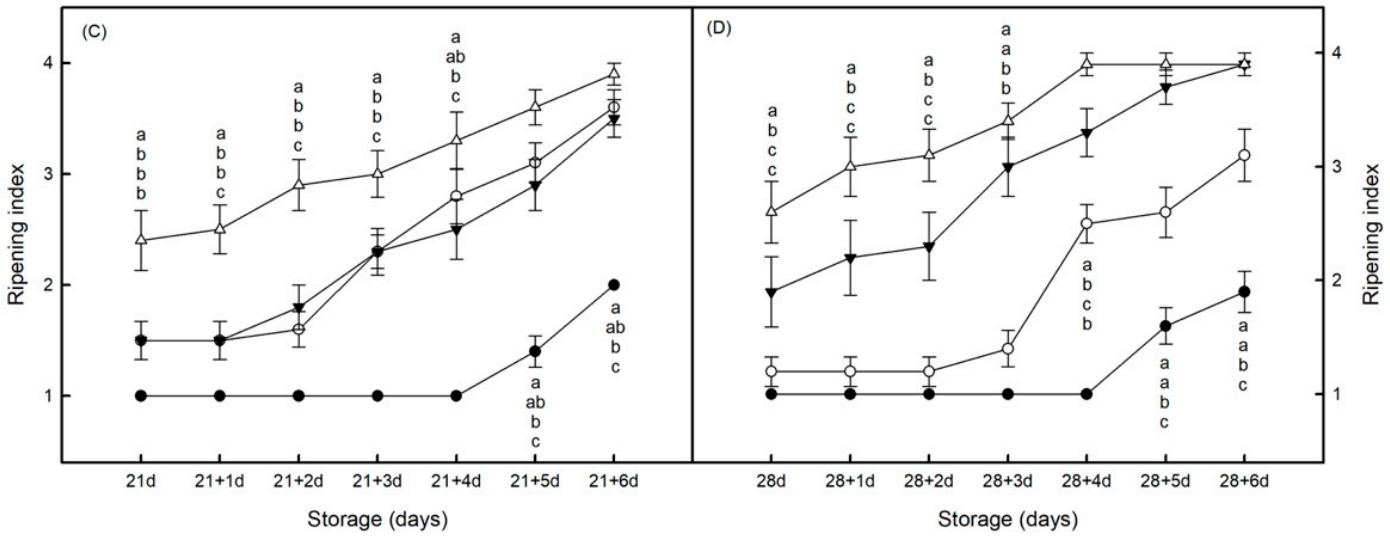

Figure A2. Effects of post-ripening time on the ripening index of post-harvest Jin Huang mango. (**A**) Storage at 4 °C; (**B**) storage at 4 °C for 14 days with rewarming (20 °C) for 6 days; (**C**) storage at 4 °C for 21 days with rewarming (20 °C) for 6 days; (**D**) storage at 4 °C for 28 days with rewarming (20 °C) for 6 days. The control group (CK; •) was without any treatment; the T1 group (○) was ripened with 500 ppm ethylene at 20 °C for 1 day; the T2 group (▼) was ripened with 500 ppm ethylene at 20 °C for 1 day and ripened at 20 °C for 1 day; the T3 group (△) was ripened with 500 ppm ethylene at 20 °C for 1 day and ripened at 20 °C for 2 days. The vertical bar represents the standard errors of the mean. Values with different letters indicate significant differences ($p < 0.05$).

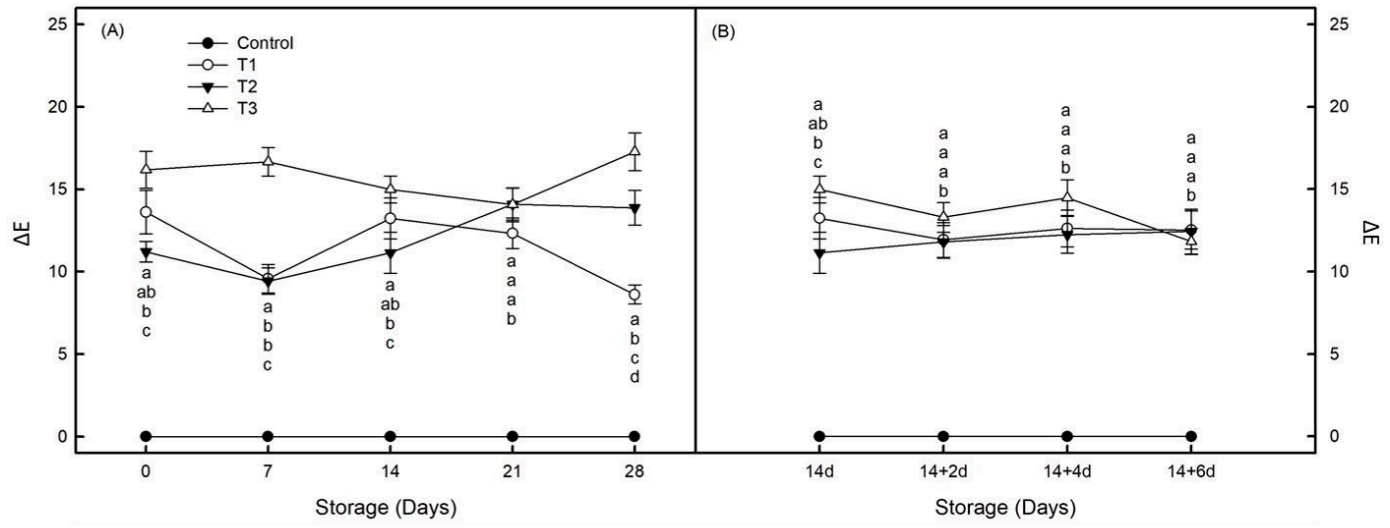

Figure A3. *Cont*.

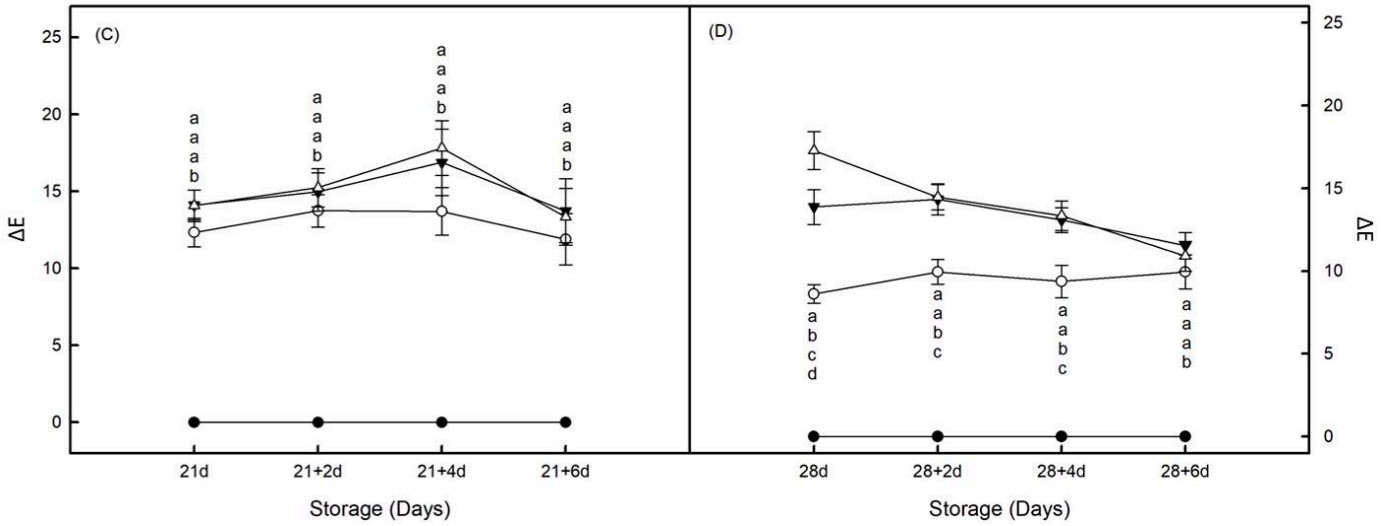

Figure A3. Effects of post-ripening time on the total color change (ΔE) of post-harvest Jin Huang mango. (**A**) Storage at 4 °C; (**B**) storage at 4 °C for 14 days with rewarming (20 °C) for 6 days; (**C**) storage at 4 °C for 21 days with rewarming (20 °C) for 6 days; (**D**) storage at 4 °C for 28 days with rewarming (20 °C) for 6 days. The control group (CK; ●) was without any treatment; the T1 group (○) was ripened with 500 ppm ethylene at 20 °C for 1 day; the T2 group (▼) was ripened with 500 ppm ethylene at 20 °C for 1 day and ripened at 20 °C for 1 day; the T3 group (△) was ripened with 500 ppm ethylene at 20 °C for 1 day and ripened at 20 °C for 2 days. The vertical bar represents the standard errors of the mean. Values with different letters indicate significant differences ($p < 0.05$).

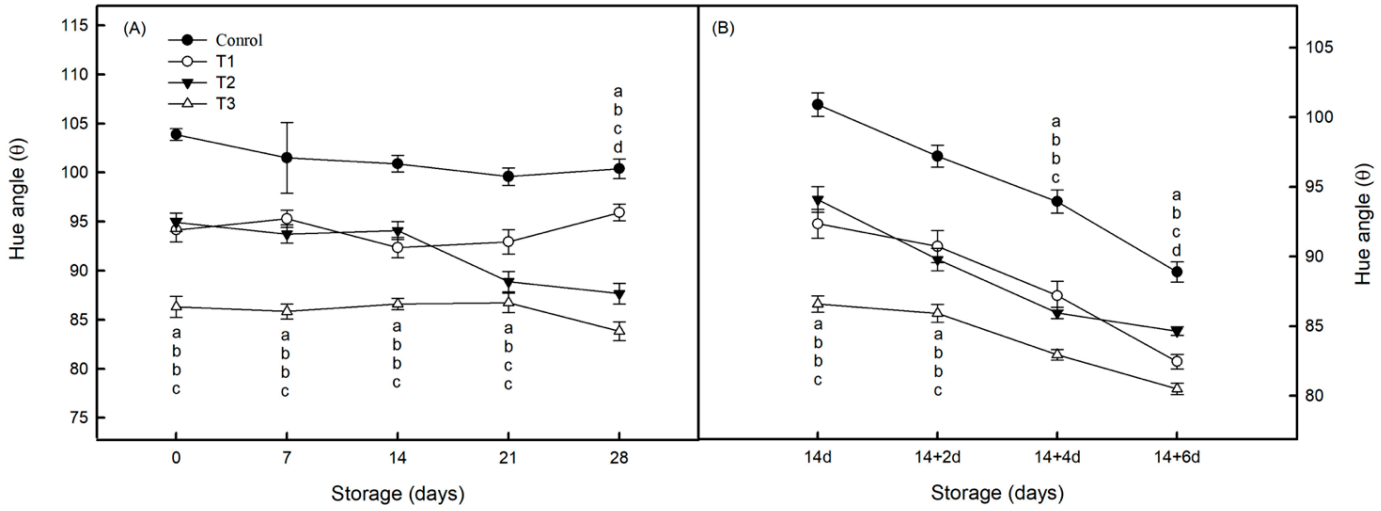

Figure A4. *Cont.*

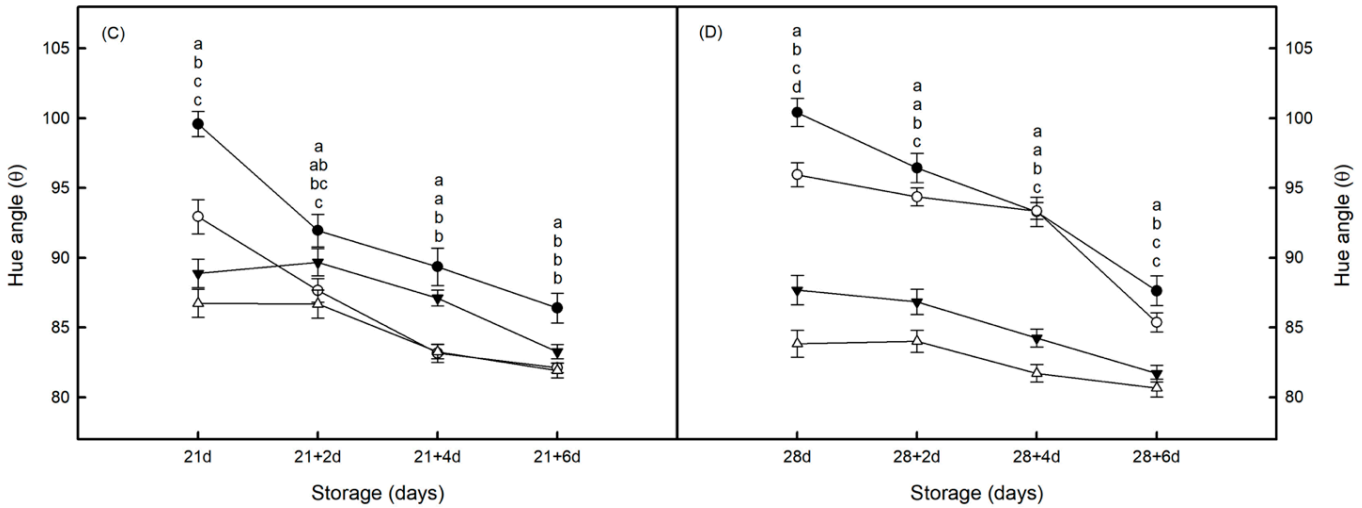

Figure A4. Effects of post-ripening time on the hue angle (θ value) of post-harvest Jin Huang mango. (**A**) Storage at 4 °C; (**B**) storage at 4 °C for 14 days with rewarming (20 °C) for 6 days; (**C**) storage at 4 °C for 21 days with rewarming (20 °C) for 6 days; (**D**) storage at 4 °C for 28 days with rewarming (20 °C) for 6 days. The control group (CK; ●) was without any treatment; the T1 group (○) was ripened with 500 ppm ethylene at 20 °C for 1 day; the T2 group (▼) was ripened with 500 ppm ethylene at 20 °C for 1 day and ripened at 20 °C for 1 day; the T3 group (△) was ripened with 500 ppm ethylene at 20 °C for 1 day and ripened at 20 °C for 2 days. The vertical bar represents the standard errors of the mean. Values with different letters indicate significant differences ($p < 0.05$).

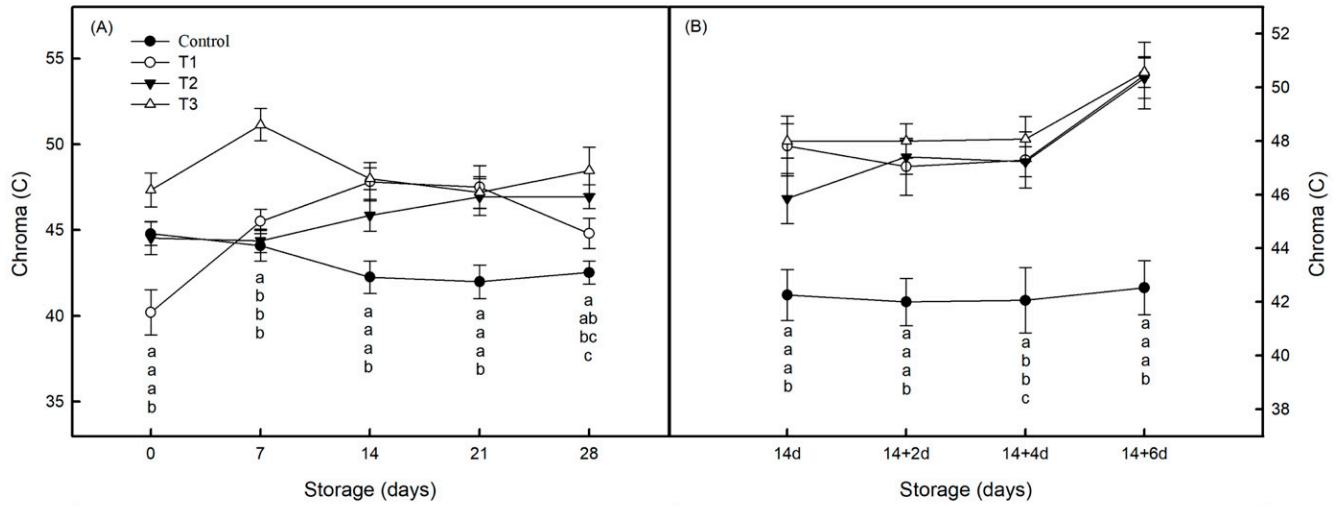

Figure A5. *Cont.*

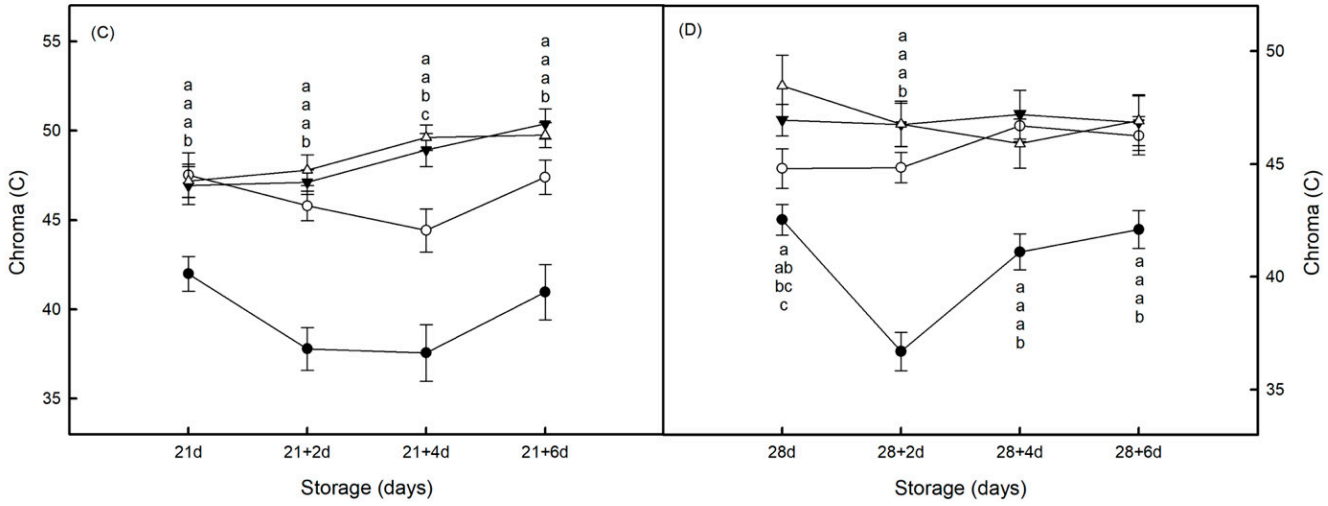

Figure A5. Effects of post-ripening time on the color concentration (C value) of post-harvest Jin Huang mango. (**A**) Storage at 4 °C; (**B**) storage at 4 °C for 14 days with rewarming (20 °C) for 6 days; (**C**) storage at 4 °C for 21 days with rewarming (20 °C) for 6 days; (**D**) storage at 4 °C for 28 days with rewarming (20 °C) for 6 days. The control group (CK; ●) was without any treatment; the T1 group (○) was ripened with 500 ppm ethylene at 20 °C for 1 day; the T2 group (▼) was ripened with 500 ppm ethylene at 20 °C for 1 day and ripened at 20 °C for 1 day; the T3 group (△) was ripened with 500 ppm ethylene at 20 °C for 1 day and ripened at 20 °C for 2 days. The vertical bar represents the standard errors of the mean. Values with different letters indicate significant differences ($p < 0.05$).

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