Acta Physiologiae Plantarum (2020) 42:119
https://doi.org/10.1007/s11738-020-03081-5

ORIGINAL ARTICLE

Impact of packaging materials on bruise damage in kiwifruit during free drop test

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Received: 10 September 2019 / Revised: 11 February 2020 / Accepted: 5 May 2020

Abstract

Inappropriate packages and packaging materials are the main causes of bruise damage in the postharvest handling of kiwifruit. This study was conducted to identify the suitable materials to be used as collection box during sorting and grading of kiwifruits. Three different materials of box, wooden box, high-density polyethylene (HDPE) box, and expanded polystyrene (EPS) box were used to simulate kiwifruit dropping in grading line. Among three treatments, the lowest weight loss (4.6%) was observed in the EPS box surface-impacted fruits, the bruise index and bruise area of fruits from EPS box were 36.2% and 47.1% less than that of wooden box, respectively. Furthermore, the peak level of ethylene production and respiration rate of fruits from EPS box was 32.6%, 28.9% lower than that of wooden box, respectively. Compared to wooden box and HDPE box surface, EPS box surface slowed softening, reduced electrolyte leakage and malondialdehyde accumulation. Additionally, lower bruise damage by the EPS box surface was also displayed in physiological attributors including hydrogen peroxide (H_2O_2), superoxide anion (O^{2-}) and the activities of antioxidant enzymes. The collective data indicated that the EPS box surface reduced the adverse physiological changes caused by dropping of kiwifruit. These results indicated the potential of EPS as packaging material of collection box in grading line to reduce bruise damage and to preserve the quality of kiwifruit.

Keywords Kiwifruit · Bruise damage · Postharvest handling · Fruit quality

Introduction

Considerable quantity of kiwifruit suffers from mechanical damage due to inappropriate postharvest handling. Bruises are undetectable mechanical injuries, which are not visible immediately (Celik 2017). These occur during transportation, sorting and packaging processes, leading to the degradation of kiwifruit, which is very sensitive to mechanical damage such as external impact.

The main reason for bruise damage during handling is excessive impact force from dropping against the package surfaces (Ahmadi et al. 2010; Polat et al. 2012; Opera and Pathare 2014). Cakmak et al. (2010) reported that the mass loss of fresh fig fruits packed with extruded and expanded polystyrene boxes showed 2.5 times lower bruise damage than that with cardboard boxes after simulated transport vibration. According to Komarnicki et al. (2017), apples which drop on rigid surface (concrete, wood) had maximum bruise damage, but foam surface inflicted the least damage among the four packaging materials in free drop tests. Wooden packaging material showed a poor protection of apples from damage during transportation, in comparison with telescopic fiberboard tray packs and plastic containers (Holt and Schoorl 1984; Timm et al. 1996). However, the damage of kiwifruit owing to dropping on packaging materials, wood, high-density polyethylene (HDPE), and expanded polystyrene (EPS) remains unclear.

Bruise prevention is essential to control the quality of fresh market kiwifruit. Among various packages during

Communicated by P. Wojtaszek.

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Published online: 20 June 2020

postharvest handling, wooden crates, HDPE box, cardboard box and EPS box are commonly used in China. However, study on the concerning package materials of collection box for reducing impact damage of kiwifruit has not yet been reported. For this reason, the aim of this study was to determine the influence of the material of the collection box on the mechanical damage of kiwifruits exposed to impact loads during free drop test. The study of the relation between packaging materials and kiwifruit quality will provide important information in minimizing external impact and ensuring the supply of high-quality fresh kiwifruit to the consumers.

Materials and methods

Materials

"Xuxiang" kiwifruit (*Actinidia chinensis* Planch) selected with uniform size and maturity and without blemish or apparent infections were harvested at 151 days after full bloom, when the soluble solid content (SSC) had reached approximately 6.2%, from a standard orchard located in Fuyang District, Hangzhou, China (119°95′ N, 30°05′ E). Hangzhou has a winter without a frost season, irrigation in summer, and suitable fertility. The vines were spaced 3 m × 4 m spacing (≈622 vines/ha), and trained to the T-bar system in a medium-textured soil (pH 5.5–6.5) with drip irrigation in the orchard. Fruits were transported to an experimental laboratory in Hangzhou City within 2 h in an air-conditioned car. Three kinds of packaging materials were used for drop test to simulate impact loads against the collection box in the sorting process (Fig. 1): wooden box, HDPE box and EPS box. The parameters of these packaging materials are listed in Table 1.

Table 1 Properties of packaging materials

Packaging materials	Thickness (mm)	Density (g cm^{-3})	Young's modulus (Gpa)*
Wood	10	6.5×10^{-1} ~ 7.5×10^{-1}	1.3 ~ 1.4
HDPE	8	9.4×10^{-1} ~ 9.6×10^{-1}	6.0×10^{-1} ~ 6.8×10^{-1}
EPS	12	1.2×10^{-2} ~ 4.5×10^{-2}	4.5×10^{-3} ~ 9.5×10^{-3}

*Young's modulus describes the stress required to produce a given strain. The rigid object has larger Young's modulus

Fruit drop test

The selected fruits were randomly assigned into four groups (360 fruits per group) and dropped from a height of 0.50 m (common height from the outlet of the grading line to the bottom of the collection box) to the surface of the wooden box, HDPE box and EPS box, respectively. kiwifruit that were not dropped were set as control. The longitudinal axis of each kiwifruit is parallel to the impact surface. It is released manually and captured after rebound to avoid the second impact. To determine the correct impact location, some white powder chalk was spread on the surface to mark the bruised area.

After drop tests, kiwifruit were stored in an incubator (HWS, Ningbo Southeast Instrument Co., Ningbo, China) at 20 °C and 90% RH for 10 days (storage life). Every 20 fruits from each group were taken for the determination every 2 days after the drop test. The wound tissue samples were frozen in liquid nitrogen and stored at − 80 °C until analysis. The entire experiment was repeated three times.

Evaluation of pulp bruise

To assess the bruise index of kiwifruit, ten fruits of each treatment was assessed on the 10th day by removing the peel

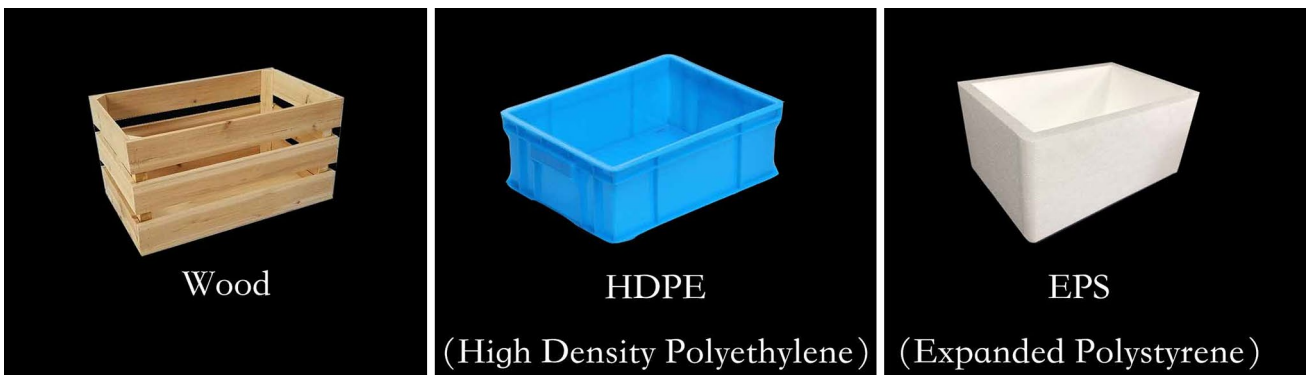

Fig. 1 Three types of collection boxes for kiwifruit. *Wood* fruits dropped on the surface of the wooden box. *HDPE* fruits dropped on the surface of high-density polyethylene box, *EPS* fruits dropped on the surface of the expanded polystyrene box

and evaluating the pulp browning on a single fruit according to the extent of the bruise area in the cross section, as 0, no bruise; 0–10%; 2, 11–30%; 3, 31–50%; 4, > 50% (Fig. 2). The bruise index was calculated according to the following equation:

$$\text{Bruise index}\,(\%) = \frac{\sum(\text{bruise scale} \times \text{number of fruits corresponding the scale})}{\text{total fruit number} \times 4\,(\text{highest number of bruise scale})} \times 100\%. \quad (1)$$

The bruise size was measured by cutting the center of the damaged area of each fruit. Bruise area was determined with the following equation:

$$\text{BA} = \frac{\pi}{4W_1W_2}, \quad (2)$$

where w_1 and w_2 are the bruise width along the major and minor axes (mm).

Determinations of firmness and weight loss

In order to assess the firmness of kiwifruit, 10 fruits from each treatment were measured by texture analyzer (TA-XT2i, Lotun Science Co., China) using probe P/5, which had a cylindrical flat bottom with a diameter of 5 mm and ranged from 1.00 mm/s at a constant speed to 10.00 mm at a depth to the equatorial region with avoiding the impact location. Assessments were performed on two opposite sides of each fruit.

To assess the weight loss of kiwifruit, fruits were weighed by an electronic balance (BSA223S, Sartorius Stedim Biotech Co., China) with an accuracy of 10^{-2} N. At the designated time point, 20 kiwifruits of each treatment were weighed to determine the weight loss and repeated three times. Weight loss is calculated as the change of fresh weight of kiwifruit at each time point divided by the initial weight and expressed as a percentage.

Determinations of rates of respiration and ethylene production

Respiration rate was measured according to Yang et al. (2018). Six fruits were placed in a 2 L chamber and sealed at 20 °C for 2 h in a dark room. CO_2 concentration was then measured by CO_2 and O_2 analyzer (Checkmate 3, PBI Dansensor Co., Denmark). Respiration rate was expressed by CO_2 mg kg^{-1} h^{-1}.

Ethylene production was measured according to Hu et al. (2014). Six fruits were placed in a 2 L chamber and sealed at 20 °C for 2 h in a dark room, and 1 mL of gas was taken and analyzed by gas chromatography (GC-14A, Shimadzu, Kyoto, Japan). Ethylene production was expressed in μL kg^{-1} h^{-1}.

Determinations of malondialdehyde (MDA) content and electrolyte leakage (EL)

To assess the MDA concentration of kiwifruit, ten fruits from each treatment were subjected to the thiobarbituric acid (TBA) method as described by Dhindsa et al. (1981). About 2 g of TBA and 20 g of TCA were weighed into a beaker, and then 100 mL of water was added to dissolve in a 95 °C water bath to obtain a TCA reaction solution. 1 g of the sample was added to 5 ml of 100 g/L TCA solution, rapidly homogenized, and then centrifuged at 10,000*g* for 20 min at 4 °C, and the supernatant was collected for use. 1 mL of supernatant (taking TCA as control) was taken and 2 mL of 0.67% TBA was added (taking 0.67 g of thiobarbituric acid, dissolved with 100 mL of 0.05 M NaOH solution), mixed and incubated for 20 min in a 95 °C water bath. The extract was immediately placed in an ice bath, cooled, and then centrifuged once. Absorbance values at 450 nm, 532 nm, and 600 nm were measured separately.

$$\text{MDA content (nmol kg}^{-1}\text{ FW)} = 6.45\left(\text{OD}_{532} - \text{OD}_{600}\right) - 0.56\text{OD}_{450}. \quad (3)$$

EL was measured according to the method of Feng et al. (2005) and calculated according to the following equation:

$$\text{EL}\,(\%) = \frac{\text{EL}_1}{\text{EL}_0} \times 100\%, \quad (4)$$

Fig. 2 Bruise scale for assessing bruise index in kiwifruit. Categories were assigned based on the extent of bruised area in cross section: 0, no bruise; 1, 1–10%; 2, 11–30%; 3, 31–50%; 4, > 50%

where EL_1 is the initial electrolyte leakage, and EL_0 is the electrolyte leakage after boiling.

Determination of H_2O_2 content and superoxide radical production

The H_2O_2 content of kiwifruit was assessed from ten fruits each treatment by the procedure previously described by Sairam et al. (2002). The frozen sample (1.0 g) was homogenized for 10 min in 2.5 mL of cold acetone. The homogenate was centrifuged at 8000 *g* for 10 min. A total of 1 mL of supernatant was added to 0.1 mL of 20% (v/v) titanium tetrachloride ($TiCl_4$) and 0.2 mL of ammonia water. After centrifuging for 15 min at 12,000 × *g*, the precipitate was collected and dissolved in 5 mL of 1 M H_2SO_4 and centrifuged for 5 min at 6000 × *g*. The absorbance was measured at 415 nm. H_2O_2 content was expressed as μmol g^{-1} FW.

Superoxide radical production rate was measured according to Song et al. (2009). The frozen sample (1.0 g) was homogenized in 5 mL of 50 mM, pH 7.8, phosphate buffer. The homogenate was centrifuged at 12,000 *g* for 20 min at 4 °C. 0.5 mL supernatant, 0.5 mL 50 mM phosphate buffer (pH = 7.8) and 1 mM hydroxylamine hydrochloride were mixed and incubated at 25 °C for 2 h. 1 mL 17 mM p-aminobenzenesulfonic acid and 7 mM naphthylamine were added and the mixture incubated at 25 °C for 20 min. The absorbance was measured immediately at 530 nm. The O^{2-} production rate was expressed in μmol g^{-1} FW min^{-1}.

Determination of the activities of stress-related enzymes

Enzyme extracts for the assay of peroxidase (POD), superoxide dismutase (SOD), and catalase (CAT) were prepared as in Tang et al. (2015) and expressed in U g^{-1} FW.

Statistical analysis

All the experiments were performed in a completely randomized block design and repeated three times at each time point. Single factor analysis of variance (ANOVA) was used to analyze the data of different storage times of kiwifruit. Differences were considered significant if $P < 0.05$ using Duncan's test by SPSS 19.0. Pearson correlations were performed to assess the relationship of bruise index and bruise area with the physical, biochemical and enzymatic parameters of kiwifruit.

Results

Bruise damage and internal appearance

The lesions on kiwifruit surface were not visible immediately after the dropping treatment. Depending on the severity of damage, the presence of a bruise may take up to 12 h or longer of to be visible (Sila et al. 2008). Percentages of bruise index and area after storage for 10 days are shown in Fig. 4. Significant differences among treatments were observed in bruise index and area of kiwifruit. The EPS box surface was much more effective in reducing the bruise index, which was 36.17% and 16.13% lower than that of the wooden box and HDPE box surface, respectively (Fig. 3a). Maximum and minimum values of bruise area were found for the wooden box and EPS box surface-impacted fruits, respectively (Fig. 3b).

The appearance of peeled kiwifruits is presented in Fig. 4. Bruise damage of kiwifruits was usually observed in the pulp under the peel. After 10 days of storage, the pulp was dull in the impacted area, while the EPS box surface impacted-fruits maintained as fresh luster and color as the control fruits.

Firmness and weight loss

After drop tests, the firmness of kiwifruit decreased significantly (Fig. 5a). The highest and lowest levels of firmness were recorded in the control samples and fruits collected in the wooden box during the storage. On the 10th day of storage, fruit firmness of three treatments decreased by 74.03%, 70.70% and 68.36%, respectively. Compared with the wooden box and HDPE box surface, the EPS box surface was more effective in maintaining the firmness of kiwifruit. Bruise area and bruise index of fruit were negatively correlated with firmness (Table 2).

From Fig. 5b, weight loss of all samples increased throughout the storage time and was more pronounced in the impacted fruits. In addition, the lowest weight loss (4.71%) was observed in the EPS box surface-impacted fruits, and the highest weight loss (5.83%) was observed in the wooden box surface-impacted fruits at the end of storage. Bruise area and bruise index of fruit were positively correlated with weight loss (Table 2).

Ethylene production and respiration rate

As shown in Fig. 6, impacted fruits had a faster response in ethylene production and respiration to impact damage, then decreased gradually over the remaining days in comparison to non-impacted fruit, showing an acceleration of the ripening process after impact damage as in previous

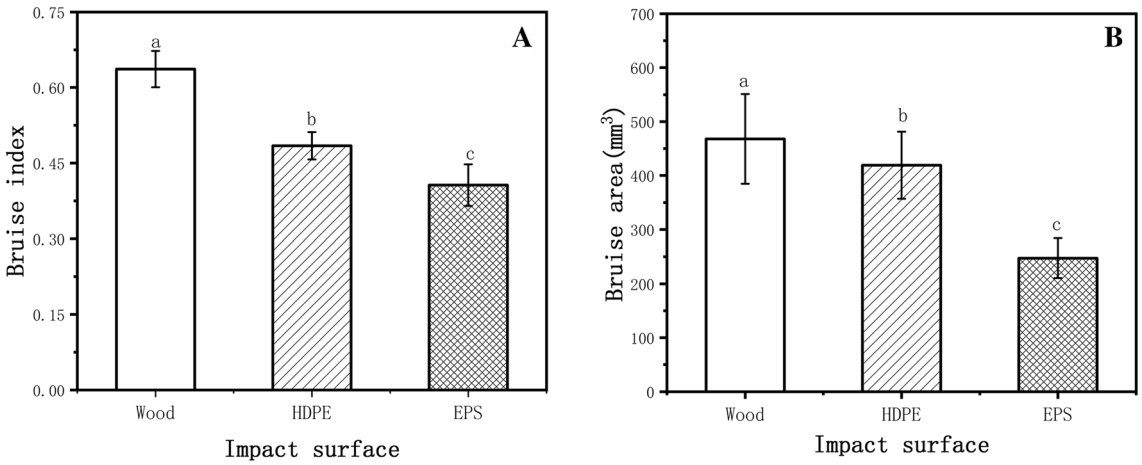

Fig. 3 Effect of different package materials on bruise index (**a**) and bruise area (**b**) of kiwifruit. Values are the means ± SD of triplicate assays. Different letters indicate statistically significant differences ($p < 0.05$). *Wood* fruits dropped on the surface of the wooden box, *HDPE* fruits dropped on the surface of high-density polyethylene box, *EPS* fruits dropped on the surface of the expanded polystyrene box

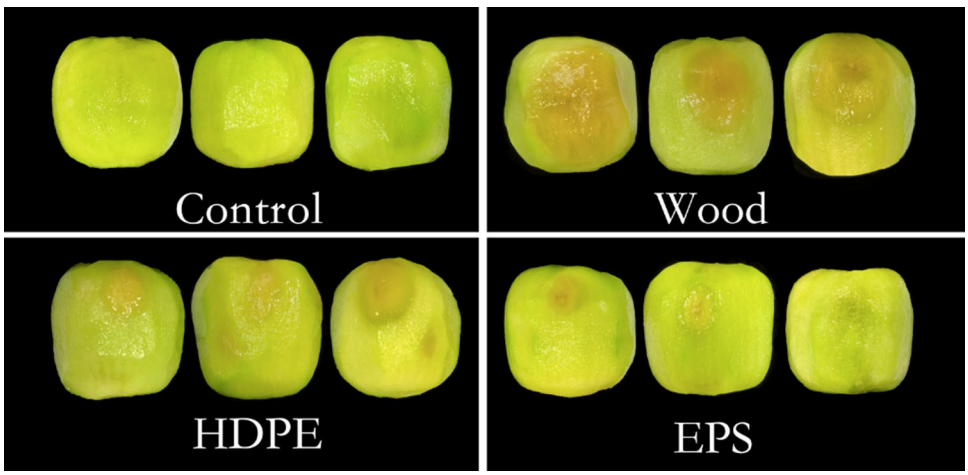

Fig. 4 Internal appearance of kiwifruit after 10 days of storage. *Wood* fruits dropped on the surface of the wooden box, *HDPE* fruits dropped on the surface of the high-density polyethylene box, *EPS* fruits dropped on the surface of the expanded polystyrene box, *Control* fruits not dropped

studies (Martínez-Romero et al. 2002; Pérez-Vicente et al. 2002). The peak level of ethylene production in fruits collected in the EPS box was 32.6%, 18.9% lower than that of the wooden box and HDPE box, respectively (Fig. 6a).

Besides, respiration rate in the impacted fruits was maintained at a high level compared with the control during storage (Fig. 6b). The highest peak of respiration rate was recorded in fruits from the wooden box and lowest in fruits from the EPS box among the impacted fruits. Both ethylene production and respiration rate were negatively associated with the bruise index and bruise area (Table 2).

MDA content and electrolyte leakage

As shown in Fig. 7, the MDA content gradually increased with the storage of all fruit samples. During the whole storage period, the content of MDA in kiwifruit after dropping was higher than that in the control, which indicated that the bruise after dropping resulted in cell membrane rupture and accumulated MDA content. Among treatment groups, fruits from EPS box showed the lowest incremental rate of MDA during the storage. By 10 days of storage, EL of fruits impacted on the EPS box surface was lower than that of the wooden box and HDPE box surface by 13.34 and 7.90%, respectively (Fig. 7b). Both MDA content and electrolyte leakage were positively associated with the bruise index and bruise area (Table 2).

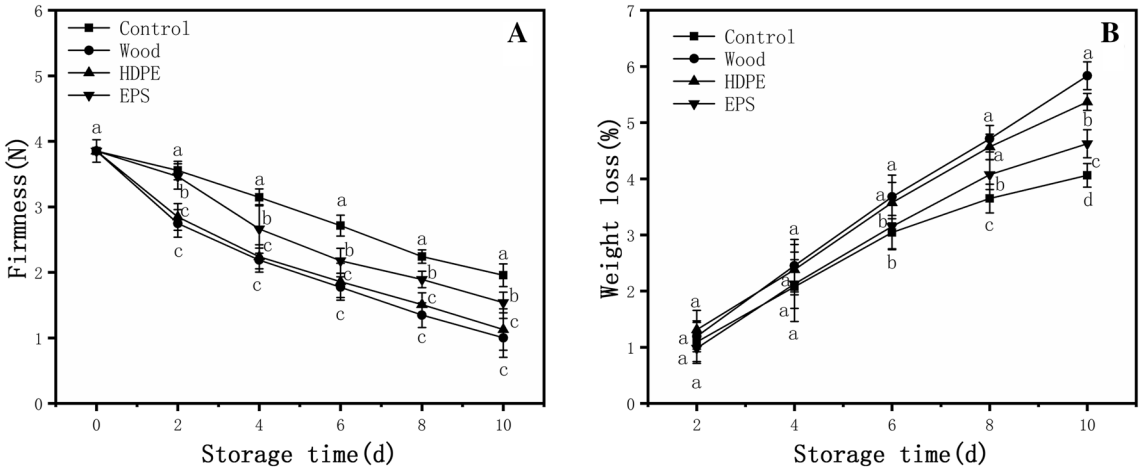

Fig. 5 Firmness (**a**) and weight loss (**b**) of kiwifruit throughout storage at 20 °C. Values are the means ± SD of triplicate assays. *Wood* fruits dropped on the surface of the wooden box, *HDPE* fruits dropped on the surface of high-density polyethylene box, *EPS* fruits dropped on the surface of the expanded polystyrene box, *control* fruits not dropped

Table 2 Pearson's correlation coefficients between bruise area, bruise index, physico-chemical attributes and enzyme activities of kiwifruit

	BA	BI	FM	WL	EL	RR	EP	MDA	H_2O_2	O^{2-}	CAT	SOD
BI	0.9084											
FM	−0.8753	−0.9290										
WL	0.9158	0.9631	−0.9803									
EL	0.8770	0.9372	−0.9556	0.9657								
RR	−0.2644	−0.5154	0.4090	−0.4136	−0.4250							
EP	−0.3086	−0.5608	0.4522	−0.4433	−0.4947	0.9010						
MDA	0.9236	0.8037	−0.8062	0.8257	0.8114	0.0371	−0.0860					
H_2O_2	−0.5373	−0.7189	0.8097	−0.7806	−0.7447	0.6591	0.6872	−0.3644				
O^{2-}	−0.5428	−0.7304	0.7549	−0.7437	−0.7636	0.6684	0.7442	−0.3694	0.8776			
CAT	−0.7625	−0.8847	0.9298	−0.9137	−0.8887	0.6132	0.6448	−0.6213	0.9215	0.8699		
SOD	−0.7554	−0.9185	0.9202	−0.9194	−0.9117	0.6479	0.6962	−0.6159	0.8878	0.8936	0.9694	
POD	−0.6486	−0.8449	0.8365	−0.8260	−0.7618	0.7115	0.6938	−0.4735	0.8726	0.8064	0.9294	0.9429

Correlation values are significant at $P \leq 0.05$

BA bruise area, *BI* bruise index, *FM* firmness, *WL* weight loss, *EL* electrolyte leakage, *RR* respiration rate, *EP* ethylene production, *MDA* malondialdehyde, *H_2O_2* hydrogen peroxide, *O^{2-}* superoxide radical production rate, *CAT* catalase, *POD* peroxidase, *SOD* superoxide dismutase

H_2O_2 content and superoxide radical production rate

In the early storage period, drop tests induced the rapid accumulation of the content of H_2O_2 and superoxide radical production rate. The H_2O_2 content in fruits collected in the wooden box, HDPE box and EPS box was 72.3%, 63.07% and 57.89% higher than that in the control on the 2nd day, respectively (Fig. 8a). The EPS box surface could keep the H_2O_2 content at a low level in the bruised fruit. The change in the superoxide radical production rate had a similar trend. The production rate of superoxide radicals in bruised fruits collected in EPS box was 25.02%, 11.58% lower than fruits collected in the wooden box and HDPE box (Fig. 8b). H_2O_2 content and superoxide had negative correlation with the bruise index and bruise area (Table 2).

Peroxidases, catalase and superoxide dismutase activities

The SOD activity in impacted fruits tended to show early increase and later decrease and was consistently higher

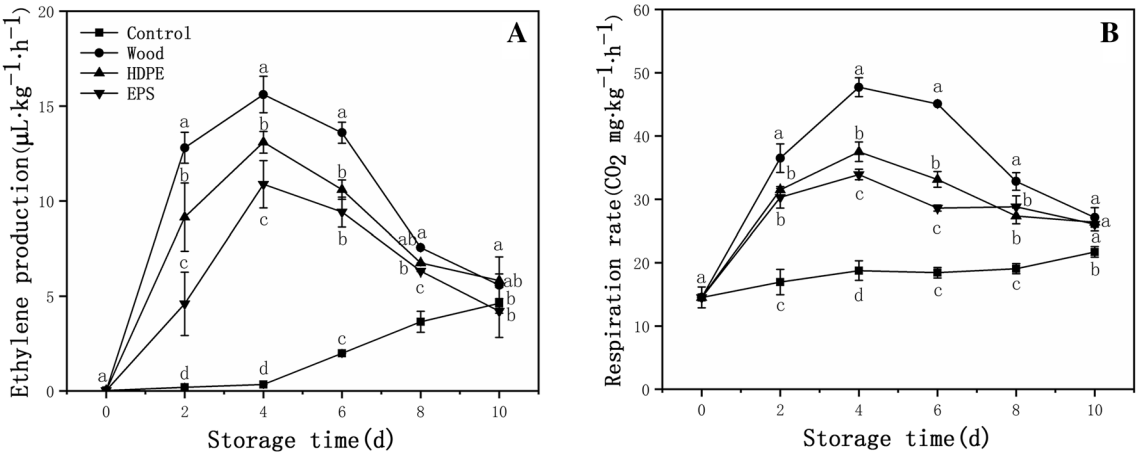

Fig. 6 Ethylene production (**a**) and respiration rate (**b**) of kiwifruit throughout storage at 20 °C. Values are the means ± SD of triplicate assays. Different letters indicate statistically significant differences among treatment factors ($p < 0.05$). *Wood* fruits dropped on the surface of the wooden box, *HDPE* fruits dropped on the surface of the high-density polyethylene box; *EPS* fruits dropped on the surface of the expanded polystyrene box, *control* fruits not dropped

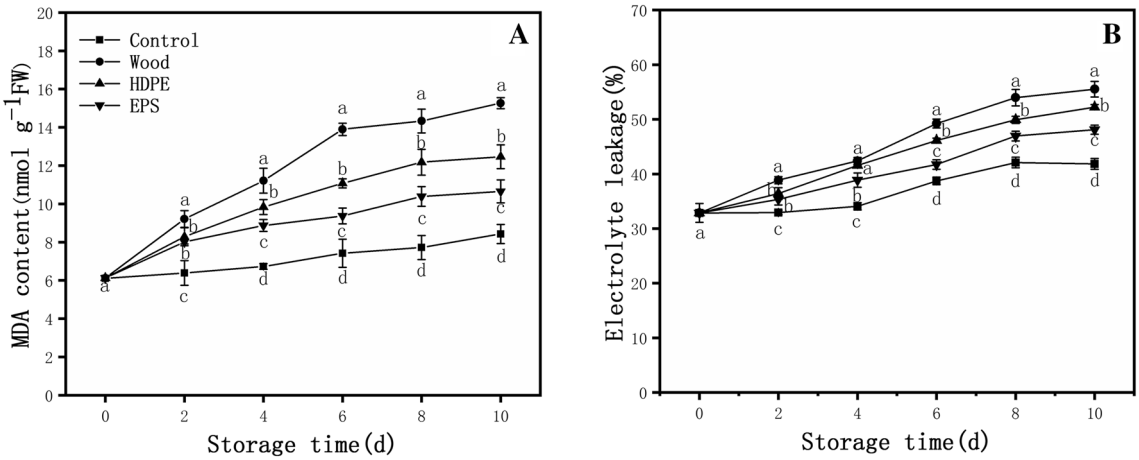

Fig. 7 MDA content (**a**) and electrolyte leakage (**b**) of kiwifruit throughout storage at 20 °C. Values are the means ± SD of triplicate assays. Different letters indicate statistically significant differences among treatment factors ($p < 0.05$). *Wood* fruits dropped on the surface of the wooden box, *HDPE* fruits dropped on the surface of the high-density polyethylene box, *EPS* fruits dropped on the surface of the expanded polystyrene box, *control* fruits not dropped

than that of the control. SOD activity kept increasing and reached the maximum level, three to five times higher than the initial level, by 2 days after dropping (Fig. 9a). Specifically, the activities of SOD in fruits from the EPS box were always lower than that of the wooden box and HDPE box over the storage time.

POD and CAT activities increased in all treatments during the first 4 days of storage, but then decreased rapidly. During the last 6 days of storage, SOD and CAT activities in fruits from the EPS box were significantly lower than those in other treatment groups (Fig. 9b, c). The results clearly showed that the levels of three enzymes in kiwifruit collected in the EPS box were lower than other impacted samples. The activities of these antioxidative enzymes (CAT, SOD and POD) had negative correlation with the bruise index and bruise area (Table 2).

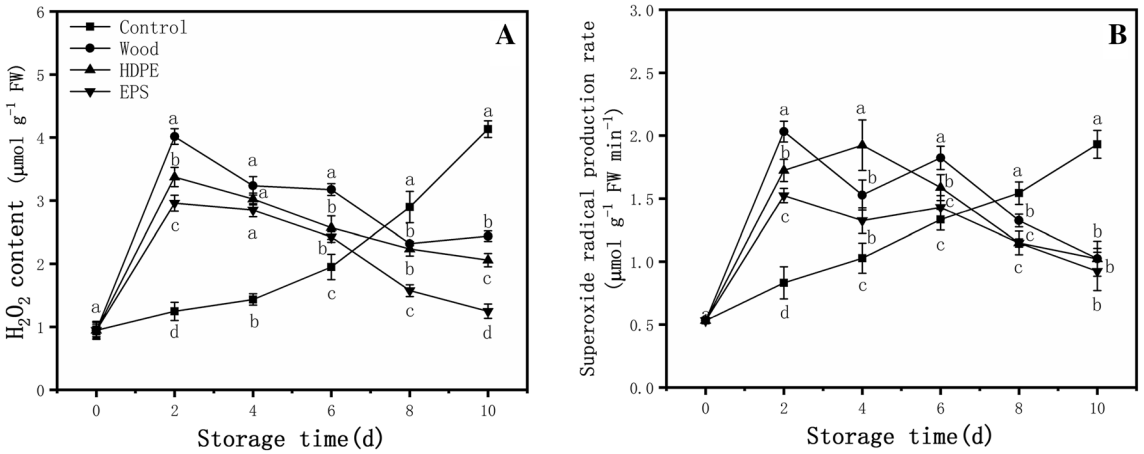

Fig. 8 H_2O_2 content (**a**) and superoxide radical production rate (**b**) of kiwifruit throughout storage at 20 °C. Values are the means ± SD of triplicate assays. Different letters indicate statistically significant differences among treatment factors ($p < 0.05$). *Wood* fruits dropped on the surface of the wooden box, *HDPE* fruits dropped on the surface of the high-density polyethylene box, *EPS* fruits dropped on the surface of the expanded polystyrene box, *control* fruits not dropped

Discussion

When subjected to external impact, internal flesh cells are distorted, leading to extension of the cell wall and rupture of membrane (Schoorl and Holt 1983; Wei et al. 2019). Due to the toughness and taupe of peel, the bruise damage is not usually visible on the peel of kiwifruit (Lü and Tang 2012; Ahmadi 2012). In this study, we observed that bruise index and bruise area differed with the different impact surfaces, which may be due to the different Young's modulus of the impact materials. Rigid impact surfaces with high Young's modulus produced higher bruise index and areas than softer materials (Lewis et al. 2007; Shafie et al. 2015). In the current study, EPS had the lowest Young's modulus among the three materials and caused lower bruise index and area than wood and HDPE.

Firmness and weight loss are important physiological indexes to measure the shelf life of kiwifruit. Mechanical damage results in modification of tissue permeability, permitting the interchange of water vapor (Martínez-Romero et al., 2003). Results showed that the EPS box surface was the most effective in reducing firmness loss and weight loss compared with the wooden box and HDPE box surface. Montero et al. (2009) found that the weight loss rate of tangerine increased with the increase of mechanical damage intensity, which is consistent with our results.

Bruise damage to plant tissue is often followed by increased respiration and ethylene production, which coincided with fruit softening at the site of injury (Moretti 1998). It was observed that respiration rate and ethylene production increased significantly following impact in this study (Fig. 5), which was consistent with the pomegranate (Hussein et al. 2019), citrus fruit (Scherrer-Montero et al. 2011), apricot (De Martino 2002) and tomato (Moretti 1998). Fruits impacted on the wooden box surface exhibited 1.5-fold higher respiration rate than fruits collected in the EPS box on day 2. Furthermore, the peak level of ethylene production in the wooden box and HDPE box surface-impacted fruit ws significantly higher than that of fruits collected in the EPS box. According to Montero et al. (2010), the respiration rates of bruised fruits increased with the degree of damage to the samples.

MDA is an end product of lipid peroxidation, and its level may directly reflect the degree of oxidative damage of cell membranes (Blokhina 2003; Lindén et al. 2000). The damage of cell membranes results in enhanced leakage of solutes into the apoplastic water; thus, the level of electrolyte leakage is inversely proportional to the integrity of the plasma membrane. (Ferguson and Watkins 1981). In the current study, impact injury promoted immediate increase in MDA content and reached the peak level on day 4, consistent with the study on pear (Zhou et al. 2007) and apple (Lu et al. 2019). Electrolyte leakage of all groups increased throughout the storage time and was more pronounced in the impacted fruits. MDA content and EL in the EPS box surface-impacted fruits were much lower than those of wooden box and HDPE box surface-impacted fruits (Fig. 6), which indicated that the EPS box surface was more suitable for protecting the structure of the biological membrane in kiwifruit.

Previous studies have shown that ROS increase the production of H_2O_2 and O^{2-} response to various biotic and abiotic stresses in plants (Navabpour et al. 2003). In the

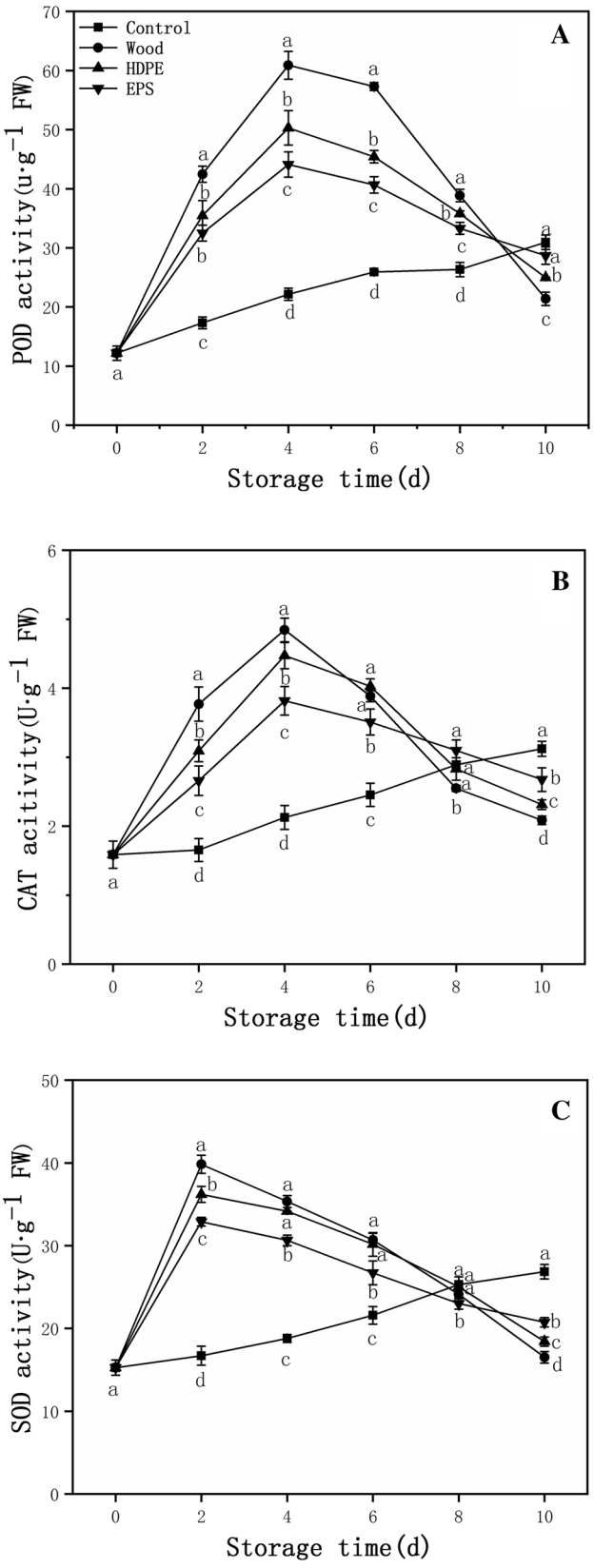

Fig. 9 Activities of peroxidase (**a**), catalase (**b**) and superoxide dismutase (**c**) in kiwifruit throughout storage at 20 °C. Values are the means ± SD of triplicate assays. Different letters indicate statistically significant differences among treatment factors ($p < 0.05$). *Wood* fruits dropped on the surface of the wooden box, *HDPE* fruits dropped on the surface of the high-density polyethylene box, *EPS* fruits dropped on the surface of the expanded polystyrene box, *control* fruits not dropped

current study, O^{2-} level in fruits from the wooden box was about threefold higher than that of in fruits from the EPS box on day 2. The H_2O_2 content of fruits collected in the EPS box showed significantly lower level than that of fruits collected in the wooden box throughout the entire storage period. The equilibrium between production and scavenging of ROS in kiwifruit is disturbed by mechanical wounding during storage and thereby it incurs fruit senescence. In response to oxidative damage, there is an increasing activity of enzymes responsible for defensive mechanisms of plant tissues, including SOD, CAT and POD (De Martino 2002). Through the action of SOD, O^{2-} is effectively converted into H_2O_2. CAT converts H_2O_2 into H_2O and O_2, whereas POD decomposes H_2O_2 by oxidizing phenolic compounds and antioxidants (Xue and Liu 2008).

Mechanical damage enhanced the antioxidant enzymes activities because of a need for ROS detoxification (Martino et al. 2006). In our work, the kiwifruit undergoing drop tests displayed increased antioxidant enzyme activities compared with control samples. The high activities of the three enzymes found in fruits collected in the wooden box showed that the fruit experienced more toxicity of H_2O_2 during storage, while the low enzyme activities found in fruits collected in the EPS box indicated that this fruit experienced less impact damage. Additionally, decreases of three enzyme activities were accelerated in fruits collected in the wooden box in comparison with the HDPE box and EPS box.

Conclusion

Our present study showed that packaging materials displayed a variety of influence on the bruising occurrence in kiwifruit. Among the three common collection boxes, the EPS box surface delayed the increase of bruise index, bruise area, weight loss and electrolyte leakage; maintained high firmness; inhibited ethylene production and respiration rate, the accumulation of malondialdehyde, hydrogen peroxide and superoxide anion; and decreased the peak level of activities of antioxidant enzymes during the storage time. Overall, a proper material for a collection box is important to minimize

bruises and reduce fruit losses due to impact damage during the postharvest processes.

Author contribution statement LCM and CJX conceived and designed the experiments. MX and XXZ performed the experiments. MX analyzed the data and wrote the manuscript. XPW, WLG and XBW also contributed to the data interpretation and writing. All authors read and approved the final manuscript.

Acknowledgements This work was financially supported by the National Key Research and Development Program of China (2018YFD0401303) and the National Natural Science Foundation of China (31772365).

References

Ahmadi E (2012) Bruise susceptibilities of kiwifruit as affected by impact and fruit properties. Res Agric Eng 58(3):107–113

Ahmadi E, Ghassemzadeh HR, Sadeghi M, Moghaddam M, Neshat SZ (2010) The effect of impact and fruit properties on the bruising of peach. J Food Eng 97(1):110–117

Blokhina O (2003) Antioxidants, oxidative damage and oxygen deprivation stress: a review. Ann Bot 91(2):179–194

Cakmak B, Alayunt FN, Akdeniz RC, Aksoy U, Can HZ (2010) Assessment of the quality losses of fresh fig fruits during transportation. Tarim Bilimleri Dergisi 16(3):180–193

Celik HK (2017) Determination of bruise susceptibility of pears (Ankara variety) to impact load by means of FEM-based explicit dynamics simulation. Postharvest Biol Technol 128:83–97

DeMartino G (2002) Temperature affects impact injury on apricot fruit. Postharvest Biol Technol 25:145–149

Dhindsa RS, Plumb-Dhindsa P, Thorpe TA (1981) Leaf senescence: correlated with increased levels of membrane permeability and lipid peroxidation, and decreased levels of superoxide dismutase and catalase. J Exp Bot 32(1):93–101

Feng G, Yang H, Li Y (2005) Kinetics of relative electrical conductivity and correlation with gas composition in modified atmosphere packaged bayberries (Myrica rubra siebold and zuccarini). LWT Food Sci Technol 38(3):249–254

Ferguson IB, Watkins CB (1981) Ion relations of apple fruit tissue during fruit development and ripening. Iii. calcium uptake. Funct Plant Biol 8(3):259–266

Holt JE, Schoorl D (1984) Package protection and energy dissipation in apple packs. Sci Hortic 24(2):165–176

Hu H, Li P, Wang Y, Gu R (2014) Hydrogen-rich water delays postharvest ripening and senescence of kiwifruit. Food Chem 156:100–109

Hussein Z, Fawole OA, Opara UL (2019) Bruise damage susceptibility of pomegranates (Punica granatum, L.) and impact on fruit physiological response during short term storage. Sci Hortic 246:664–674

Komarnicki P, Stopa R, Daniel S, Lukasz K, Tomasz K (2017) Influence of contact surface type on the mechanical damages of apples under impact loads. Food Bioprocess Technol 10(8):1479–1494

Lewis R, Yoxall A, Canty LA, Romo ER (2007) Development of engineering design tools to help reduce apple bruising. J Food Eng 83(3):356–365

Lindén L, Palonen P, Lindén M (2000) Relating freeze-induced electrolyte leakage measurements to lethal temperature in red raspberry. J Am Soc Hortic Sci 125(4):429–435

Lu F, Xu FX, Li Z, Liu YF, Wang JW, Zhang L (2019) Effect of vibration on storage quality and ethylene biosynthesis-related enzyme genes expression in harvested apple fruit. Sci Hortic 249:1–6

Lü Q, Tang M (2012) Detection of hidden bruise on kiwi fruit using hyperspectral imaging and parallelepiped classification. Proc Environ Sci 12:1172–1179

Martínez-Romero D, Castillo S, Valero D (2003) Forced-air cooling applied before fruit handling to prevent mechanical damage of plums (Prunus salicina Lindl.). Postharv Biol Technol 28:135–142

Martinez-Romero D, Serrano M, Carbonell A, Burgos L, Riquelme F, Valero D (2002) Effects of postharvest putrescine treatment on extending shelf life and reducing mechanical damage in apricot. J Food Sci 67(5):1706–1712

Martino GD, Vizovitis K, Botondi R, Bellincontro A, Mencarelli F (2006) 1-MCP controls ripening induced by impact injury on apricots by affecting sod and pox activities. Postharvest Biol Technol 39(1):38–47

Mohammad Shafie M, Rajabipour A, Castro-García S, Jiménez-Jiménez F, Mobli H (2015) Effect of fruit properties on pomegranate bruising. Int J Food Prop 18(8):1837–1846

Moretti CL (1998) Chemical composition and physical properties of pericarp, locule, and placental tissues of tomatoes with internal bruising. J Am Soc Hortic Sci 123(4):656–660

Montero CRS, Schwarz LL, Santos LCD, Andreazza CS, Kechinski CP, Bender RJ (2009) Postharvest mechanical damage affects fruit quality of 'Montenegrina' and 'Rainha' tangerines. Pesqui Agropecu Bras 44(12):1636–1640

Montero CRS, dos Santos LC, Andreazza CS, Bender RJ (2010) Influence of impact and compression mechanical damage on respiration of Fuji Suprema and Royal Gala apples. Semina Ciênc Agrár 31(4):967–974

Navabpour S, Morris K, Allen R, Harrison E, Mackerness S, Buchanan-Wollaston V (2003) Expression of senescence-enhanced genes in response to oxidative stress. J Exp Bot 54(391):2285–2292

Opara UL, Pathare PB (2014) Bruise damage measurement and analysis of fresh horticultural produce—a review. Postharvest Biol Technol 91:9–24

Pérez-Vicente A, Martinez-Romero D, Carbonell A, Serrano M, Riquelme F, Guillén F, Valero D (2002) Role of polyamines in extending shelf life and the reduction of mechanical damage during plum (Prunus-salicina Lindl.) storage. Postharvest Biol Technol 25:25–32

Polat R, Aktas T, Ikinci A (2012) Selected mechanical properties and bruise susceptibility of nectarine fruit. Int J Food Prop 15(6):1369–1380

Sairam RK, Rao KV, Srivastava G (2002) Differential response of wheat genotypes to long term salinity stress in relation to oxidative stress, antioxidant activity and osmolyte concentration. Plant Sci 163:1037–1046

Scherrer-Montero CR, Dos Santos LC, Andreazza CS, Getz BM, Bender RJ (2011) Mechanical damages increase respiratory rates of citrus fruit. Int J Fruit Sci 11(3):256–263

Schoorl D, Holt JE (1983) Mechanical damage in agricultural products: a basis for management. Agric Syst 11(3):143–157

Sila DN, Duvetter T, De Baerdemaeker J, Hendrickx M (2008) Effect of mechanical impact-bruising on polygalacturonase and pectinmethylesterase activity and pectic cell wall components in tomato fruit. Postharvest Biol Technol 47(1):98–106

Song L, Gao H, Chen H, Mao J, Zhou Y, Chen W et al (2009) Effects of short-term anoxic treatment on antioxidant ability and membrane integrity of postharvest kiwifruit during storage. Food Chem 114:1216–1221

Tang J, Liu Y, Li H, Wang L, Huang K, Chen Z (2015) Combining an antagonistic yeast with harpin treatment to control postharvest decay of kiwifruit. Biol Control 89:61–67

Timm EJ, Brown GK, Armstrong PR (1996) Apple damage in bulk bins during semi-trailer transport. Appl Eng Agric 12(3):369–377

Wei X, Xie D, Mao L, Xu C, Luo Z, Xia M, Lu W (2019) Excess water loss induced by simulated transport vibration in postharvest kiwifruit. Sci Hortic 250:113–120

Xue YF, Liu ZP (2008) Antioxidant enzymes and physiological characteristics in two Jerusalem artichoke cultivars under salt stress. Russ J Plant Physiol 55(6):776–781

Yang D, Li D, Xu W, Liao R, Shi J, Fu Y, He X (2018) Design and application of a passive modified atmosphere packaging for maintaining the freshness of Chinese cabbage. LWT 94:136–141

Zhou R, Su S, Yan L, Li Y (2007) Effect of transport vibration levels on mechanical damage and physiological responses of Huanghua pears (Pyrus pyrifolia Nakai, cv. Huanghua). Postharvest Biol Technol 46(1):20–28