

Investigation on the protection ability of two commonly packaging methods to apples during express transportation

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Abstract: Packaging plays a vital role in the post-harvest sales process of apples. This study conducted express transportation tests to evaluate the protective effectiveness of two commonly used packaging methods for apples. Key parameters assessed included real-time changes in temperature, humidity, vibration load, and CO₂ levels inside the packaging boxes during transit, as well as the storage quality of apples after transportation. Results showed significant variations in load distribution within corrugated partition-based cardboard boxes (CP combination packaging). Conversely, foam holder-based cardboard boxes (FP combination packaging) exhibited CO₂ accumulation. Furthermore, mechanical damage was predominantly localized to the fruit belly. Compared to CP combination packaging box, FP combination packaging box provided more stable shock resistance at lower vibration forces (< 10 N) across transit routes, likely due to its EPS foam design, which restricted fruit movement and absorbed external vibrations. Post-storage analysis showed that damaged apples experienced a 0.16 % increase in mass loss, a 0.83 % rise in soluble solids content (SSC), and a 0.19 MPa reduction in firmness compared to undamaged controls. These findings provide valuable insights into optimizing packaging design to minimize transport-induced damage and enhance apple preservation.

Keywords: Apple fruit; Mechanical damage; Packaging method; Protection ability; Transportation

1 Introduction

While apples possess favorable commodity qualities, their thin skin and sensitive flesh render them vulnerable to external influences that can cause mechanical damage, accelerate fruit deterioration, and lead to nutrient loss (Al-Dairi et al., 2021), which is not conducive to maintaining human health and promoting food safety (Win et al., 2019). Due to the advancement of Internet technology, online sales have emerged as a primary avenue for distributing fresh apple fruit, while concurrently, the challenge of fruit loss associated with logistics has garnered increasing attention (Pathare & Al-Dairi, 2021). According to literature, about 80 % of fruit losses occur in transportation (Jiao et al., 2021). Mechanical damage to fruits, including dropping, bumping, colliding, and vibration, primarily occurs during rapid transit (Lin et al., 2022; Zheng et al., 2022). Moreover, the combination of excessive temperature and humidity levels during transportation, coupled with fluctuation in transport load, accelerate apple loss, with temperature changes alone contributing to a significant loss rate ranging from 30-49 % (Othman et al., 2021; Al-Dairi et al., 2022). These factors lead to increased fruit loss during logistics while also compromising the apples' edible quality and shelf life.

Effective packaging technology is crucial for mitigating mechanical damage, minimizing water evaporation, and preserving the quality of apples (Al-Dairi et al. 2023). Jiang et al. (2021) concluded that packing fresh bayberries in EPS boxes and fruit baskets using semi-vacuum packaging was effective for express transportation. The authors identified damage to the fruit during transit primarily resulted from repeated shocks (6 times) and high-intensity vibration (12 times). Additionally, bayberries packed in semi-vacuum packaging exhibited 13.58 % lower hardness compared to those placed directly in foamed polyethylene (EPS) boxes during transportation. Lin et al. (2020) demonstrated that, under the same vibration conditions, the damage rate, damage area and storage decay rate of peaches packaged with polyurethane (PU) + corrugated cardboard box (CFB) were 1.37 %, 43.2 % and 15 % lower than those packaged with foamable polyethylene (EPE) + CFB, respectively. Zheng et al. (2022) subjected "Hongmeiren" citrus fruits to vibration at 20 °C and 90 % RH for 3 h using three different packaging methods. The authors found that citrus fruit packaged with C packaging (which included plastic partition boards to separate the folding plastic basket, a PU foam layer, and an inner EPE foam layer) had damage rates that were 80 % and 1.11 % lower than those packaged with A packaging (plastic bulk containers) and B packaging (gift packaging), respectively. Fernando et al. (2021) found that bananas were more susceptible to vibration damage during transit when packed in cross-stacked pallets, though their

vibration levels were reduced when packaged in column-stacked pallets. Despite this, bananas packed in cross-stacked pallets experienced less overall damage compared to those in column-stacked pallets. Wang et al. (2023) observed that pears positioned at the top layer suffered significantly more damage from response vibration amplitude during simulated vibration, which was notably higher than the damage sustained by pears in the bottom and intermediate layers. Additionally, the respiration rate of the pear fruit increased by 21.4 % - 76.5 % after 72 hours of random vibration compared to the control group. Hou et al. (2024) reported that decay in winter jujubes appeared on the 3rd day of storage in the vibration group, in contrast to the 6th day in the control group, following a 40-minute simulated vibration at 0.75 g acceleration. After a 12-day storage period, the decay rate of winter jujubes in the vibration group was 46 %, 2.76 times higher than that of the control group.

In the previous studies, great progress has been made on the impact of packaging techniques on fruit mechanical damage and storage quality, mostly using vibration test benches. The main research contents included: (i) fruit damage was analyzed after simulated transport test; and (ii) the location of damaged fruit within the transport truck during actual transportation. Until now no experiments of the real express transportation environment, the stress conditions experienced by the apple fruit and the microenvironmental changes within the packaging box have been reported. Furthermore, few studies investigated the protection ability of packaging methods to fruit under real express transportation conditions. Simulated transportation experiments have notable limitations: (i) they are carried out within a controlled time and space, which does not accurately reflect the dynamic fluctuations in temperature, humidity, and gas concentration that occur during actual transportation environment; (ii) simulated experiments do not comprehensively accounted for damage resulting from collisions between fruits, impacts with the inner walls of packaging, or interactions between packages, all of which can significantly influence fruit quality during transit. In contrast, real-world transportation conditions can offer a more comprehensive view of how fluctuations in temperature, humidity, and gas concentration within the packaging box affect fruit quality. Additionally, real express transport conditions account for various forces, such as violent sorting, which influence the extent of damage and the placement of damaged fruits within the packaging box. This information is essential for selecting appropriate packaging methods and designing new packaging box structures for express transportation. Therefore, the study aims to investigate on the protection ability of two commonly packaging methods to apples during express transportation.

2 Materials and methods

2.1 Fruit supply, packaging materials, and transportation protocols

"*Fuji*" apples grown in the orchards of Luochuan Jinyuan Fruit Industry Co., Ltd. (35°26'29"N, 109°33'54"E) were selected as the study sample. From October to November 2023, apples were manually picked every six days. To ensure uniform maturity, apples with a red blush coverage of 60-70 % were chosen (Farcuh, 2021). Each time, 40 fresh apples were carefully picked for the express transportation test. Before transportation, 24 apples without damage or lesions were selected from the 40 picked apples and wrapped in fruit mesh covers. Then, the wrapped apples were placed into CP combination packing boxes and FP combination packaging boxes (UPS codes: 4G5 /S 22CHN), with separate compartments created by corrugated partitions or fruit foam brackets (Fig. 1A and 1B). Each box consists of two layers, with each layer holding 12 apples, totaling 24 apples per box. The CP combination packaging box comprises an outer layer of corrugated cardboard (44 cm × 28 cm × 18 cm), a corrugated partition (39 cm × 24 cm × 0.4 cm), and an inner fruit foam packing net (11 cm × 10.5 cm × 0.5 cm). During use, the carton was divided into individual compartments with a corrugated partition, and each apple, wrapped in a fruit foam packing net, was placed into its own compartments. The FP combination packaging box consists of an outer layer of corrugated cardboard (44 cm × 28 cm × 18 cm), an EPS foam holder (39.5 cm × 29.5 cm × 10 cm), and a fruit foam packing net (11 cm × 10.5 cm × 0.5 cm) on the inside. In this setup, the EPS foam holder was first placed inside the corrugated cardboard box, and then the apples, wrapped in fruit foam packing nets, were placed within the EPS foam holder. Given that Hainan, Heilongjiang, and Xinjiang are located in the southernmost, northernmost, and westernmost regions of China respectively, the distances from these locations to Yangling are relatively long, and they have significantly different temperature and humidity conditions. Therefore, Yangling was chosen as the starting point for transportation. One box of apples was sent to each destination (Hainan, Heilongjiang, and Xinjiang) and subsequently returned to Yangling via express delivery (Fig. 1D). In total, 6 (2 package types × 3 places) express transport tests were conducted.

2.2 Determination of the microenvironment in the packaging box and the loads acting on the e-apple during express transportation

Before transportation: To monitor conditions within the packaging, two apples were removed from the center of the top layer in each packaging box and replaced with an electronic apple (7602A8, Martin Lishman Ltd, UK) and an information-detecting sensor (S21A2, Xuzhou Fara Electronic Technology

Co., Ltd, China) (Fig. 1C). After connecting the electronic apple to the “ML Sensing” program, "START MEASUREMENT" was clicked to initiate real-time recording of the apple’s acceleration during express transit. Simultaneously, variations in temperature, humidity, and carbon dioxide (CO₂) during express transit were displayed on a mobile phone screen by scanning the QR code on the sensor’s surface to establish a connection. Following the completion of each transportation test, data from both the information-detecting sensor and the electronic apple were exported to a designated PC folder for further processing and analysis.

2.3 Determination of the mechanical damage in apples after transportation

The apples were divided into three sections: the top, the belly, and the shoulder. The top and shoulder each accounted for one-quarter of the apple, while the belly accounted for half. After transportation, the apples in the packing boxes were inspected, and any damaged apples were recorded, noting the specific region of damage on each apple. Then, the area of the damaged area was calculated by measuring its length and width using a Digimizer Software (5.4.4, MedCalc Software Co., Ltd., USA). To ensure accurate measurement, an image of the apple’s damaged region was imported into Digimizer Software, with a guideline of known length (such as a ruler) placed in the image to set the scale within the program. Using the free shape measurement tool in Digimizer, the outline of the damaged area was carefully traced along its perimeter for precise edge alignment. Once the outline was complete, Digimizer automatically calculated the damaged area and subsequently determined the damage area rate based on the measured area. Damage rate of apples was then calculated using Eq. (1) proposed by Khodaei et al. (2019). Each apple was categorized into five levels based on the extent of damage: (1) no damage, (2) light damage, (3) moderate damage, (4) severe damage, and (5) lacerated fruit. The fruit mechanical damage index (*FDI*) for the entire box of apples was then calculated using Eq. (2) as proposed by (David et al., 2022):

$$D_r = \frac{D_n}{T_n} \times 100\% \quad (1)$$

$$FDI = \frac{0 \cdot X_0 + 1 \cdot X_1 + 2 \cdot X_2 + 3 \cdot X_3 + 4 \cdot X_4}{X_0 + X_1 + X_2 + X_3 + X_4} \quad (2)$$

where: D_r - Damage rate, %; D_n - Number of damaged fruit; T_n - Total number of fruit; X_i - the number of fruit; $i=0$ - without bruising (sound); $i=1$ - slight damage, covering < 10 % of the fruit surface; $i=2$ - moderate damage, covering 10 – 30 % of the fruit surface; $i=3$ - severe damage, covering 40 – 60 % of the fruit surface; $i=4$ - fruit with cracks, covering more than 70 % of the fruit surface.

The microscopic morphology of damaged apple tissue was observed by Safranin-O fast green staining. Apple tissues that were not tested for transportation and those that were severely damaged during transportation, were cut into approximately 0.5 cm³ squares using R35 blades. The tissues were then fixed in 5 % formalin-acetic acid (FAA) solution for 48 hours and subsequently embedded in paraffin wax. Using a microtome (RM2016, Shanghai Leica Instruments Co., Ltd, China), the paraffin-embedded tissues were sectioned into 2 µm slices, which were then mounted onto slides for staining. The sections were stained with safranin for 1.5 hours to color cell walls and other structures, followed by an 8-second alcohol decolorization. Next, solid green dye was applied for 60 seconds to highlight the nucleus and other cell wall structures, enabling the observation of tissue damage. After staining, the sections were treated with aqueous ethanol and xylene for 5 minutes each. The morphological features of the stained apple tissue were then examined and photographed under a microscope (CI-S, Nikon, Japan) (Chen et al., 2021).

2.4 Determination of the quality indicators of apples during storage

Following each transportation test, the apples assessed for damage were placed in a laboratory constant temperature and humidity box (HWS-50B, Tianjin Hongnuo Instrument Co., Ltd., China). The storage conditions were maintained at 25 ± 1 °C and 60 % relative humidity for a period of 12 days. Quality indicators of the apples were measured every 3 days.

2.4.1 Determination of the color of fruit skin

The color difference meter (WR10-8M, Shenzhen Weafu Photoelectric Technology Co., Ltd., China) was first calibrated at the zero point and light source. The measuring light hole of the meter was then placed against the surface of each apple sample, and the test button was pressed to measure and record the apple peel's L^* , a^* , and b^* values once the sample surface fully covered the measuring area. Each sample was measured five times, with the total number of samples corresponding to the number of apples damaged after each transportation. Color measurements were conducted every 3 days over the 12-day storage period.

2.4.2 Determination of the mass loss of fruit

Before transportation, the initial mass of each apple was measured using an electronic balance with 0.01 g accuracy (JCS-2000, Kaifeng Group Co., Ltd., China). The balance was placed on a stable surface and calibrated to zero before each weighing. After transportation, mass measurements were conducted every 3 days during the 12-day storage period to monitor changes in apple weight. All stored samples

were included in each measurement. The mass loss rate for each apple was calculated using Eq. (3) (Wang et al., 2022).

$$M_l = \frac{M_i - M_s}{M_i} \times 100\% \quad (3)$$

where M_l - Mass loss rate, %; M_i - Initial mass of apple, g; M_s - Mass of apple during storage, g.

2.4.3 Determination of the fruit tissue firmness

To assess fruit tissue firmness, each apple was sliced in half lengthwise. A 2 cm² square was marked on the surface of one half using a scale and marker, then the skin within the marked square was carefully removed with an R35 blade. The exposed apple pulp was tested for firmness using a texture analyzer (Universal TA, Shanghai Tengba Instrument Technology Co., Ltd., China). The puncture depth of the upper plate was set to 2 cm, with a puncture speed of 1 mm/s. During testing, the cut apple half was securely positioned in the center of the texture analyzer's substrate, ensuring stability without external force. The P/2 probe was inserted along the length of the apple sample, and force-time data were recorded in real time by a computer (An et al., 2023a). The fruit tissue firmness was calculated using Eq. (4) (Yi et al., 2022). For each firmness assessment, five apple samples were tested, with three measurements per sample. This procedure was repeated every three days during the storage period.

$$P = \frac{F}{S} \quad (4)$$

where P - fruit tissue firmness, MPa; F - puncture force during measurement, N; S - probe area, mm².

2.4.4 Determination of soluble solid content (SSC)

The remaining halves of the apples during the firmness test were peeled and seeded. A 100 g sample was diced and then processed in a juicer for extraction. The resulting juice was filtered through gauze to obtain a clear filtrate. This filtrate was then placed over the measuring light hole of a Digital Brix Sugar Refractometer Electronic Handheld Sweetness Meter (BM-04, Tianjin Lookout Optoelectronics Technology Co., Ltd., China) (Hu et al., 2022). The test button was pressed to record the SSC value displayed on the device screen. For each measurement, five samples were tested, with each sample measured three times. This procedure was repeated every three days, using a fresh apple half for each measurement.

2.5 Statistical analysis

Analysis of variance (ANOVA) was performed using SPSS software, version 22.0 (IBM Inc., Chicago, IL, USA) with a significance level set at 0.05. Figures were plotted using the Origin software,

version 2018 (Origin Laboratories, Ltd., Northampton City, MA, USA) and GraphPad Prism software, version 9.0 (GraphPad Software Inc., San Diego, CA, USA).

3 Results and discussion

3.1 Express transportation experiment results

3.1.1 Transport load during express transportation

Figure 2 presents the statistical relationship between vibration force and vibration frequency for apples in different packaging forms transported to various regions during express transportation. For the Yangling to Hainan route, apples in CP and FP combination packaging boxes vibrated with a force of 3 ~ 4 N at equivalent frequencies of 394 and 212 times, respectively. At a transport vibration force of 59 ~ 60 N for apples packaged in CP and FP combination packaging boxes, the vibration frequencies were 2 times and 4 times, respectively. The maximum transport vibration forces for CP and FP combination packaging boxes were 59.72 N and 60.90 N, respectively. When apples in the FP combination packaging box vibrated with a force of 60 to 61 N, the vibration frequency was 3 times. Moreover, for vibration forces ranging from 10 N to 60 N, the vibration frequency of apples in the CP combination packaging box was higher than in the FP combination packaging box (Fig. 2 A1 and A2).

On the Yangling to Heilongjiang route, the range of vibration forces with the highest vibration frequency in the CP combination packaging box (220 times) and the FP combination packaging box (258 times) were 5 ~ 6 N and 3 ~ 4 N, respectively. The maximum transport vibration forces were 56.21 N for CP and 60.92 N for FP combination packaging boxes. When the vibration force was 10 ~ 20 N, the transport vibration frequency of the CP combination packaging box was lower than that of FP combination packaging box. However, When the transport vibration force exceeded 20 N, the CP combination packaging box had a higher transport vibration frequency (Fig. 2 B1 and B2).

For the Yangling to Xinjiang route, at a vibration force of 3 ~ 4 N, the vibration frequencies were 326 times for CP and 355 times for FP combination packaging boxes. When the transport vibration force exceeded 10 N, the transport vibration frequency for CP combination packaging boxes was lower than that for FP combination packaging boxes (Fig. 2 C1 and C2).

In conclusion, the FP combination packaging consistently exhibited lower overall vibration forces across all transport routes compared to the CP combination packaging, particularly at lower vibration forces, demonstrating more stable shock resistance. At higher vibration forces (> 10 N), CP combination packaging box frequently exhibited a higher vibration frequency. For CP combination packaging, the

pressure from apples and external forces during transit caused continuous deformation of the corrugated partitions, increasing the freedom of movement of the apples within the box. In contrast, the interior of the FP combination packaging box includes an EPS foam holder with an arc-shaped design that allows direct contact with the apple's outer surface, which wrapped in an EPE foam mesh sleeve (An et al., 2023b), ensuring a secure fit. This design significantly restricts the movement of the apples within the box. Additionally, the thick EPS foam supports efficiently absorb vibration energy from the external environment, suggesting that the FP combination packaging may reduce mechanical damage to apples during transportation by dispersing vibration shocks. Insights from the FP combination packaging form can guide the development of damage-preventive packaging materials and inform structural enhancements for future packaging solutions.

3.1.2 Microenvironment in the packaging box during express transportation

Figure 3 illustrates the changes in the microenvironment within the packaging box of apples packaged in different forms during transportation to various regions in the express transportation process, alongside the duration of transportation. On the transportation route from Yangling to Hainan, the temperature, humidity, and CO₂ accumulation in the CP combination packaging box gradually increased with transportation time. Towards the end of the transportation cycle, both types of combination packing boxes exhibited higher CO₂ accumulation, reaching approximately 31,000 ppm in both the CP and FP combination packaging boxes (Fig. 3 A1 and A2). The maximum humidity recorded in the CP combination packaging box was 89.4 %, while in the FP combination packaging box, it reached 94.5 %. Overall, the humidity in the FP combination packaging box tended to be higher than that in the CP combination packaging box. Regarding temperature changes, the CP combination packaging box initially experienced a decrease followed by an increase, although the declining process was not distinctly evident. In contrast, the temperature change in the FP combination packaging box showed a pattern of initial decrease, followed by an increase, and then a subsequent decrease. The maximum temperature recorded for CP and FP combination packaging box were 32.3 °C and 28.9 °C, respectively. Throughout the transportation procedure, the CP combination packaging box consistently maintained a higher temperature compared to the FP combination packaging box (Fig. 3 A1 and A2).

During the Yangling to Heilongjiang transportation route, the temperature in both types of combination packing boxes (CP and FP) decreased. Humidity changes in both packaging boxes initially increased and then stabilized. The CO₂ accumulation patterns in the two types of packaging boxes

differed significantly. In the CP combination packaging box, CO₂ accumulation fluctuated, initially declining consistently before rising. Conversely, in the FP combination packaging box, CO₂ accumulation slowly increased and then stabilized at around 15000 ppm until the end of transportation. There was a significant difference in CO₂ accumulation between the two packaging boxes during the early phases of transportation. The CO₂ levels in both packaging boxes only became similar towards the end of the transportation cycle. Throughout the transportation period, the FP combination packaging box consistently had higher CO₂ accumulation compared to the CP combination packaging box. Additionally, both temperature and humidity levels within the FP combination packaging box were consistently higher than those within the CP combination packaging box for the same duration of transportation (Fig. 3 B1 and B2).

On the transportation route from Yangling to Xinjiang, CO₂ accumulation in the CP combination packaging box initially increased, then progressively declined, reaching a maximum of 15439 ppm. In contrast, the CO₂ accumulation in the FP combination packaging box initially rose and then fluctuated within the range of 13000 ppm ~ 15000 ppm. Overall, CO₂ levels in the CP combination packaging box were lower than those in the FP combination packaging box, with an increase observed in the CP box towards the end of transportation. Humidity changes in both packaging boxes followed a similar pattern, first rising and then stabilizing. The maximum humidity levels were 88.0 % for the CP combination packaging box and 96.4 % for the FP combination packaging box, with the FP box consistently maintaining higher humidity. Temperature variations between the two packaging types also differed significantly. In the CP combination packaging box, the temperature initially dropped, then rose, and finally dropped again. Conversely, the FP combination packaging box exhibited an unstable vibration in temperature changes throughout the transportation process (Fig. 3 C1 and C2).

In conclusion, the FP combination packaging consistently maintained higher levels of CO₂ and humidity compared to the CP packaging across all transit routes, while the CP packaging exhibited a low temperature fluctuation range. Actually, under non-cold chain transportation conditions, most fluctuations in temperature and humidity within the packaging box result from changes in the external environment. However, other reason can be attributed to the greater vibration-induced mechanical damage sustained by apples in the CP packaging, causing increased CO₂ release and subsequently raising humidity within the packaging box (Zhang et al., 2020). Notably, compared to corrugated partition, EPS foam provides superior insulation, better maintaining humidity levels within the box.

Once the humidity in the box stabilizes, EPS foam slows down humidity fluctuations, reducing the fruit's transpiration rate and preserving apple quality (Reyt et al., 2021). The increased humidity in the FP combination packaging box may introduce additional moisture, which is beneficial for short-term preservation. Therefore, FP packaging is better suited for short-term transit, while the CP combination packaging, with its lower humidity levels, is more appropriate for long-distance transportation.

3.2 Mechanical damage after transportation

3.2.1 FDI, damage rate and damage region rate

Table 1 presents the impact of various packaging techniques on the mechanical damage of apples during express transportation. Significant differences were observed in the FDI, damage rate, and damage region rate between the various apple packages. Mechanical damage predominantly occurred in the fruit's belly region (See table 1). Apart from the Yangling to Xinjiang transportation route, the FDI and damage rate of the apples packed in the CP combination packing box were higher compared to those in the other two transportation routes. The shoulder, belly, and top regions of the apple fruit experienced damage, with the belly being the most severely affected. The transportation route from Yangling to Heilongjiang exhibited the highest damage rate and FDI for apples packaged in CP combination packaging boxes across all packaging types and routes (See table 1).

In conclusion, apples packaged in FP experienced less damage compared to those wrapped in CP. However, adding hand and ventilation holes to the carton may reduce its strength by 10 % – 40 % (Mukama et al., 2020). Fernando et al. (2020) assessed the damage resistance of bananas packaged in different boxes through simulated vibration tests. The authors found that one-piece corrugated boxes were more effective in minimizing banana damage from transit vibration compared to two-piece corrugated boxes. These results align closely with the findings presented in this present study. The fruit belly sustained the most damage, indicating that it was subjected to greater pressure and friction during transit. The top and shoulders of the fruit were also damaged, although to a lesser extent than the belly. This research suggests that specially designed supports could be considered in express transportation packaging to better protect the apple's more delicate areas and reduce the likelihood of damage. Although corrugated partitions play a significant role in minimizing mechanical damage, they are less elastic than soft foams (Chen et al., 2018). In another study by Dunno et al. (2021), the authors found that apple packaged in EPS trays had a 40 % lower risk of bruising.

3.2.2 Damage region in two types packaging box and microscopic damage morphology of apples

Figure 4A and 4B illustrate the damage patterns observed in different types of apple packaging during express transportation, with the overall positioning of damaged apples within the boxes. In CP combination packaging boxes, damaged apples were typically found near the inner walls or folding corners of the package. Specifically, the bottom apples in the CP combination packaging boxes exhibited damage primarily at the top and along the sides of the fruit. The damaged regions of the top layer apples in the CP combination packaging boxes were mainly the belly and top of the fruit. This suggests that the structure of the packaging box may be insufficient to protect apples from hard surfaces during transit, leading to repetitive impact or friction and potential damage. Also, the elevated position of the apple tops also makes them more susceptible to lateral impacts during transportation vibration, concentrating damage in the top and belly regions of the fruit. In contrast, damaged apples in the FP combination packaging boxes were typically located at the corners of the bottom box, opposite the edge of the EPS foam holder. The damaged region of the bottom layer apples in the FP combination packaging boxes was predominantly the fruit belly, while the top layer apples in the FP combination packaging boxes remained undamaged. The purpose of the EPS foam bracket was to reduce pressure and impact on the top layer, providing added protection during transit. Analysis of the damaged positions and regions of the apples in the packaging boxes indicated that compression and impact were the main causes of apple damage. Notably, the vibration transfer rates of EPS foam and corrugated cardboard differed significantly. It suggests that EPS foam may absorb and disperse energy from shocks or vibrations through deformation, thereby minimizing damage to the apples. According to Zhu et al. (2022), apple fruit stored at (5 ± 0.5) °C for 16 days could sustain compression damage from pressures exceeding 40 N.

Figure 4C and 4D present the comparison of tissue morphology of apples damaged during transportation and apples that were not transported. In non-transported apples, the tissue cells were uniformly sized and orderly arranged, with minimal cell rupture observed (Figure 4C). Transportation-induced mechanical damage significantly altered the apple tissue structure. Healthy cells exhibited greater structural integrity and resilience to external stress (Hussein et al., 2020). As shown in Figure 4D, transported damaged apples had obvious cell rupture, tissue collapse and fracture, suggesting that the structural integrity of apple cell walls was compromised by external forces, such as shock, compression, and vibration encountered during transport (Nikara et al., 2020). When subjected to external forces, the interaction between the fruit cell wall and internal hydrostatic pressure intensifies,

altering the cell arrangement within the fruit tissue and decreasing the mechanical strength of the fruit cell wall (Liu et al., 2023).

3.3 Alterations in apple storage quality

3.3.1 Skin color change

Table 2 shows the changes in color skins of the apple in both the damaged and control groups during storage. The L^* value, representing the brightness of the apple peel, consistently decreased with extended storage time, indicating a gradual darkening and greasiness of the apple surface (See table 2). This decline was statistically significant ($p < 0.05$) when comparing apples stored for 0 days to those stored for 12 days. Specifically, L^* value dropped by 7.19 in the damaged group and 13.58 in the control group, highlighting that apple in the damaged group had darker skins. The primary cause of browning in the fruit peel was a reaction triggered by mechanical damage during transit. When cells are disrupted due to mechanical injury, oxidative enzymes such as polyphenol oxidase (PPO) come into contact with polyphenols inside the cell, initiating oxidation processes that lead to the production of brown pigments (Sui et al., 2023). In the control group, the a^* value, which denotes the shift from green to red, increased over the storage period, signifying a gradual reddening of the apples. The findings demonstrated that the peel was gradually turning red and losing its green hue, consistent with the natural color change pattern observed during an apple's typical ripening phase. Conversely, in the damaged group, the a^* value decreased, indicating less red coloration. Significant differences in a^* values between the damaged and control groups were observed after 6, 9, and 12 days of storage ($p < 0.05$). Regarding the b^* value, which measures the blue to yellow shift, no significant differences were found between the two groups during most of the storage period, except for a notable difference on day 9 ($p < 0.05$) (Table 2). These findings are consistent with previous studies. Zhu et al. (2022) investigated the degree of compression damage of "Fuji" apple fruits under different storage conditions, with the compression ratio of 2 mm/s and under various compression forces (0, 40, 80, 160, 320 and 640 N). The results showed browning significantly increased with both storage time and compression force ($p < 0.05$) (Zhu et al., 2022).

Figure 5 shows the comparison of apple appearance during storage between the control group and the damaged group. Throughout the storage period, the surface wax of the apples in both control and damaged groups became greasy, leading to a decline in their brightness. As the storage time increased, the degree of apple browning in damaged group was higher than that of the control group. The results of this study further suggest that mechanically damaged apples are not suitable for storage, as

transportation damage accelerates the browning process. The mechanism of browning due to mechanical damage involves cell membrane rupture and oxidative stress. In line with the oxidation reaction mechanism, the mechanical stress experienced by the damaged apples during transportation compromised their cell membranes, increasing permeability. This allowed polyphenols to leak out and react with PPO to produce brown quinones. Additionally, mechanically damaged cells generate large amounts of free radicals, which intensify oxidative stress, accelerate cell membrane degradation, and ultimately speed up the browning process in apples (Wang et al., 2023).

3.3.2 Internal quality change of apple during storage

Figure 6 illustrates the quality changes in apples between the damaged group and the control group over different storage periods. As depicted in Fig. 6A, the mass loss rate for apples in both groups increased over time, with the damaged group exhibiting a significantly higher weight loss rate than the control group. Notably, except at 3 days, the mass loss rate of apples in the damaged group was consistently and significantly greater than that of the control group throughout the storage period ($p < 0.05$ or $p < 0.01$). After 12 days of storage, the mass loss for apples in control group and damaged group increased by 0.06 % and 0.22 %, respectively. Mechanical damage compromises the natural barrier provided by the apple skin, accelerating water loss, particularly in the later stages of storage. The findings are consistent with previous published research. According to Shu et al. (2022), the mass loss rate of ‘*Golden delicious*’ apple subjected to random vibration was 0.8 % higher than that of non-vibrated apples after 25 days of storage. Similar findings have been observed in other fruits, such as kiwifruit (Wei et al., 2019) and blueberries (Xu et al., 2021).

The firmness changes of apples in damaged group and control group at different storage times are shown in Fig. 6B. The firmness of the two groups of apples decreased with storage time. Compared with the control group, the firmness of apples in the damaged group decreased significantly at days 3, 6, and 9 of storage ($p < 0.05$). By the end of the 12-day storage period, the firmness of apples in the control group and the damaged group decreased to 0.95 MPa and 0.76 MPa, respectively. Apples in the damaged group lost firmness more rapidly than those in the control group over the storage period. Mechanical injury accelerates the degradation of pectin and cell wall structures, weakening intercellular adhesion and making the flesh of the apples more susceptible to softening. Additionally, this reduction in firmness stimulates pectin and cell wall breakdown, increasing the activity of intracellular enzymes such as polygalacturonase and cellulase, which can hasten the softening process in damaged fruit (Hua et al.,

2023). Shu et al. (2022) reported that after 25 days of storage, the hardness of "*Golden delicious*" apples subjected to vibration treatment was 19.25 % lower than that of the control group. Costa et al. (2021) observed that mangoes transported 529 km on a road with a vibration frequency of 40 Hz had a hardness reduction of 30 N compared to mangoes transported without vibration after 28 days of storage at 12 °C and 58 % RH. Lu et al. (2019) also found that vibration significantly accelerated the decline in apple fruit hardness, with longer vibration times resulting in lower fruit hardness.

Figure 6C depicts the changes in SSC in apples stored in the damaged and control groups at different storage periods. The SSC of apples in both groups increased with storage time. Compared to the control group, the SSC of apples in the damaged group showed a significant increase at day 0 of storage ($p < 0.05$). However, from the 3rd day of storage to the end of the storage period, there was no significant difference in SSC between the damaged group and the control group ($p > 0.05$). By the end of the 12-day storage period, the SSC of apples in the control group and the damaged group increased to 12.61 % and 13.44 %, respectively. Mechanical damage induces an increase in the respiration rate of fruit (Horvitz et al., 2021). This heightened metabolic activity accelerates the hydrolysis of polysaccharides into monosaccharides, leading to a slightly higher SSC in the damaged group compared to the control group (Walkowiak-Tomczak et al., 2021). These findings imply that early sugar accumulation in apples may be impacted by mechanical damage, which is unfavorable for apple preservation.

4 Conclusion

This study investigated on the protection ability of two commonly packaging methods to apples during express transportation, revealing significant differences in the effectiveness of CP (corrugated partition) and FP (foam holder) combination packaging boxes in preserving fruit integrity. CP packaging was associated with substantial fluctuations in transportation load, with packaged apples on the Yangling-to-Heilongjiang route exhibiting a FDI of 1.18 % and a mechanical damage rate of 63.64 %, primarily affecting the fruit belly. Conversely, the FP combination packaging boxes demonstrated an environment with CO₂ accumulation, attributed to the limited ventilation in foam structures. Despite this, mechanical damage in FP-packaged apples was localized at specific contact points, such as the corners opposite the EPS foam holder. Overall, FP combination packaging provided superior shock absorption and stability, minimizing vibration-induced mechanical damage to apples, particularly under high-frequency vibrations. Fruit damage was associated with observable tissue collapse, increased

browning, and significant changes in key quality parameters: mass loss increased by 0.16 %, soluble solids content (SSC) rose by 0.83 %, and firmness decreased by 0.19 MPa compared to undamaged apples. The findings indicated that CP combination packaging box, with its split structure, may be unsuitable for maintaining apple quality during express transport, as it provides inadequate protection against mechanical stress. Additionally, these findings highlight the potential value of integrating smart sensors within packaging to dynamically monitor internal conditions, as well as the importance of developing innovative packaging designs and materials that more effectively mitigate transit-induced stresses. Future research could build on these findings by refining packaging design to balance rigidity and cushioning, thereby enhancing protection against transit vibrations.

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CRedit authorship contribution statement

Jincheng Yu: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing - original draft. **Hongli Qiang:** Conceptualization, Investigation, Writing - original draft. **Mingwei Shi:** Methodology, Writing - original draft. **Zhiguo Li:** Conceptualization, Project administration, Resources, Supervision, Writing - review & editing. **Tobi Fadiji:** Supervision, Writing - review & editing. **Ali Abas Wani:** Writing - review & editing. **Clément Burgeon:** Writing - review & editing.

Declaration of Competing 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.

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Figures and Tables

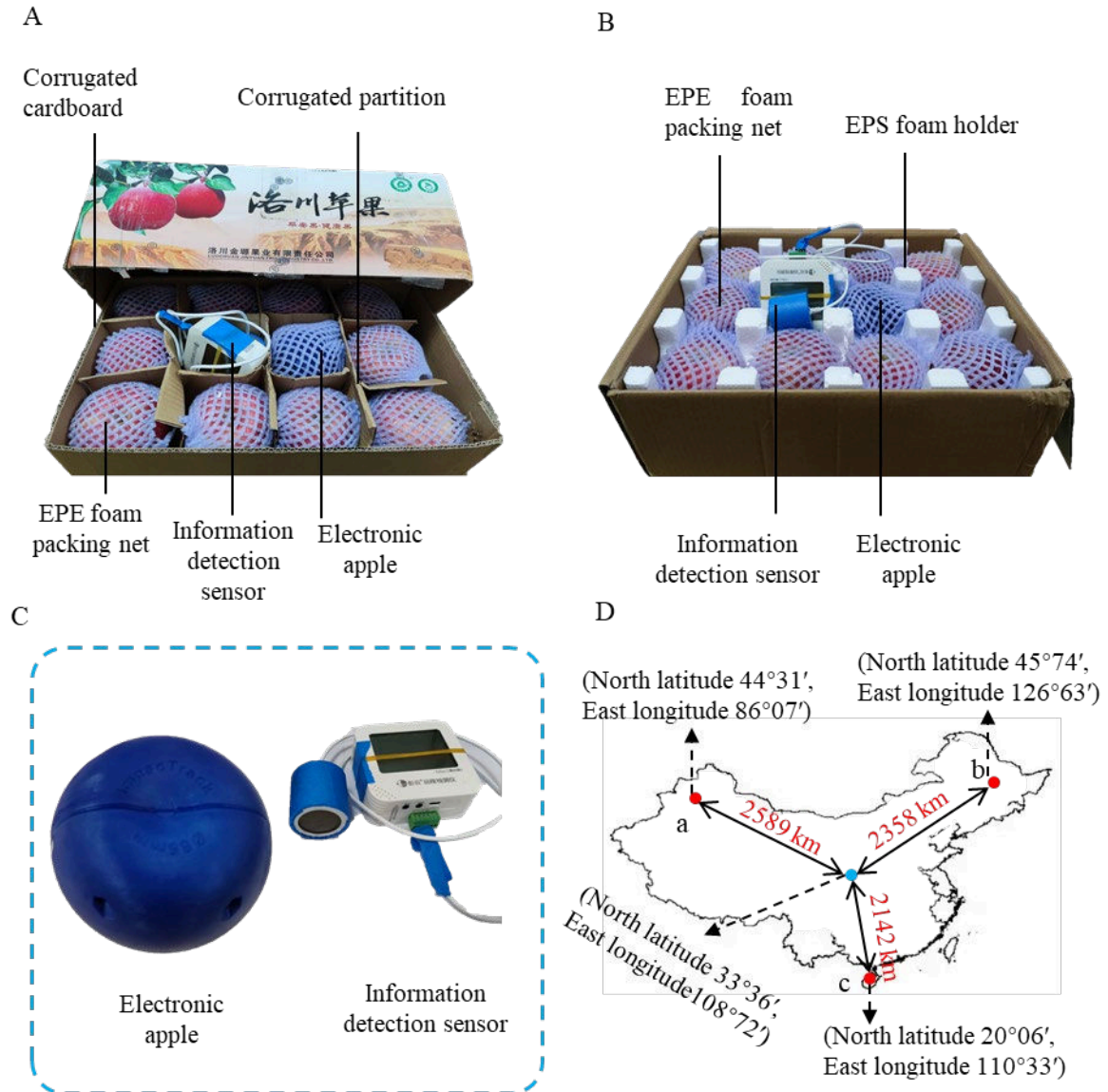


Fig. 1 Two common forms of apple transportation packaging boxes available on the market and the devices used in the transportation process and the transportation destination. (A): Apple packaged in a corrugated partition-based cardboard box (CP combination packaging box); (B): Apple packaged in a foam partition-based cardboard box (FP combination packaging box); (C): Electronic apple and information sensor used during transportation; (D): Yangling → three different regions categorized by distance and the regions' longitude and latitude (a: Xinjiang; b: Heilongjiang; c: Hainan).

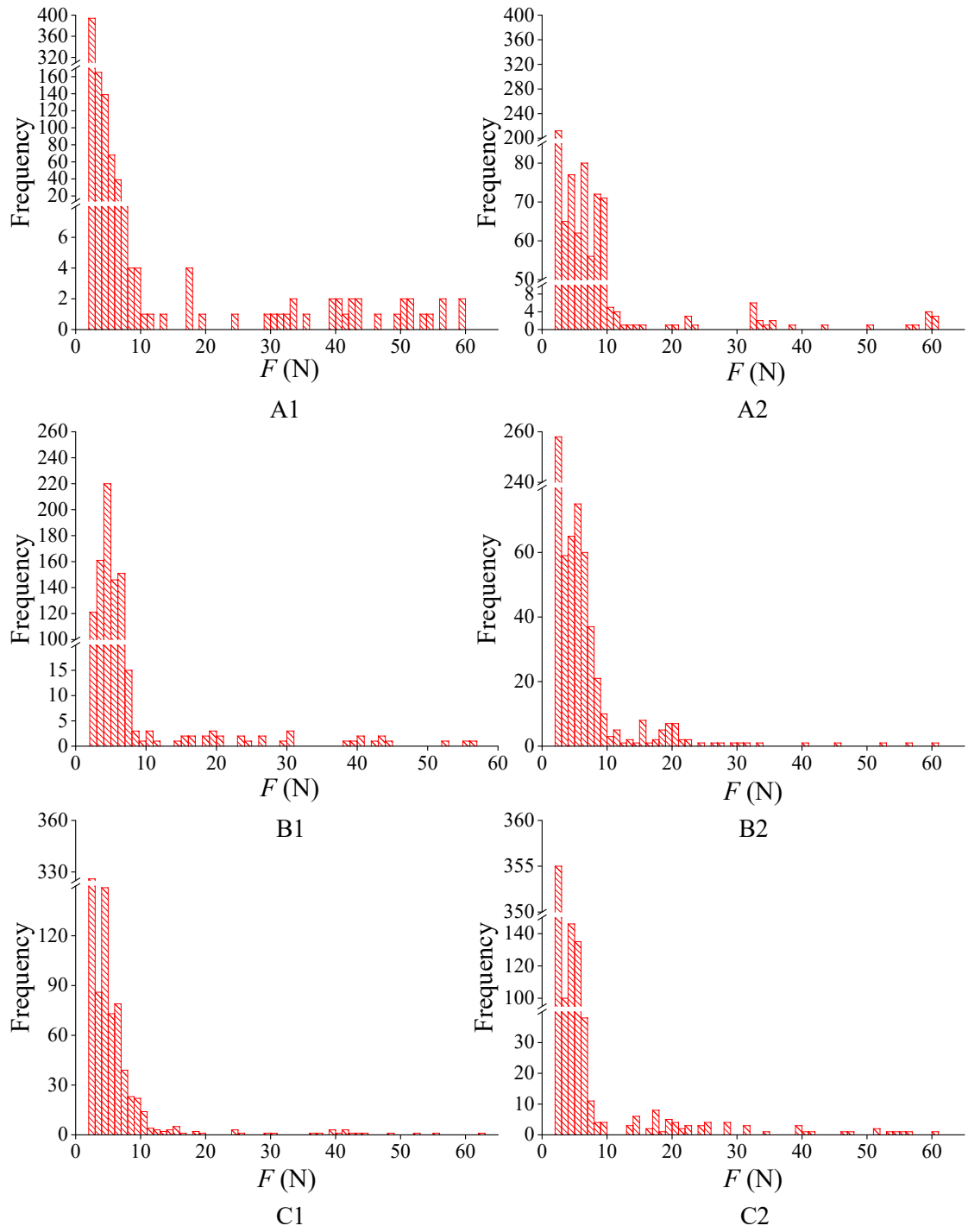


Fig. 2 Distribution of apple load during express transportation. (A1): Yangling $\rightarrow$ Hainan $\rightarrow$ Yangling - CP combination packaging box; (A2): Yangling $\rightarrow$ Hainan $\rightarrow$ Yangling - FP combination packaging box; (B1): Yangling $\rightarrow$ Heilongjiang $\rightarrow$ CP combination packaging box; (B2): Yangling $\rightarrow$ Heilongjiang $\rightarrow$ Yangling - FP combination packaging box; (C1): Yangling $\rightarrow$ Xinjiang $\rightarrow$ Yangling - CP combination packaging box; (C2): Yangling $\rightarrow$ Xinjiang $\rightarrow$ Yangling - FP combination packaging box.

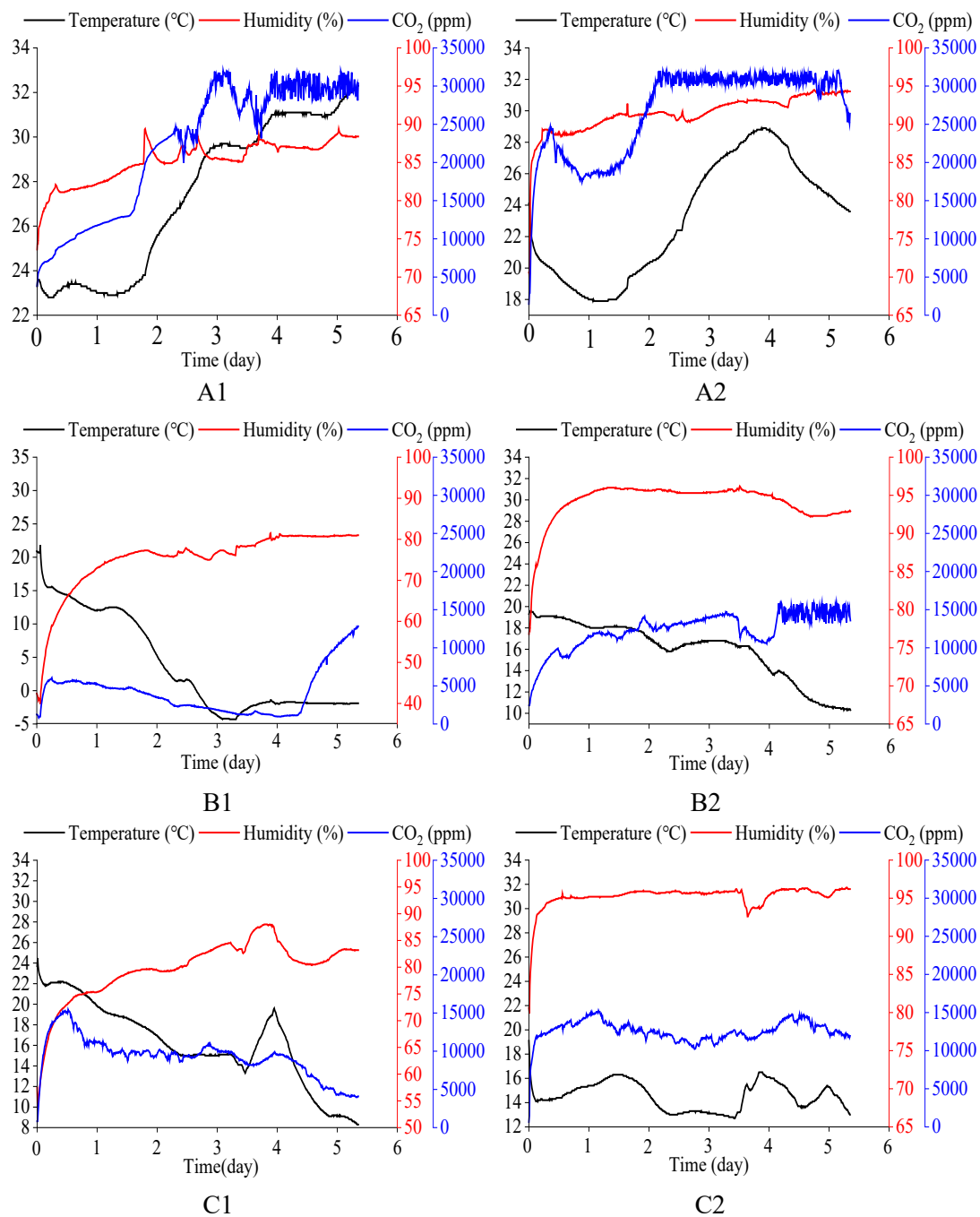


Fig. 3 Changes in the microenvironment within the combination packaging box during transportation.

(A1) Yangling → Hainan → Yangling - CP combination packaging box; (A2): Yangling → Hainan → Yangling - FP combination packaging box; (B1): Yangling → Heilongjiang → CP combination packaging box; (B2): Yangling → Heilongjiang → Yangling - FP combination packaging box; (C1): Yangling → Xinjiang → Yangling - CP combination packaging box; (C2): Yangling → Xinjiang → Yangling - FP combination packaging box.

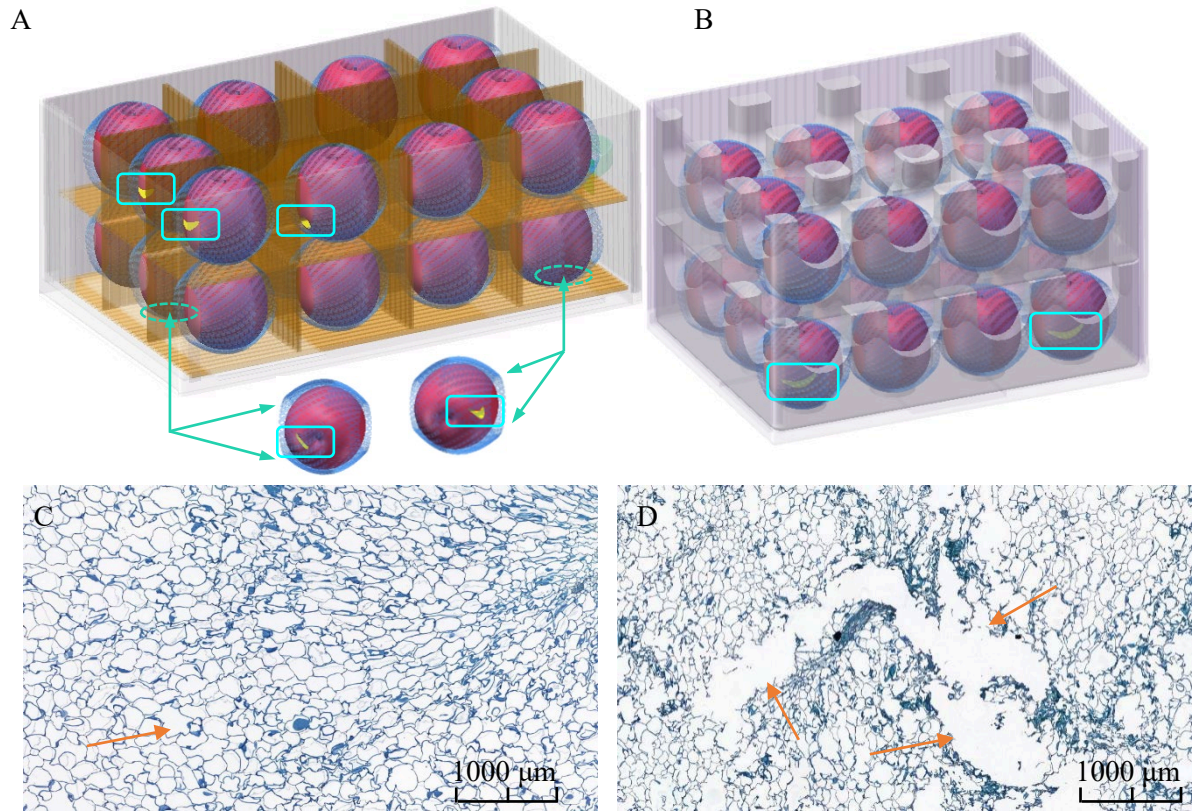


Fig. 4 Position and microstructure of apple damage. (AB): The damaged position of the apple in two different packing cases, A: CP cardboard box, B: FP cardboard box; (CD): Comparing the microstructure of damaged and undamaged apple tissues, C: undamaged apple tissue, D: damaged apple's tissue.

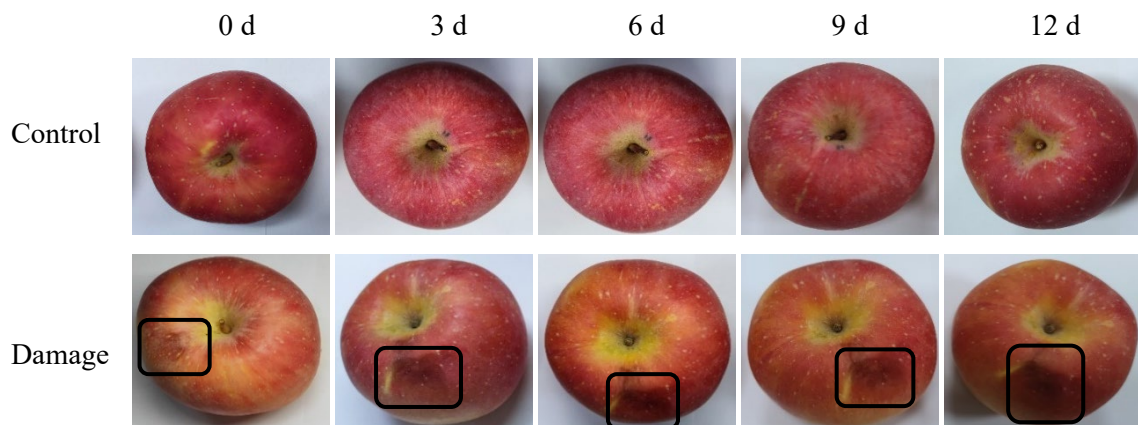


Fig. 5 Comparing the surface of damaged and undamaged apples.

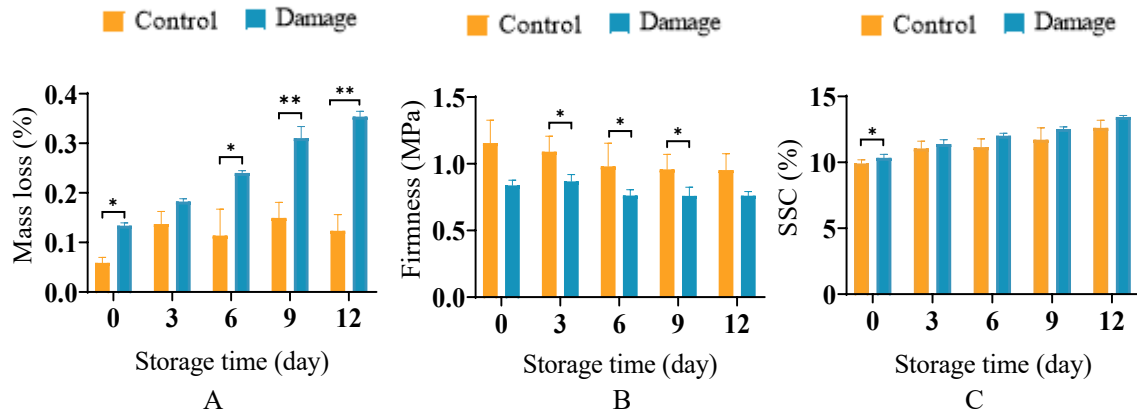


Fig. 6 Quality changes of damaged and control group apples during storage. Asterisks denote statistical significance of the differences (* = $p < 0.05$, ** = $p < 0.01$).

Table 1 Impact of various packing techniques on apple mechanical damage.

Group	YL-HN-CP	YL-HN-FP	YL-HLJ-CP	YL-HLJ-FP	YL-XJ-CP	YL-XJ-FP
<i>FDI</i>	0.18	0.14	1.18	0.09	0.09	0.14
Damage rate (%)	18.18	13.64	63.64	9.09	9.09	13.64
Damage region	Fruit shoulder	Fruit belly	Fruit belly	Fruit belly	Fruit shoulder	Fruit belly
rate (%)	(25%), Fruit top (75%)	(33.3%), Fruit shoulder (66.6%)	(85.7%), Fruit shoulder (14.3%)	(100%)	(50%), Fruit belly (50%)	(100%)

Note: YL-HN-CP: Yangling → Hainan → Yangling - CP combination packaging box; YL-HN-FP: Yangling → Hainan → Yangling - FP combination packaging box; YL-HLJ-CP: Yangling → Heilongjiang → Yangling - CP combination packaging box; YL-HLJ-FP: Yangling → Heilongjiang → Yangling - FP combination packaging box; YL-XJ-CP: Yangling → Xinjiang → Yangling - CP combination packaging box; YL-XJ-FP: Yangling → Xinjiang → Yangling - FP combination packaging box.

Table 2 Comparison of skin color between damaged and undamaged apples.

Group	Storage time (day)	L^*	a^*	b^*
Control	0	59.83 ± 4.95	23.14 ± 8.21	14.77 ± 5.55
Damage	0	43.95 ± 4.12^a	26.34 ± 10.13	12.47 ± 3.48
Control	3	57.06 ± 5.33	30.24 ± 7.28	11.30 ± 3.97
Damage	3	40.09 ± 2.49^a	26.52 ± 10.08	12.95 ± 4.65
Control	6	52.52 ± 3.73	25.16 ± 7.27	15.32 ± 5.51
Damage	6	36.93 ± 3.72^a	17.45 ± 7.35^a	15.02 ± 4.69
Control	9	51.30 ± 2.26	27.48 ± 4.00	12.27 ± 3.20
Damage	9	34.50 ± 3.60^a	20.85 ± 8.98^a	17.23 ± 3.90^a
Control	12	52.64 ± 4.04	28.18 ± 4.18	11.57 ± 3.92
Damage	12	30.37 ± 4.12^a	13.13 ± 6.37^a	12.69 ± 4.25

Note: L^* represents lightness, a^* represents greenness-redness and b^* blueness-yellowness; Lowercase letters indicate significant differences ($p < 0.05$).



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