Fruits 75(1), 3–13 | ISSN 0248-1294 print, 1625-967X online | https://doi.org/10.17660/th2020/75.1.1 | © ISHS 2020

Original article

Physiological responses of Indian jujube (*Ziziphus mauritiana* Lam.) fruit after postharvest hot water dipping

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Summary

The effects of hot water dipping (HWD) on the physiological response in Indian jujube (*Ziziphus mauritiana* Lam.) fruit and its storability were investigated. Hot water dipping significantly inhibited polyphenol oxidase (PPO) activity, and enhanced the activities of peroxidase (POD) and catalase (CAT), but not ascorbate peroxidase (APX), in jujube fruit peel, which resulted in a reduction of peel browning and a lower occurrence of chilling injury during cold temperature storage. The weight loss of all treatments increased throughout storage; however, HWD significantly reduced the fresh weight loss when Indian jujube fruit was stored at 2 °C. The fruit immersed in 58 °C water for 15 seconds not only showed a significant reduction in the decay ratio, but also maintained better commercial quality (*e.g.*, appearance) in comparison with other treatments. In addition, fruit treated with hot water dipping (58 °C for 15 seconds) was able to prolong its storage life to 23 days when stored at 2 °C.

Keywords
chilling injury, decay, temperature

Significance of this study

What is already known on this subject?

- Horticultural crops face many postharvest problems including skin browning, decay, and water loss, and short storage life.

What are the new findings?

- HWD significantly inhibited polyphenol oxidase (PPO) activity, and enhanced the activities of peroxidase (POD) and catalase (CAT).

What is the expected impact on horticulture?

- This method can be applied on Indian jujube not only to reduce the fresh weight loss during storage period but to prolong its storage life to 23 days.

Introduction

Indian jujube fruit (*Ziziphus mauritiana* Lam.) is now commercially grown in southern areas of Taiwan because of increased consumer demand for its nutritive value and antioxidant capacity (Pareek *et al.*, 2009). In general, harvested fruit face many issues in the market, including peel browning, decay and water loss, and short storage life under ambient temperature; issues which are also noted in Indian jujube fruit production in Taiwan. A cold storage temperature is thus often used to extend postharvest life and maintain quality of commodities; however, Indian jujube fruit as well as oranges (Bassal and El-Hamahmy, 2011), loquat (Cao *et al.*, 2011), bananas (Chen *et al.*, 2008), kiwifruits (Ma *et al.*, 2014), and peaches (Tsantili *et al.*, 2010), is very sensitive to low storage temperatures leading to chilling injury (CI) (Lin and Shiesh, 2010; Jat *et al.*, 2012; Tembo *et al.*, 2008). The CI symptoms are like peel browning, pitting, and postharvest decay associated with either the loss of membrane permeability or membrane peroxidation.

Heat treatments, in the forms of hot air, vapor heat, and hot water dips/brushes are non-chemical postharvest methods applied to horticultural crops, such as apples (Bai *et al.*, 2006; Maxin *et al.*, 2012), peaches (Jemric *et al.*, 2011), and muskmelons (Yuan *et al.*, 2013), to reduce CI, inhibit postharvest decay, and manage exocarp browning during cold storage, thus prolonging both storability and market value (Fallik, 2004; Lu *et al.*, 2010; Paull and Chen, 2000). Heat treatments are not only to induce defensive proteins (*e.g.*, heat shock proteins) to tolerate the heat stress, but also up-regulate antioxidant enzymes (*e.g.*, PPO, POD, CAT, and APX) to resist against reactive oxygen species (ROS), which are associated with chilling injury (Cao *et al.*, 2011; Khademi *et al.*, 2013; Liu *et al.*, 2012; Yang *et al.*, 2012). In addition, little information is currently known regarding the beneficial effects of postharvest heat treatments on Indian jujube fruit.

In this study jujube fruits were treated with various HWD conditions and then stored at low and ambient temperatures in order to examine the effects of HWD treatments on physiological responses and postharvest quality of jujube fruits, and also to assay the antioxidant enzymes in response to these treatments.

Materials and methods

Plant material

The fruit of Indian jujube (locally called cv. 'San Mu') were obtained from a commercial orchard in Juchi, Chiayi, Taiwan, (lat. 23.50°N, long. 120.60°E, elevation 150 m). The fruit were harvested at the commercially mature stage and immediately delivered to the laboratory. All fruit samples were selected to be as uniform as possible (*e.g.*, in terms of fruit size, appearance, and being free from damage and disease) for later hot water dipping (HWD).

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Treatment

Fruit were randomly divided into four treatment groups, each with 300 fruit. The first group was subjected to HWD at 56 °C for 30 sec, the second group was subjected to HWD at 56 °C for 1 min, the third group was subjected to HWD at 58 °C for 15 sec, and the fourth group was untreated and used as the control. After HWD, the fruit were tap water-cooled (25 °C) for 3 min, and then air-dried at room temperature (25 °C) for 24 h. Every five fruit were then placed in a polyethylene (PE) bag (specification: 0.03 mm in thickness, 28.5 cm in length, and 22.0 cm in width) and sealed. Thereafter, each treatment group was divided into three subgroups of 20 bags, and each subgroup was stored at 2 °C, 5 °C, and 25 °C, respectively. The subgroups stored at 2 °C and 5 °C, respectively were kept for three weeks and then shifted to 25 °C (80–85% RH) for one week to simulate a period when the fruit is being sold, and the other subgroup was stored at 25 °C for one week only. The samples stored at 2 °C and 5 °C, respectively were taken weekly for further quality determination and compound analysis, and fruit stores at 25 °C were tested every day. All experimental fruit were subjected to physical analysis (*e.g.*, weight loss, chilling injury, and decay ratio), chemical analysis (*e.g.*, total soluble solids (TSS)%, titratable acid (TA)%, sugar to acid (TSS/TA) ratio), polyphenol oxidase (PPO) activity, peroxidase (POD) activity, catalase (CAT) activity, ascorbate peroxidase (APX) activity, and shelf-life.

Weight loss

Ten fruit (two bags) were randomly picked and marked from each subgroup (*e.g.*, 2 °C, 5 °C, and 25 °C) of each treatment for weight loss calculation. The initial fresh weight of these 10 marked fruit was recorded using a digital balance (Scaltec SBA-51, Germany) before storage. Weight loss was averaged and expressed as the percentage loss of the initial fresh weight of the fruit.

Evaluation of chilling injury

Twenty fruit from each subgroup were randomly selected and marked for the evaluation of chilling injury symptoms (peel pitting and brown staining). The score of chilling injury (CI) was set according to the fraction of total surface areas affected by sheet pitting or browning; 0 (C_0); 1, 5% pitting or browning (C_1); 2, 6–25% pitting or browning (C_2); 3, 26–50% pitting or browning (C_3); and 4, more than 50% pitting or browning (C_4) (Figure 1A). The CI incidence was calculated as follows:

$$\Sigma((n \times C_1)+...+(n \times C_4))/ (N \times C_4) \times 100\%$$

where n is the number of CI fruit per grade; C_x is the degree of CI; and N is the total number of fruit examined multiplied by the maximum numerical CI degree, *i.e.*, 4.

Decay assessment

Another 20 fruit (four bags) from each subgroup were randomly selected and marked for the decay assessment. Each fruit was visually evaluated for the presence and severity of decay. A non-decayed jujube fruit was scored as 0 (D_0); 1, 5% decay (D_1); 2, 6–25% decay (D_2); 3, 26–50% decay (D_3); and 4, more than 50% decay (D_4) (Figure 1B). The decay ratio was expressed as the percentage of decay, as follows:

$$\Sigma((n \times D_1)+...+(n \times D_4))/(N \times D_4) \times 100\%$$

where n is the number of decayed fruit per grade; D_x is the grade of decay; and N is the total number of fruit examined multiplied by the maximum numerical decay grade, *i.e.*, 4.

Total soluble solids, titratable acid, and sugar to acid ratio

Another 20 fruit from each subgroup were used to assess the soluble solids, titratable acid, and sugar to acid ratio. The jujube fruit were peeled and the pits removed, and then the

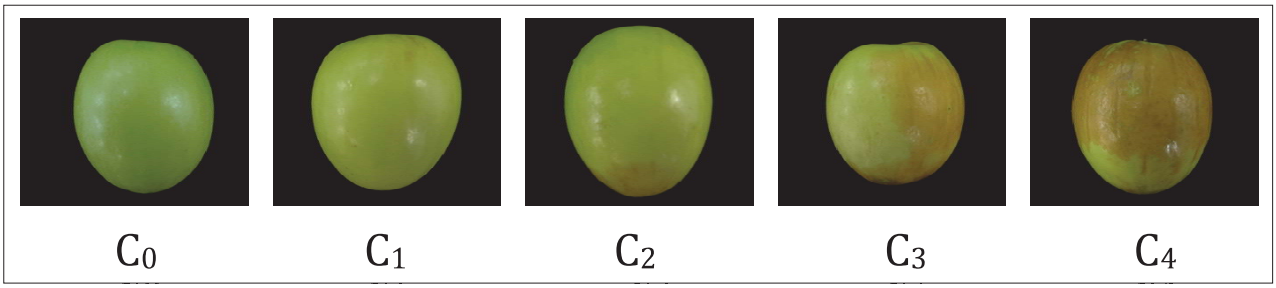

Figure 1A. The level of chilling injury of Indian jujube fruit. A non-decayed jujube fruit was scored as 0 (C_0); 1, 5% pitting or browning (C_1); 2, 6–25% pitting or browning (C_2); 3, 26–50% pitting or browning (C_3); and 4, more than 50% pitting or browning (C_4).

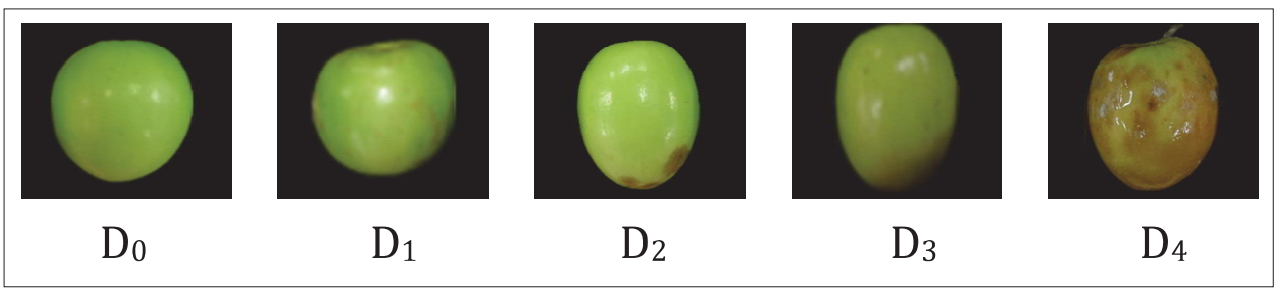

Figure 1B. The severity of decay of Indian jujube fruit. A non-decayed jujube fruit was scored as 0 (D_0); 1, 5% decay (D_1); 2, 5–25% decay (D_2); 3, 26–50% decay (D_3); and 4, more than 50% decay (D_4).

material was homogenized and filtered. A few drops of juice were placed on a refractometer (Mater-M, Tokyo, Japan) to measure TSS expressed as a percentage (%). Titratable acid was determined by titrating 0.1 N sodium hydroxide (NaOH) to pH 8.2, and expressed as percentage of citric acid. The sugar/acid ratio was represented as percentage of sugar/acid.

Enzyme extracts

Fruit samples were taken for enzyme assays according to the method in Yang *et al.* (2012) with some modifications. One gram fresh Indian jujube fruit peel was homogenized by using a mortar and pestle with 5 mL of 0.05 M phosphate buffer (pH 7.8) containing 0.2 g of polyvinylpyrrolidone at 4 °C. The homogenate was filtered through Whatman No.41 filter paper (Sigma-Aldrich, USA) and then centrifuged at 12,000 × *g*, 4 °C for 20 min. The supernatant was used to examine the activity of the enzyme.

Polyphenol oxidase (PPO) activity

The PPO activity was determined according to the method in Promyou *et al.* (2012) with some modifications. We added 2.75 mL of 0.05 M phosphate buffer solution (pH 7.0), 0.15 mL of 0.2 M catechol as a substrate, and 0.1 mL of the enzyme extract into a test tube and mixed thoroughly. The absorbance of the reaction mixture was recorded in 30 sec intervals at 25 °C for 5 min using UV/vis spectrophotometer (Hitachi, U-1800, Japan) at 420 nm. One unit of PPO activity was defined as a change of 0.01 in absorbance per minute. The PPO activity was expressed in U g^{-1} FW min^{-1}. Each treatment was conducted with three replications.

Peroxidase (POD) activity

The POD activity was assayed according to the method in Yang *et al.* (2012) with some modifications. The total 3.0 mL mixed solution contained 0.1 mL of 4% (v/v) guaiacol, 0.1 mL of 0.3% H_2O_2, 2.75 mL of 0.05 M phosphate buffer (pH 7.0), and 50 µL of the enzyme extract. The absorbance of POD at 470 nm was recorded for 5 min using a UV/vis spectrophotometer (Hitachi, U-1800, Japan). One unit of POD activity was defined as a change of 0.01 in absorbance per minute. The POD activity was expressed in U g^{-1} FW min^{-1}. Each treatment was conducted with three replications.

Catalase (CAT) activity

The CAT activity was recorded according to the method in Yang *et al.* (2012) with some modifications. The 3.0 mL reaction mixture contained 1.0 mL of 0.3% H_2O_2, 1.95 mL H_2O, and 50 µL of the enzyme extract. The oxidation of H_2O_2 was measured by the decrease in absorbance at 240 nm in 30 sec intervals for 5 min. The unit of CAT activity was defined as a change of 0.01 in absorbance per minute, which was expressed in U g^{-1} FW min^{-1}. Each treatment was conducted with three replications.

Ascorbate peroxidase (APX) activity

The APX was detected according to the method in Yang *et al.* (2012) with some modifications. The total 3.0 mL reaction mixture contained 2.60 mL of 0.1 mM EDTA, 0.15 mL 5 mM ascorbate, 0.15 mL 20 mM H_2O_2, and 0.1 mL of the enzyme extract. The absorbance of APX at 290 nm was recorded for 5 min using a UV/vis spectrophotometer (Hitachi, U-1800, Japan). One unit of APX activity was defined as the amount that caused a change of 0.01 in absorbance per minute. The APX activity was expressed in U g^{-1} FW min^{-1}. Each treatment was conducted with three replications.

Shelf life evaluation

When the stored fruits were moved to a 25 °C environment, each one was visually evaluated for either skin pitting or browning every day. Once pitting or browning had occurred over 5% of a fruit's surface area, then this was defined as the end of the fruit's shelf life, as such specimens no longer have any market value.

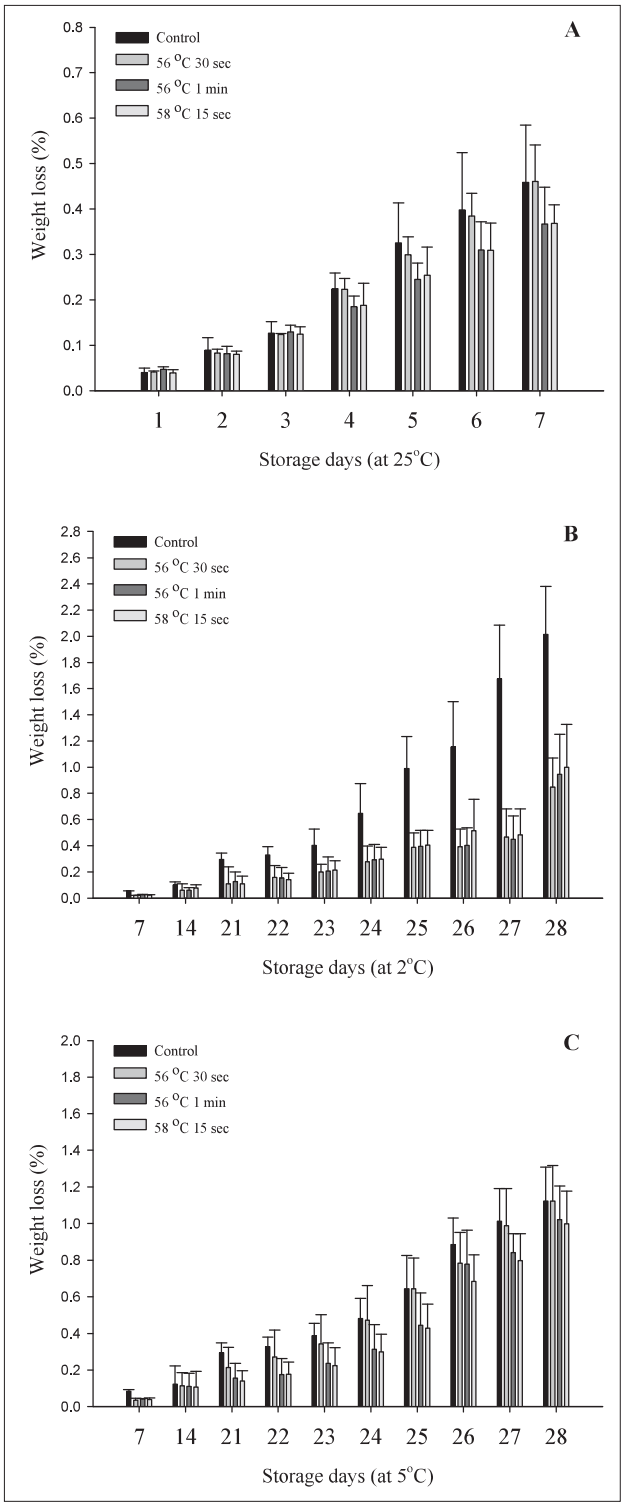

Figure 2. Changes in weight loss of Indian jujube fruit treated with hot water dips under various conditions: (A) fruit stored at 25 °C for 7 days, (B) fruit stored at 2 °C for 21 days and at 25 °C for another 7 days, and (C) fruit stored at 5 °C for 21 days and at 25 °C for a further 7 days. Values are means ± SE, for $n = 10$.

Statistical analysis

All data were analyzed by one-way analysis of variance (ANOVA) using SAS (version 9.2; SAS Institute, Cary, NC). Mean value separations were performed using a least significant difference (LSD) test at 5% ($P \leq 0.05$) level.

Results

Weight loss

The weight loss of Indian jujube fruit immersed in different HWDs and then stored at 25 °C, 2 °C, and 5 °C is shown in Figures 2A–C, respectively. The weight loss of the fruit increased significantly throughout storage when jujube fruit were stored at 25 °C. Although a higher weight loss rate was calculated in the control fruit, there was no significant difference in the weight loss among all treatments when the fruit was stored at 25 °C (Figure 2A). There was also no significant difference in weight loss among all treated fruit when stored at 2 °C for two weeks; however, the weight loss of the controls was significantly higher than seen with the fruit treated with 56 °C HWD for 1 min and 58 °C HWD for 15 sec in the third week. At the end of 2 °C storage and when moving to 25 °C, the weight loss of the controls was significantly higher than that of other HWD treated fruit, but no significant difference was found among HWD treatments (Figure 2B). An increase in weight loss was found for all treatments when the fruit were stored at 5 °C for three weeks and subsequently moved to 25 °C for one week; however, there was no significant difference in weight loss among all the treatments (Figure 2C).

Chilling injury (CI)

The degree of CI severity depended on both HWD and the number of storage days, and this was not only detected during the low temperature storage period, but also after shifting to 25 °C. The earliest CI symptoms were recorded on the control fruit when these were stored at either 2 °C or 5 °C on day 14, and the CI of the jujube fruit in all treatments increased continuously throughout storage. Fruit treated with 56 °C HWD for 1 min and 58 °C HWD for 15 sec, respectively, and stored at both 2 °C and 5 °C for three weeks and shifted to 25 °C for one day (day 22) both saw no CI (Figures 3A and 3B). A significantly lower occurrence of CI was found for jujube fruit treated with 56 °C HWD for 1 min and 58 °C HWD for 15 sec in comparison to the control and those treated with 56 °C HWD for 30 sec after moving from 2 °C to 25 °C (Figure 3A). Similar results were found when jujube fruit were stored at 5 °C for three weeks and then moved to 25 °C for one week (Figure 3B).

Decay assessment

The decay ratios of jujube fruit that underwent different HWDs and was then stored at 25 °C, 2 °C, and 5 °C are shown in Figures 4A–C, respectively. When the fruit was stored at 25 °C, slight decay symptoms occurred on the control and that treated with 56 °C HWD for 30 sec, but was not on the fruit treated with 56 °C HWD for 1 min and 58 °C HWD for 15 sec on the first two days. Thereafter, all treatments exhibited different severities of decay symptoms, and the decay ratio was over 10% on the fruit treated with 58 °C HWD for 15 sec on the seventh day (Figure 4A). The HWD treatments significantly inhibited the occurrence of decay compared with the control when stored at 2 °C for two weeks. However, the decay ratio reached at least 5% in all treatments in the third week. After fruit was moved to a 25 °C environment on the 23rd day, 58 °C HWD for 15 sec significantly reduced the development of decay to 6%. Thereafter, an increasing decay ratio was found during the storage period (Figure 4B). On the other hand, decay symptoms occurred in the control and HWD treated fruit when they were kept at 5 °C in the first week; the HWD treatments at 56 °C for 30 sec, 56 °C for 1 min, and 58 °C for 15 sec significantly decreased the occurrence of decay to only 20, 2, and 2%, respectively, of that seen with the control fruit (Figure 4C). The HWD treated fruit showed better reductions in the development of decay than the control during the first three weeks at 5 °C storage. Similarly, 58 °C HWD for 15 sec significantly lowered the fruit decay ratio to 5% after the fruit shifted to a 25 °C environment on the 22nd day (Figure 4C).

Fruit chemical characteristics

The various HWDs did not significantly affect the Indian jujube's fruit chemical properties, such as TSS, TA, and TSS/TA, during storage (Figures 5 and 6). The average TSS among all HWDs was 13.5%, 13.8%, and 13.6%, and the average TA was 0.208%, 0.207%, and 0.21% when the fruit were stored at 25 °C, 2 °C, and 5 °C, respectively, with neither TSS/TA showing any significant differences among these treatments which were 64.9, 66.7, and 64.8 for 25 °C, 2 °C, and 5 °C, respectively.

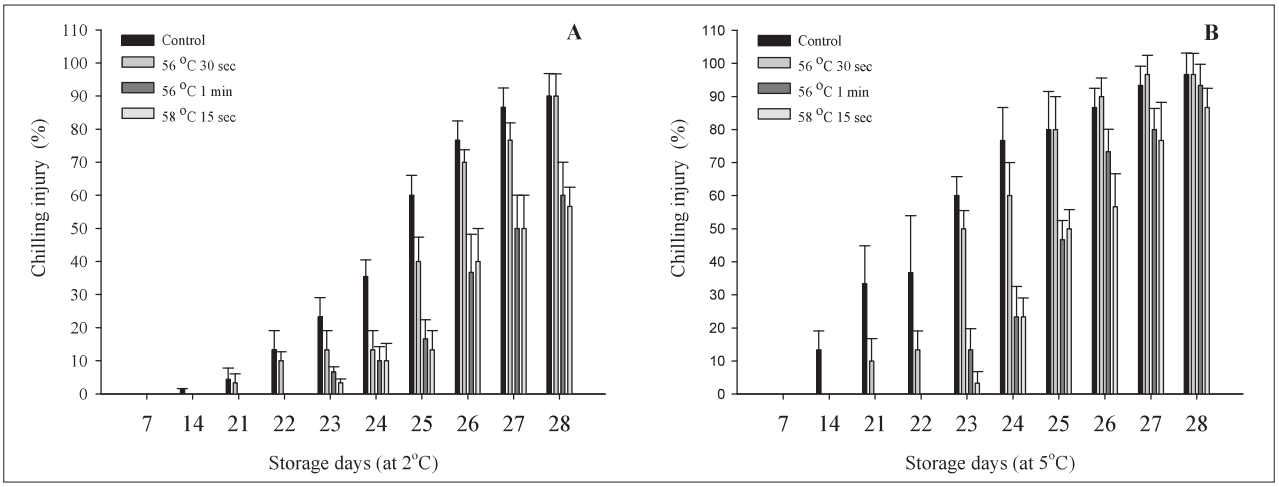

Figure 3. Chilling injury score of Indian jujube fruit treated with hot water dips under various conditions: (A) fruit stored at 2 °C for 21 days and at 25 °C for another 7 days and (B) fruit stored at 5 °C for 21 days and at 25 °C for a further 7 days. Values are means ± SE, for $n = 20$.

PPO, POD, CAT, and APX activities

The PPO, POD, CAT, and APX activities in jujube fruit treated by different HWDs and then stored at 25 °C, 2 °C, and 5 °C were investigated (Figures 7–10). The PPO activity of all treatments increased over storage (Figures 7A–C); however, PPO activity in the jujube peel immersed in hot water was significantly lower than that of the untreated fruit during storage. In addition, HWD treatments significantly enhanced the POD activity in the jujube fruit and kept this at higher levels than seen in the control fruit throughout the storage at 25 °C, 2 °C, and 5 °C, respectively (Figures 8A–C). The CAT activity in the HWD treated jujube fruit was significantly higher than that in the control fruit after being immersed in hot water immediately. Although the CAT activity of all the treatments varied during storage, fruit treated with 58 °C HWD for 15 sec had in the highest CAT activity throughout

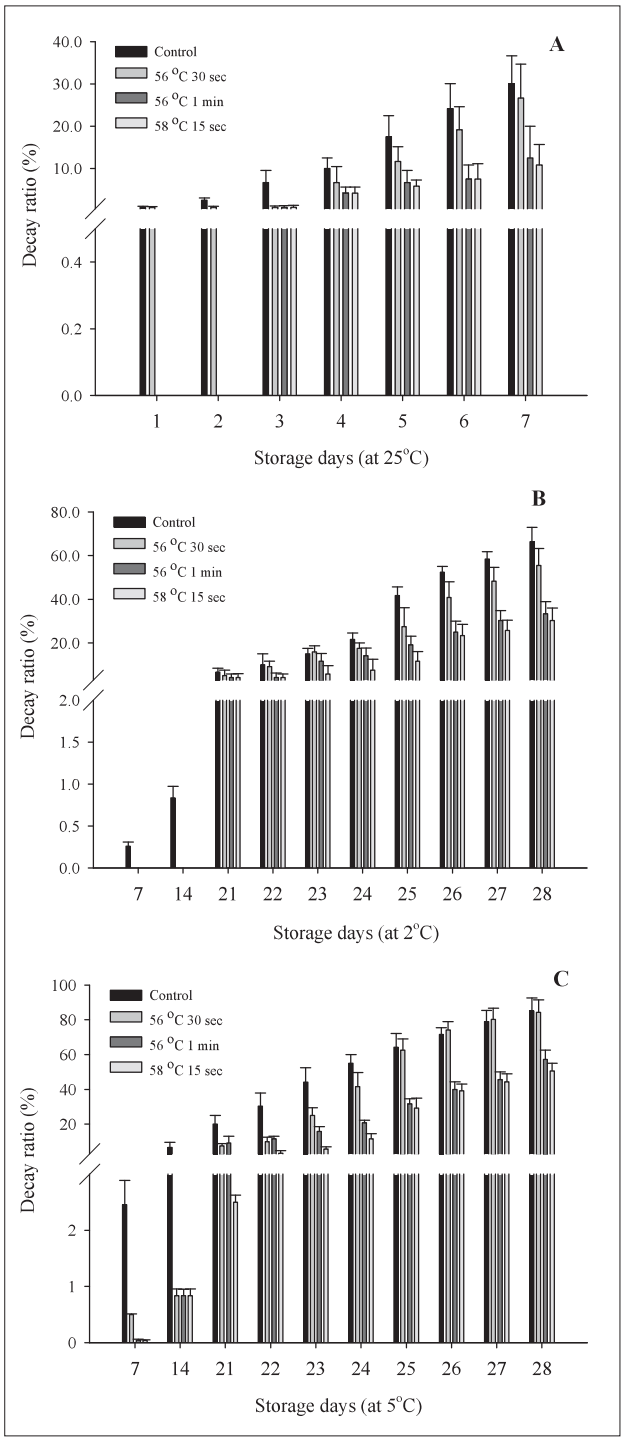

Figure 4. Decay ratio of Indian jujube fruit treated with hot water dips under various conditions: (A) fruit stored at 25 °C for 7 days, (B) fruit stored at 2 °C for 21 days and at 25 °C for another 7 days, and (C) fruit stored at 5 °C for 21 days and at 25 °C for a further 7 days. Values are means ± SE, for $n = 20$.

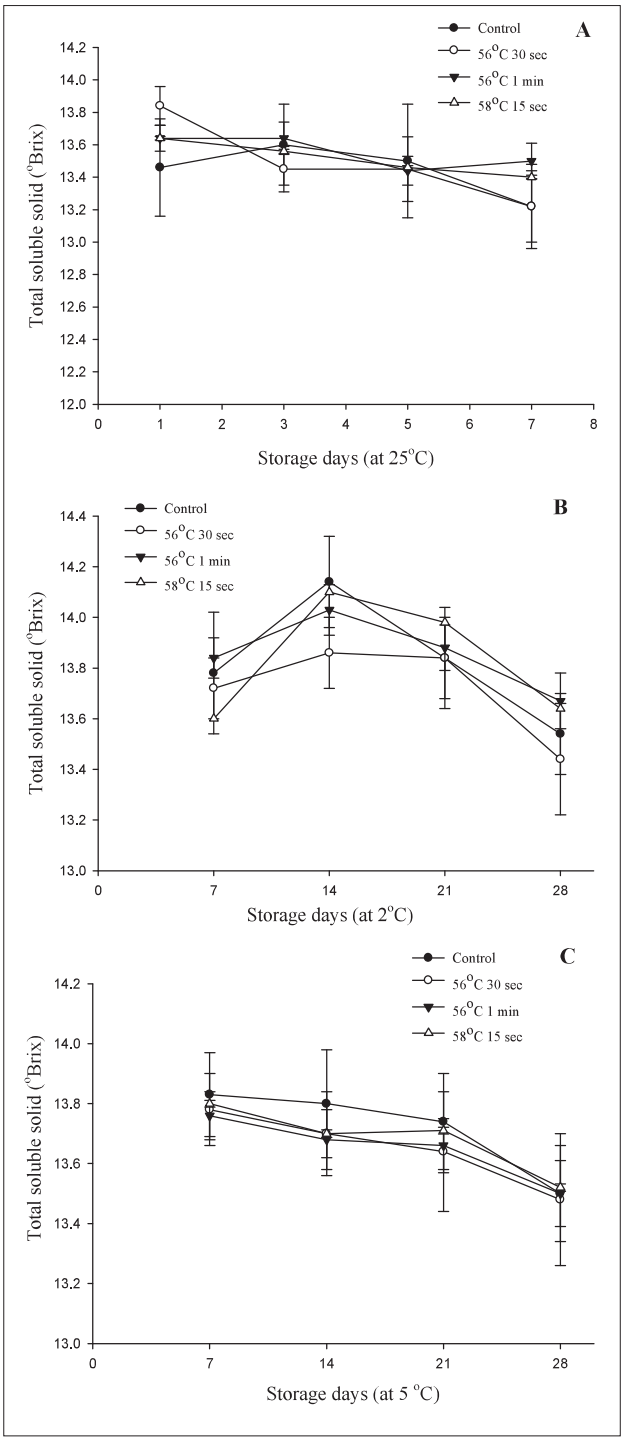

Figure 5. Changes in total soluble solids (TSS) of Indian jujube fruit treated with hot water dips under various conditions: (A) fruit stored at 25 °C for 7 days, (B) fruit stored at 2 °C for 21 days and at 25 °C for another 7 days, and (C) fruit stored at 5 °C for 21 days and at 25 °C for a further 7 days. Values are means ± SE, for $n = 20$.

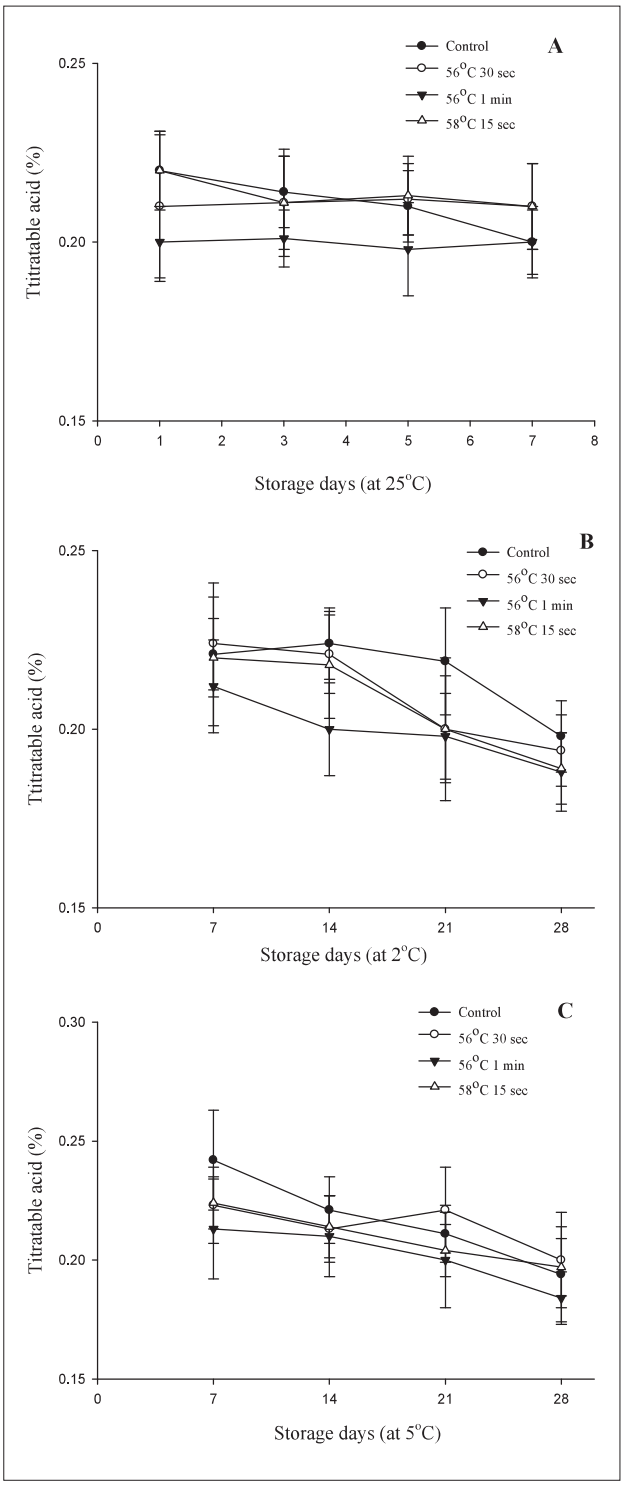

Figure 6. Changes in titratable acid (TA) of Indian jujube fruit treated with hot water dips under various conditions: (A) fruit stored at 25 °C for 7 days, (B) fruit stored at 2 °C for 21 days and at 25 °C for another 7 days, and (C) fruit stored at 5 °C for 21 days and at 25 °C for a further 7 days. Values are means ± SE, for $n = 20$.

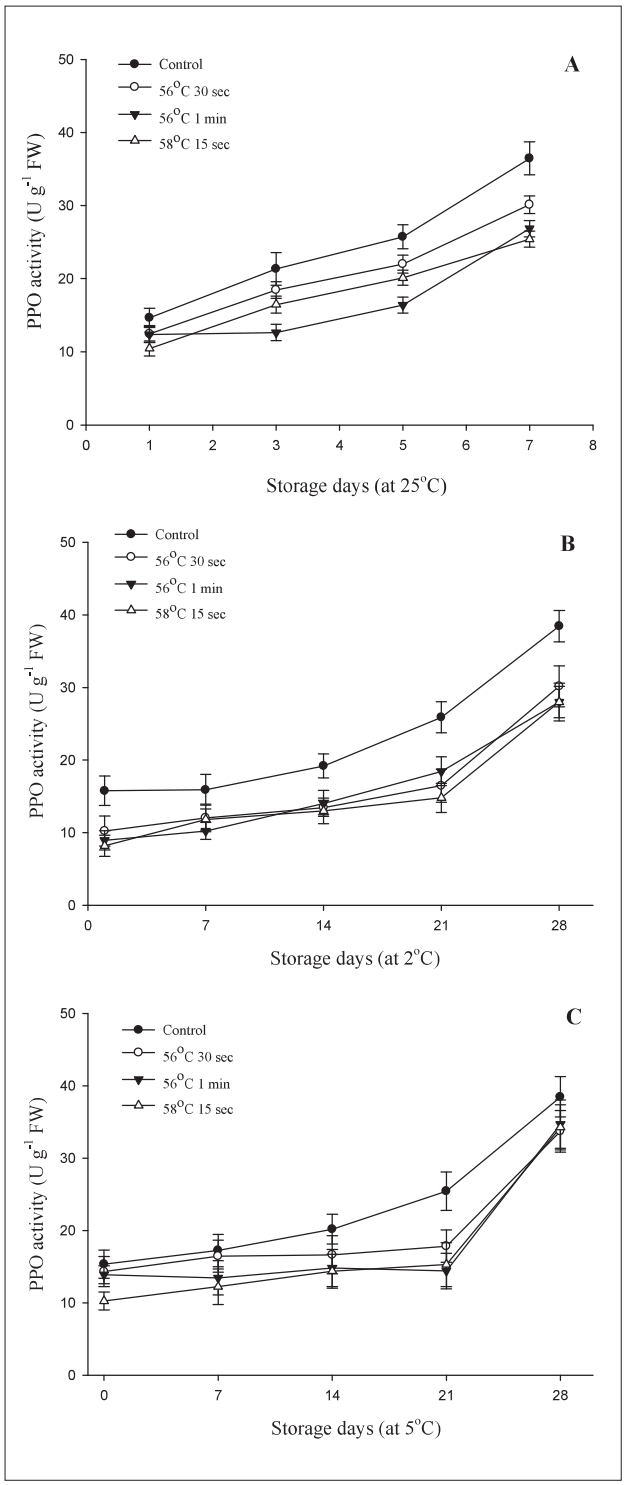

Figure 7. Changes in the polyphenoloxidase (PPO) activity of Indian jujube fruit treated with hot water dips under various conditions: (A) fruit stored at 25 °C for 7 days, (B) fruit stored at 2 °C for 21 days and at 25 °C for another 7 days, and (C) fruit stored at 5 °C for 21 days and at 25 °C for a further 7 days. Values are means ± SE, for $n = 10$.

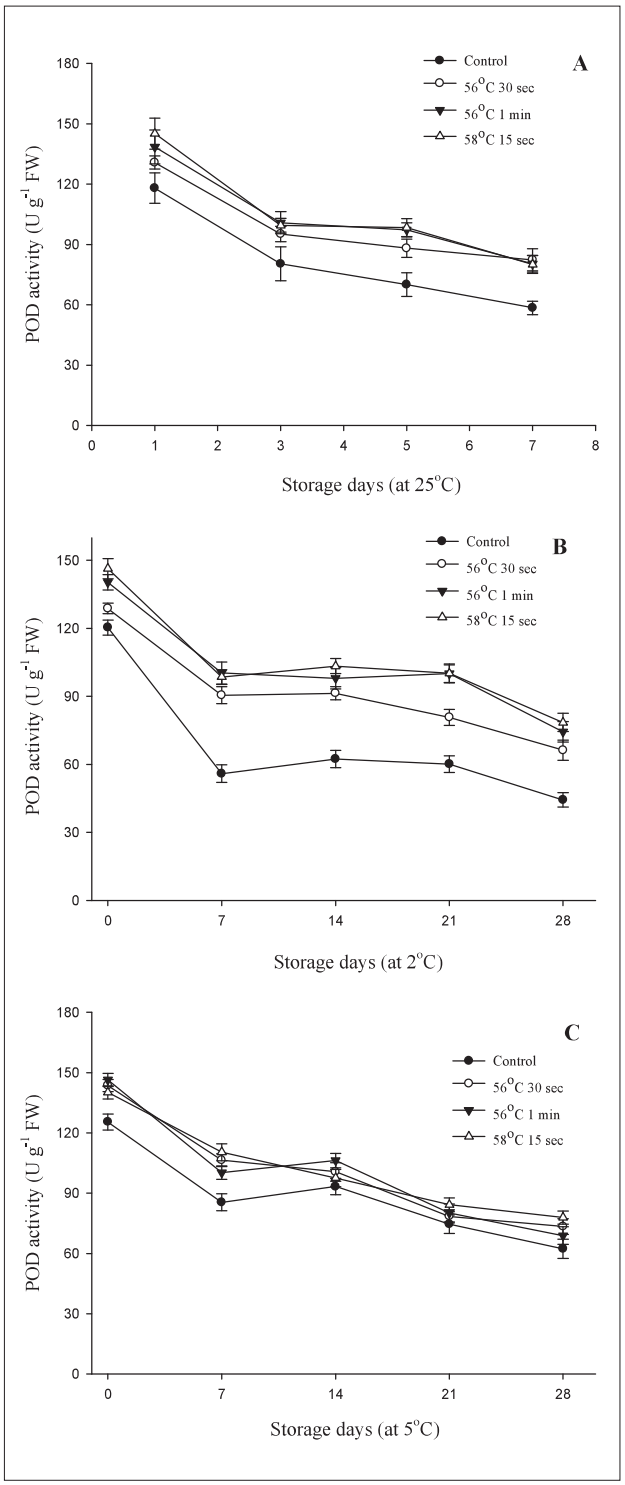

Figure 8. Changes in the peroxidase (POD) activity of Indian jujube fruit treated with hot water dips under various conditions: (A) fruit stored at 25 °C for 7 days, (B) fruit stored at 2 °C for 21 days and at 25 °C for another 7 days, and (C) fruit stored at 5 °C for 21 days and at 25 °C for a further 7 days. Values are means ± SE, for $n = 10$.

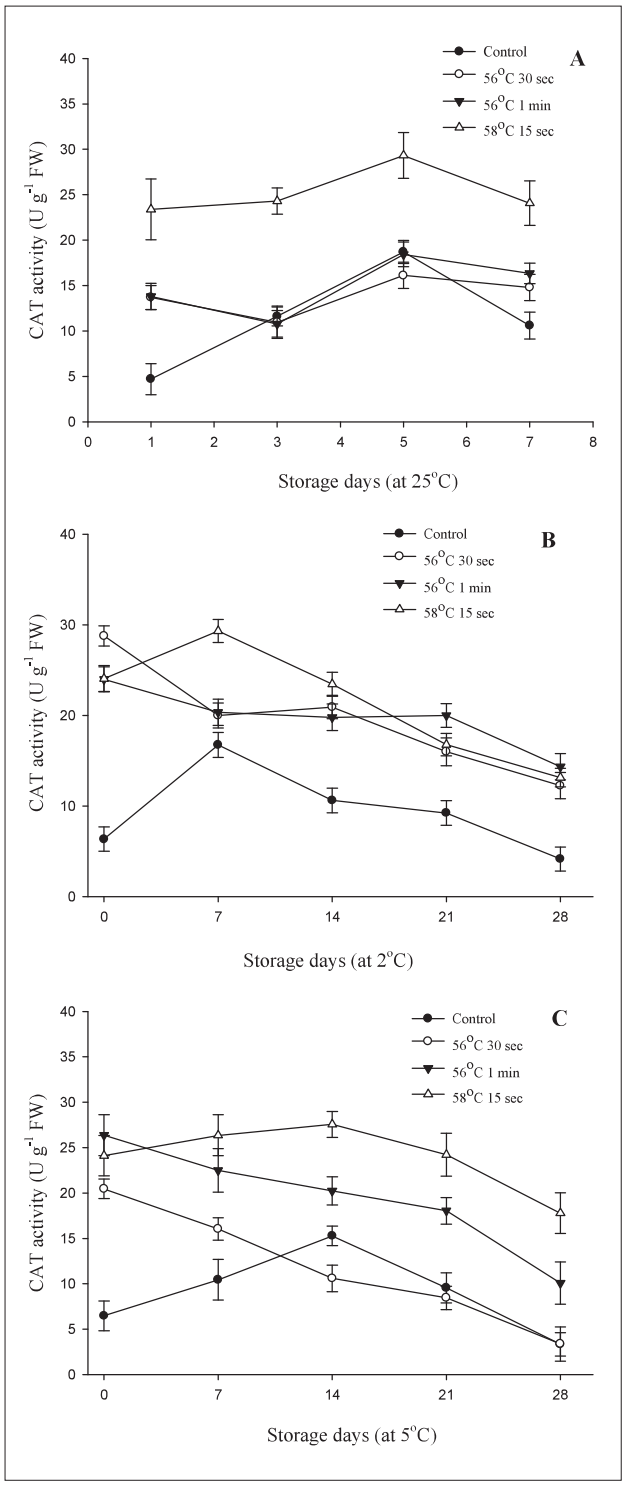

Figure 9. Changes in the catalase (CAT) activity of Indian jujube fruit treated with hot water dips under various conditions: (A) fruit stored at 25 °C for 7 days, (B) fruit stored at 2 °C for 21 days and at 25 °C for another 7 days, and (C) fruit stored at 5 °C for 21 days and at 25 °C for a further 7 days. Values are means ± SE, for $n = 10$.

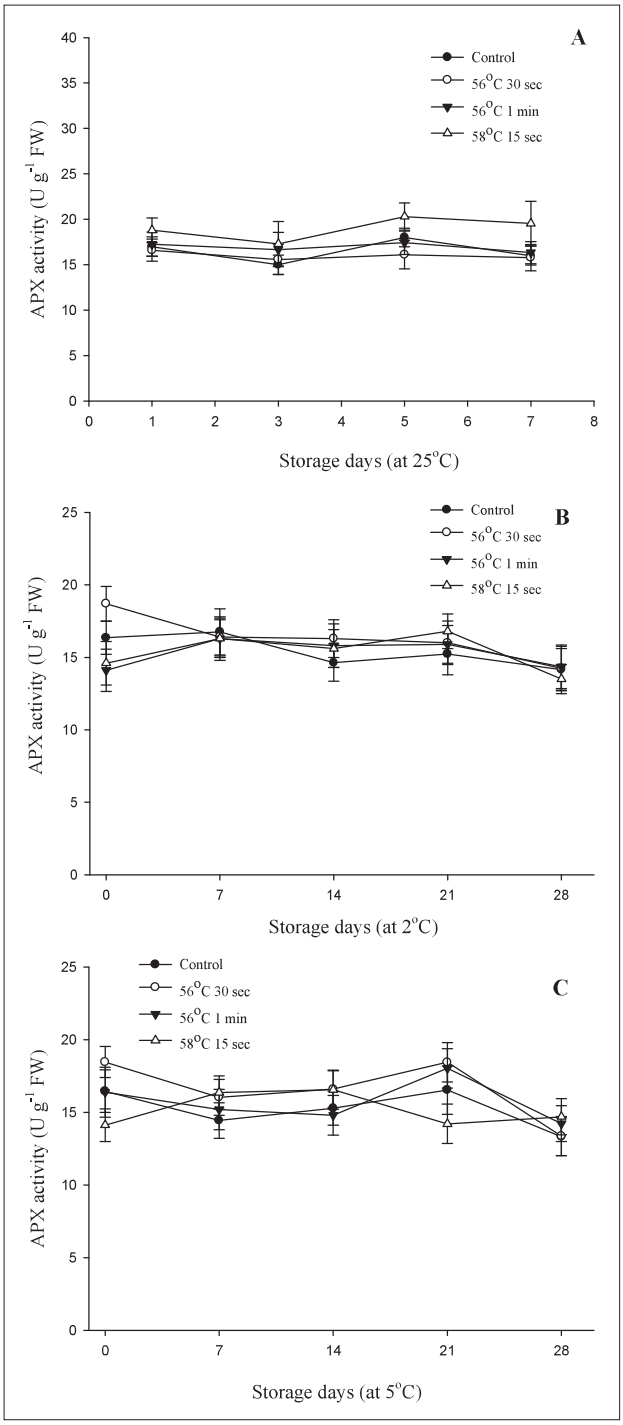

Figure 10. Changes in the ascorbate peroxidase (APX) activity of Indian jujube fruit treated with hot water dips under various conditions: (A) fruit stored at 25 °C for 7 days, (B) fruit stored at 2 °C for 21 days and at 25 °C for another 7 days, and (C) fruit stored at 5 °C for 21 days and at 25 °C for a further 7 days. Values are means ± SE, for $n = 10$.

this period (Figures 9A–C). In contrast, there was no significant difference in APX activity in the fruit of all treatments conditions during storage (Figures 10A–C).

Shelf-life evaluation

Fruit treated with 58 °C HWD for 15 sec showed the longest shelf-life among the different storage conditions (Table 1). There was no significant difference in shelf-life between HWDs of 56 °C for 1 min and 58 °C for 15 sec when the fruit were stored at either at 2 °C or 25 °C conditions, but a difference was found for fruit stored at 5 °C.

Discussion

The weight loss of Indian jujube fruit was increased for all HWDs and storage conditions during the storage period. However, less weight loss was found in the HWD-treated fruit, and this was also associated with a low incidence of CI, except for the fruit stored at 25 °C (Figures 2 and 3). Schirra and D'hallewin (1997) indicated that HWD between 56–58 °C was optimal with regard to reducing CI and causing less weight loss of 'Fortune' mandarin. Promyou *et al.* (2012) reported that hot water immersion (35 °C, 10 min) resulted in the lowest CI and weight loss in jujube fruit (*Ziziphus jujube* Mill.) stored at 4 ± 1 °C. Heat treatment could induce resistance to CI and decay during cold storage (Biolatto *et al.*, 2005; Schirra *et al.*, 2004), as it can help maintain the completeness of the cell membrane and cell wall (Promyou *et al.*, 2008), resulting in less weight loss, which is supported by the observation that CI occurrence is associated with an increase in cell permeability (Gómez-Galindo *et al.*, 2004). Similarly, Erkan *et al.* (2005) suggested that hot water dipping is effective in reducing the weight loss of citrus, because of either the integrity of the cell membrane or cuticular properties of the fruit surface.

Pathogens generally penetrate into the epidermis or are located in the injured tissue on surface of fruit developing decay. Previous studies have shown that HWD treatment could not only clean and disinfect, but also melt any waxes on the fruit surface, which inhibited or reduced the pathogen development, lowered the occurrence of decay on many fruits, such as mandarins (Schirra and D'hallewin, 1997), kiwifruits (Chen *et al.*, 2015), peaches (Jemric *et al.*, 2011), citrus (Porat *et al.*, 2000), melons (Sui *et al.*, 2014), and strawberries (Vila-Rojas *et al.*, 2011). In this study, the various HWDs were found to be effective in reducing decay as compared with that seen in the control fruit.

In addition, HWDs did not affect TSS, TA, and TSS/TA which is consistent with previous studies of Satsuma mandarin (Hong *et al.*, 2007), jujube fruit (Lal *et al.*, 2002), and 'Star Ruby' grapefruit (Porat *et al.*, 2000). In general, shorter HWD and HWB do not affect the internal and external fruit quality, whereas longer heat treatments caused variations in fruit quality depending on the heating conditions (Lurie, 1998).

Heat treatments are adopted as postharvest methods because they can activate the antioxidant systems of fruit, which regulate active oxygen species during inappropriate storage conditions (Hodges *et al.*, 2004; Sala and Lafuente, 2000). Heat treatments can thus increase resistance to low temperature and delay CI in many fruit (Fallik, 2004; Lurie, 2006). Peel browning and blackening are two of the CI symptoms due to increased PPO activity, which also reduce the amount of lower phenolics in harvested litchi fruit (Jiang *et al.*, 2004). Previous studies have indicated that lower PPO activity is associated with less fruit blackening and browning in bananas (Chen *et al.*, 2008; Promyou *et al.*, 2008), pawpaw fruit (Galli *et al.*, 2009), jujube fruit (Promyou *et al.*, 2012), and grapes (Zhang *et al.*, 2005). Although the activity of PPO increased over the storage period, the HWD-treated fruit had significantly lower PPO activity than seen with the control fruit, and this corresponds to the lower CI score and decay ratio found in the present study. POD, another antioxidant enzyme was immediately induced by HWD treatment. The higher POD activity in HWD-treated Indian jujube fruit re-

Table 1. Shelf-life of Indian jujube fruit treated with different hot water dips under various conditions.

Storage condition	HWD treatments	Total shelf life (day)[z]
25 °C, 7 days	Control	2.4 b[y]
	56 °C, 30 sec	3.5 b
	56 °C, 1 min	4.6 ab
	58 °C, 15 sec	5.6 a
2 °C, 3 weeks + 25 °C, 7 days	Control	20.3 b
	56 °C, 30 sec	21.2 b
	56 °C, 1 min	22.1 ab
	58 °C, 15 sec	23.4 a
5 °C, 3 weeks + 25 °C, 7 days	Control	13.4 c
	56 °C, 30 sec	19.6 b
	56 °C, 1 min	18.1 b
	58 °C, 15 sec	23.3 a

[y] Mean separation in column by LSD test at $P \leq 0.05$.
[z] Values are means, for $n = 10$.

flects the greater amount of phenolics that are induced to cope with other stresses. Previous studies have indicated the positive relationship between POD activity and phenolic compounds induced by heat treatments, which can effectively delay CI and/or resist postharvest pathogens (Kamdee *et al.*, 2009; Yuan *et al.*, 2013). Although POD activity decreased gradually in the current study, POD activity was maintained at a significantly higher level in HWD fruit than the control, which is consistent with other reports on kiwifruits (Chen *et al.*, 2015) and bayberry fruit (Wang *et al.*, 2010). Furthermore, the HWD treatments quickly increased CAT activity in fruit peel, which is similar to previous studies of oranges (Bassal and El-Hamahmy, 2011; Sala and Lafuente, 2000) and in kiwifruits (Chen *et al.*, 2015). In this study, CAT activity declined rapidly when Indian jujube fruit were moved to cold storage, which is associated with increased CI in previous study (Sala and Lafuente, 2000). However, CAT activity was significantly higher in HWD-treated fruit than the control, and thus may similarly be responsible for the greater chilling tolerance. Generally, APX activity increases along with the activities of other enzymes, such as CAT, SOD, and glutathione (GSH) reductase; however, APX activity did not change during cold storage in the current study. It is possible that the HWDs did not induce APX activity, and thus there was no clear response to cold storage with regard to this, and so the ascorbate-glutathione cycle may not be involved in antioxidant protection against cold storage for Indian jujube fruit.

Conclusion

The results of this study show that HWD could be beneficial for extending the shelf-life and reducing postharvest decay and CI in Indian jujube fruit without affecting fruit quality during cold storage. The HWD treatment (58 °C for 15 sec) was effective in enhancing POD and CAT activities but decreased PPO activity, and thus the treated fruit had more antioxidant capacity compared to the untreated fruit. Other advantages of HWD are that it can also reduce the loss of fresh weight. Moreover, HWD can be easily be applied in the Indian jujube fruit industry, because it requires a relatively short exposure time of 15 sec–1 min. As a result, precise and effective HWD techniques cooperated with optimal storage temperature can be applied to a broader range of fresh harvested crops in the future.

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Received: Jan. 16, 2018
Accepted: Sep. 5, 2019