



Article

Packaging Design to Protect Hongmeiren Orange Fruit from Mechanical Damage during Simulated and Road Transportation

Dandan Zheng ^{1,2,3,†}, Jiahui Chen ^{1,2,3,†}, Menghua Lin ^{1,2,3}, Da Wang ⁴, Qiong Lin ^{5,6}, Jingping Cao ^{1,2,3}, Xiangzheng Yang ⁴, Yuquan Duan ^{5,6}, Xianming Ye ⁷, Chongde Sun ^{1,2,3}, Di Wu ^{1,2,3,*}, Jun Wang ⁸ and Kunsong Chen ^{1,2,3}

- ¹ College of Agriculture & Biotechnology, Zijingang Campus, Zhejiang University, Hangzhou 310058, China; 22016153@zju.edu.cn (D.Z.); 21816131@zju.edu.cn (J.C.); 21616066@zju.edu.cn (M.L.); 0017165@zju.edu.cn (J.C.); adesun2006@zju.edu.cn (C.S.); akun@zju.edu.cn (K.C.)
- ² Zhejiang Provincial Key Laboratory of Horticultural Plant Integrative Biology, Zijingang Campus, Zhejiang University, Hangzhou 310058, China
- ³ The State Agriculture Ministry Laboratory of Horticultural Plant Growth, Development and Quality Improvement, Zijingang Campus, Zhejiang University, Hangzhou 310058, China
- ⁴ Jinan Fruit Research Institute, All China Federation of Supply and Marketing Cooperatives, Jinan 250200, China; wangda19910@163.com (D.W.); yangxiangzheng318@163.com (X.Y.)
- ⁵ Key Laboratory of Agro-Products Quality and Safety Control in Storage and Transport Process, Ministry of Agriculture and Rural Affairs, Beijing 100193, China; linqiong@caas.cn (Q.L.); duanyuquan@caas.cn (Y.D.)
- ⁶ Institute of Food Science and Technology, Chinese Academy of Agricultural Sciences, Beijing 100193, China
- ⁷ Zhejiang Jianong Fruit & Vegetable Co., Ltd., Quzhou 324000, China; zhgx219@163.com
- ⁸ Jiangsu Key Laboratory of Advanced Food Manufacturing Equipment and Technology, Department of Packaging Engineering, Jiangnan University, Wuxi 214122, China; wangj_1982@jiangnan.edu.cn
- * Correspondence: di_wu@zju.edu.cn; Tel.: +86-571-88982226
- † These authors contributed equally to this work.



Citation: Zheng, D.; Chen, J.; Lin, M.; Wang, D.; Lin, Q.; Cao, J.; Yang, X.; Duan, Y.; Ye, X.; Sun, C.; et al. Packaging Design to Protect Hongmeiren Orange Fruit from Mechanical Damage during Simulated and Road Transportation. *Horticulturae* **2022**, *8*, 258. <https://doi.org/10.3390/horticulturae8030258>

Academic Editors: Tianbao Yang and Jorge M. Fonseca

Received: 14 February 2022

Accepted: 15 March 2022

Published: 17 March 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Abstract: Hongmeiren is a high-quality orange fruit but susceptible to mechanical damage. This work proposes a new packaging format (Packaging C), which used the plastic partition boards to separate the folding plastic basket to avoid the fruits from crushing each other, and used a PU foam layer and placed it along the inside of the EPE foam layer to meet the different sizes of fruits. The results show that under both 3 and 10 h of simulated transportation, Packaging C achieved a much lower damage and decay rates than Packaging A (plastic bulk containers), and this was further verified by the road transportation. Besides, Packaging C could avoid dents in the peel of some large fruits compared to the gift packaging (Packaging B). Although the use of inner packaging could increase the use of packaging, it can reduce the waste of cultivation and transportation resources caused by not being able to deliver the fruit to the consumer, as well as environmental pollution caused by fruit decay. Moreover, low temperature (10 °C) and high humidity (90% RH) during transportation could further reduce the damage and packages at the rear position obtained a higher damage rate than at the front position, but no obvious difference was found between stack heights.

Keywords: citrus; mechanical damage; transportation; packaging; temperature

1. Introduction

Fruit is an important part of people's daily diet. During the postharvest supply chain, fruit products are subject to severe losses. Between 45% and 55% of fruits and vegetables worldwide are lost or wasted in the supply chains [1]. Compression, vibration, and impact are the most common forces causing mechanical damage to postharvest fruit [2–4]. The damaged fruit usually has an appearance that is unattractive to consumers. The damage can also cause an increased rate of respiration and make fruit more susceptible to disease, resulting in more rapid ripening and the acceleration of decay and the deterioration of fruit [5,6]. Therefore, reducing the mechanical damage of fruit during transit in supply chains is an important task.

Hongmeiren ('Ehime Kashi No. 28') is a high-quality early-maturing citrus cultivar originating from Japan [7]. It was bred from hybrid seedlings by crossing the 'Nankou' and 'Amakusa' varieties [7]. Nankou was originally produced in Kuchinotsu, Nagasaki, from a hybrid seedling of "Miho-wase" (Citrus unshiu Marc.) × "Clementine" (C. clementina hort. ex Tanaka), and "Amakusa" was produced from "(Kiyomi × Okitsu wase)—No. 14", an early maturing citrus type strain and "Page" were produced by crossing [8,9]. Hongmeiren citrus has been widely cultivated in China in recent years. Its pericarp is very thin and moderately smooth, it is dark-orange, the puffing is rare, and peeling is moderately difficult [7]. Hongmeiren orange fruit is of a superior quality with a sugar content of usually more than 13 °Brix and a citric acid content of approximately 1.1% [7]. Nevertheless, Hongmeiren orange fruit is more susceptible to mechanical damage when compared with many other citrus cultivars. There is a lack of research on packaging methods that protect citrus cultivars susceptible to mechanical damage during transportation currently.

Packaging is a common and efficient method to protect produce and reduce losses during supply chains [10–15]. Some studies have investigated the protection of packaging for horticultural products against mechanical damage [16,17]. Barchi et al. [18] studied the damage of loquats under simulated transportation using vibration parameters obtained in real transportation and found that the damage could be reduced by using a liner. Chonhenchob and Singh [19] carried out a vibration test of papaya fruit packed in a variety of packaging containers and found that the RPC-US-A (Solo, Foam net) had better protection than five other packaging types. Zhou et al. [20] demonstrated that foam-net packages reduced the vibration levels of pears more effectively than paper-wrap packages. Fadiji et al. [21] assessed the susceptibility of apples in two ventilated corrugated paperboard packages with different sizes based on simulated transportation and found that apples inside the MK4 package with a higher length-to-height ratio had less damage. Chonhenchob et al. [22] compared reusable and single-use plastic and paper shipping containers for the transportation of fresh pineapples and found that corrugated containers obtained the best protective performance. The above studies show that the beneficial effects of packaging to reduce fruit losses cannot be ignored.

The susceptibility of fruit to mechanical damage could be influenced by temperature, humidity, distance and vibration frequency during transportation. Our previous work shows that ripe peaches which vibrated at 10 °C suffered less damage than those vibrated at 20 °C and 30 °C, indicating that lower temperatures during transport would reduce the susceptibility of ripe peaches to mechanical damage [23]. For humidity, to the best of our knowledge, there are few studies on the effect of transportation humidity on the levels of mechanical damage when mechanical forces act upon the fruit. Previous research has mainly been about the effect of humidity on fruit decay during storage after the occurrence of mechanical damage, rather than the effect of humidity on fruit decay during transportation.

The level of mechanical damage is also affected by transportation distance. The transportation distances of fruit after harvest are usually different according to the locations of orchards and sales areas. Short-distance transportation usually causes less damage in fruit, so internal packaging is not used in many cases in order to reduce transportation cost and environmental pollution. For fruit that is susceptible to mechanical damage and requires long-distance transportation, reasonable packaging and protection methods must be considered in order to reduce fruit damage and avoid losses of economic value. Especially for countries like China, where fruit transportation often exceeds hundreds or thousands of kilometers, it is even more necessary to study the methods of protecting Hongmeiren orange fruit.

Mechanical damage to fruit, caused during transportation from the orchard gate to the supermarket, can significantly increase the decay rate during storage and reduce consumers' intention to purchase that fruit in the future. Therefore, in this study, besides determining the damage rate after transportation, the decay rate during storage was also determined.

The aim of this work is to investigate the susceptibility to mechanical damage of Hongmeiren orange fruit during simulated and road transportation. Three packaging formats were evaluated through both vibration transmissibility analysis and transportation experiments to determine the best method of transporting Hongmeiren orange fruit. The effects of transportation temperature, humidity, distance, and stack position and the height for a lorry on causing mechanical damage to fruit were studied. The results of this study will contribute to provide suitable packaging methods and transportation conditions for perishable orange fruit like Hongmeiren, thus reducing the mechanical damage to fruits during transportation, expanding the sales range, extending the shelf life, and increasing the commercial value.

2. Materials and Methods

2.1. Packaging Formats

2.1.1. Format of Packaging A

Packaging A (Figure 1a) is a reusable plastic container (RPC) used for transporting fruit in bulk, and is commonly used in the bulk wholesale of citrus in China. The dimensions (length $\times$ width $\times$ height) of Packaging A were $445 \times 320 \times 160$ mm. Around 50 Hongmeiren orange fruits could be stored in Packaging A. Therefore, the cargo density (the number of fruit per unit volume) of Packaging A was about 2195 fruits/m^3 ($50 \text{ fruits}/(445 \times 320 \times 160 \text{ mm})$).



Figure 1. Three packaging formats for protecting Hongmeiren orange fruit during simulated and road transportation: (a) Reusable plastic containers (RPCs) for transportation of fruit in bulk (Packaging A). (b) Paper box with expandable polyethylene (EPE) as the internal packaging (Packaging B). (c) Self-designed packaging (Packaging C).

2.1.2. Format of Packaging B

Packaging B (Figure 1b) is a cardboard box with an expandable polyethylene (EPE) inside, and is commonly used as gift packaging for transporting Hongmeiren orange fruit in practice. The dimensions of Packaging B were $385 \times 285 \times 100$ mm. Packaging B could store 12 Hongmeiren orange fruits. The cargo density of Packaging B was 1094 fruits/m^3 .

2.1.3. Format of Packaging C

Packaging C (Figure 1c) was specially designed for packaging Hongmeiren orange fruit in this work. As shown in Figure 2, it was composed of a folding plastic basket (type: SHG-604022F, external dimensions: $600 \times 400 \times 220$ mm, internal dimensions: $570 \times 370 \times 210$ mm, texture: high density polyethylene, weight: 1.55 kg, capacity: 40 L, load-bearing: 25 kg, heights after folding were 43 mm), a hard polypropylene (PP) board with a thickness of 4 mm, 16 hard plastic partition boards, and EPE and polyurethane (PU) foam. The folding plastic basket was divided into upper and lower layers by the hard PP board (Figure 2c). Each layer was separated into 24 units by the hard plastic partition boards (Figure 2a,e), resulting in 48 units in one Packaging C box. The bottom of each layer was covered by an EPE ($570 \times 370 \times 10$ mm) foam covering the whole layer area (Figure 2a,d). An EPE ($275 \times 80 \times 5$ mm) foam layer was placed along the inside of the wall of each unit, and a PU ($270 \times 80 \times 10$ mm) foam layer was placed along the inside of the EPE foam layer (Figure 2b). One citrus fruit, tightly wrapped by the PU foam layer, was placed in one unit (Figure 2f). The reason for using the plastic partition boards to

separate the folding plastic basket rather than directly using the EPE and PU foam layers to wrap fruit was that the EPE and PU foam layers were soft, and their direct use could not fix the fruit in the basket and would cause impact and compression damages. A total of 48 fruits were packaged in one Packaging C box. The cargo density of Packaging C was 1084 fruits/m³. It can be seen that the cargo density of Packaging B and C was similar, and that of Packaging A was about twice those of Packaging B and C.

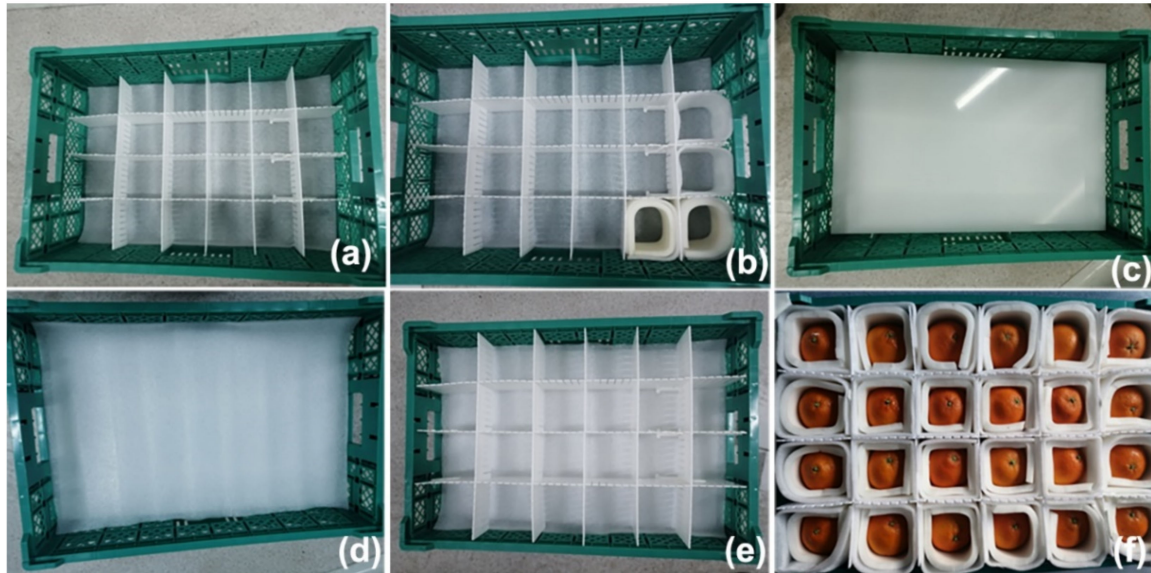


Figure 2. Structure of Packaging C: (a) The bottom of the lower layer was covered by an EPE foam board covering the whole layer area, and the lower layer was separated into 24 units by hard plastic partition boards. (b) An EPE foam layer was placed along the inside of the wall of each unit, and a polyurethane (PU) foam layer was placed along the inside of the EPE foam layer. (c) A hard polypropylene (PP) board was used to divide the folding plastic basket into upper and lower layers. (d) The bottom of the upper layer, which was the hard PP board, was covered by another EPE foam board. (e) The upper layer was separated into 24 units by hard plastic partition boards. (f) One unit had one citrus fruit, tightly wrapped by the PU foam layer, resulting in 24 fruits in one layer.

2.2. Transportation Experiment

The transportation experiment had two phases, simulated and road transportation. The simulated transportation compared the protective effect of three packaging formats based on two transportation times of 3 and 10 h in the laboratory and studied the influence of temperature and humidity on the mechanical damage of fruit packaged by Packaging C during transportation. Road transportation tests were further carried out to verify if Packaging C could provide vibration damping in actual transportation. The influence of stack position and height on a lorry during transportation was also studied in the road transportation tests. However, there are many routes to transport Hongmeiren orange fruit produced in Zhejiang Province to various regions of China. If all of them were tested for actual transportation, there would be high experimental costs. Therefore, two classical routes were chosen for this study. One is from Hangzhou, Zhejiang Province to Jinan, Shandong Province (890 km) using a heavy semi-trailer truck in a smooth autobahn and the other one from Quzhou, Zhejiang Province to Beijing (1500 km) using a lorry in a smooth autobahn. Beijing and Jinan are two major cities in China; therefore, the experimental design of these two road transportation routes was representative. Moreover, another transportation route test was carried out from Quzhou, Zhejiang Province to Beijing (1500 km) using a truck in a smooth autobahn, and the acceleration of the vehicle for this route was measured to evaluate whether it was similar to that of the simulated transportation.

2.2.1. Simulated Transportation

A vibration test system TH-600 (Suzhou Sushu Testing Instrument Co., Ltd., Suzhou, China) was used. It was mainly composed of an electro-dynamic shaker, an amplifier, a data acquisition system, a control system, several acceleration sensors, and an environmental cabinet for temperature-humidity control. The environmental cabinet gives the test system the capability of simulating road transportation under different temperature and humidity conditions, which is important to study fruit packaging during supply chains. Since the road spectra are different in the actual road transportation for Hongmeiren orange fruit in China, a typical road spectrum was chosen to conduct the simulation transportation. The composite truck spectrum described in ASTM D4169-16 Assurance Level II was used [24]. The overall root-mean-square acceleration (Grms) of the vibration test was 0.52 G. Table 1 shows the experimental design of the simulated transportation.

Table 1. Experimental design of simulated transportation.

Section Materials and Methods	Results	Packaging Format	Temperature (°C)	Humidity (% RH)	Time (h)
Section 2.2.1	Section 3.2.1	Packaging A, B, C	20	90	3
Section 2.2.1	Section 3.2.2	Packaging A, B, C	20	90	10
Section 2.2.1	Section 3.3.1	Packaging C	10 and 20	90	3 and 10
Section 2.2.1	Section 3.3.2	Packaging C	20	70 and 90	3 and 10

To evaluate the protective performance of three packaging formats against mechanical damage based on different transportation distances, the simulated transportation test was carried out in triplicate at 20 °C and 90% RH for 3 and 10 h (Table 1, first two rows). There were three replicates per treatment. Specifically, there were three RPCs for Packaging A, and each RPC had 50 fruits, each replicate had 50 fruits from one RPC; Packaging B had 12 paper boxes, each box had 12 fruits, and each replicate had 48 fruits from four boxes; Packaging C had three baskets, each basket had 48 fruits, and each replicate had 48 fruits from one basket.

The capability of Packaging C to protect Hongmeiren orange fruit against mechanical damage was further analyzed under different transportation temperatures and humidity conditions. Specifically, to study the effect of transportation temperature on mechanical damage, the performances of Packaging C under the simulated transportation at two temperatures (10 and 20 °C) and 90% RH for both 3 and 10 h were evaluated (Table 1, the 3rd row). Besides this, to evaluate the effect of humidity on the mechanical damage, two humidity levels of 70 and 90% RH were compared when the simulated transportation was carried out at 20 °C for 3 and 10 h (Table 1, the 4th row). There were three replicates per treatment with 48 fruits per replicate for both temperature and humidity analyses.

2.2.2. Road Transportation

Interprovincial supply chains in China often exceed hundreds, or even thousands of kilometers, and the long-distance transportation of Hongmeiren orange fruit is more likely to increase the risk of mechanical damage. Therefore, three road routes over 800 km were chosen for the study of road transportation. Specifically, to further evaluate the protection capacity of Packaging C on Hongmeiren orange fruits, a road transportation (Road Test A) was carried out in December 2018 (Table 2, the 1st row). Three baskets of Packaging C were transported for 13 h (890 km) from Hangzhou, Zhejiang Province to Jinan, Shandong Province by a heavy semi-trailer truck. Three RPCs of Packaging A were also transported as the control group. The truck (actros 3344, manufactured by Mercedes-Benz Corporation, Stuttgart, Germany) had a 32-ton payload capacity and 24 wheels.

Table 2. Experimental design of road transportation.

Section Materials and Methods	Results	Transportation	Packaging Format	Time (h)	Distance (km)
Section 2.2.2	Section 3.4.1	Road Test A	Packaging A and C	13	890
Section 2.2.2	Section 3.4.2	Road Test B	Packaging C	30	1500

Besides, to compare the performances of different stack positions and heights on the carriage of a lorry against the mechanical damage to the fruit protected by Packaging C, another road transportation test was conducted from Quzhou, Zhejiang Province to Beijing for 30 h (1500 km) in December 2019 (Road Test B) (Table 2, the 2nd row). The lorry (J6P-CA4180, manufactured by China First Automobile Workshop Group Corporation, Changchun, China) had a 16-ton payload capacity and 10 wheels. As shown in Figure 3a, three boxes of Hongmeiren orange fruit were placed on one tier, and the first, third, and fifth tiers at the front, middle, and rear positions on the lorry were evaluated, resulting in a total of 27 boxes. The second and fourth tiers were *Citrus reticulata* Blanco cv. Ponkan (Figure 3b). In addition to the packaging used in this study, the rest of the compartment was loaded with boxes filled with Ponkan. All the packages in the carriage will not be displaced due to truck transportation. After being transported to Beijing, Hongmeiren orange fruit was stored at 10 °C for the subsequent determination of the decay rate.

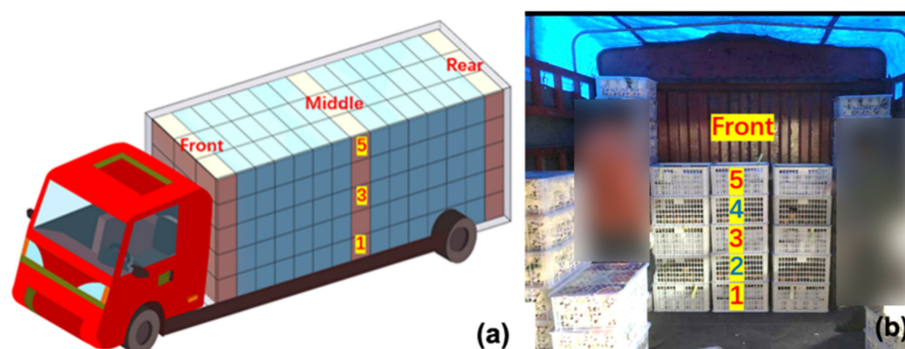


Figure 3. Placement of boxes containing Hongmeiren orange fruit in a lorry: (a) Placement of the boxes in the front, middle, and rear of the lorry. (b) Placement of the first, third and fifth tiers of the boxes in the front of the lorry. The second and fourth tiers were *Citrus reticulata* Blanco cv. Ponkan.

Moreover, to verify whether the composite truck spectrum used in the simulated transportation could be used to simulate the Hongmeiren orange fruit transport on actual roads, the acceleration of the vehicle was measured in an acceleration acquisition experiment (Road Test C) from Quzhou, Zhejiang Province to Beijing for a total of 29.5 h in December 2020. A portable acceleration recorder (ZDW-BX, Hangzhou ZEDA Instruments Co., Ltd., Hangzhou, China) with real-time data recording capabilities was used (Figure 4a) to collect the acceleration levels. The recorder was fixed to the fruit box during transport (Figure 4b). At the end of the transport, the data from the acceleration recorder was exported for data processing.



Figure 4. Truck acceleration collection test: (a) Accelerometer. (b) The position of the accelerometer in the truck.

2.3. Fruit Supply

For simulated transportation and Road Test A, Hongmeiren orange fruit at commercial maturity was picked manually at an orchard in Xiangshan, Zhejiang Province on 8 December 2018, and was transported to the laboratory in Hangzhou, on the same day of harvest. The transportation duration from the orchard and the laboratory was about 3 h. Once arrived, Hongmeiren orange fruit, uniform in maturity and color and free from mechanical damage or disease, was selected for the simulated transportation and Road Test A. For Road Test B, Hongmeiren orange fruit (Ehime Kashi No. 28) at commercial maturity was picked manually at an orchard in Quzhou, Zhejiang Province, China on 2 December 2019, and was transported on the same day of harvest to Beijing.

2.4. Damage Rate and Decay Rate Statistics

The damage rates of fruits were determined after the experiments of both simulated and road transportation. Damaged fruit was defined as not available for sale at retail, which included both cracked fruit and bruised fruit. The damage rate was calculated by dividing the total number of fruits by the sum of the number of cracked fruits and the number of bruised fruits. After transportation, the fruits were stored in a cold storage at 10 °C and 90% RH, and the number of decayed fruits was counted during storage at 1, 3, 6, 9, and 12 w. The decay rate was calculated by dividing the total number of fruits by the number of decayed fruits.

2.5. Vibration Transmissibility

The vibration test system TH-600 was used to examine the vibration transmissibility of three packaging formats in the simulated transportation. The package to be tested was placed on an electro-dynamic shaker. One acceleration sensor was attached to the underside of the shaker with a specific double-sided tape (Tesa 4965). Another acceleration sensor was attached to the flat surface of one fruit (the sensor plane was parallel to the vibration table). The test was performed using the sweep method, and the acceleration was set to 0.5 g and allowed to scan from 3 to 100 Hz [25]. The rate of scanning frequency was pre-set to 3.5 Octave for each minute. The scanning was repeated five times. The vibration transmissibility was calculated using the following equation [21,25]:

$$Tr = ab/at \times 100\%$$

where Tr was vibration transmissibility (%), ab was the response acceleration (g) of the product, and at was the excitation acceleration (g) of the shaker. The vibration transmissibility-

frequency curve was drawn by taking the frequency of the shaker as the abscissa and the vibration transmissibility formed during the experiment as the ordinate.

2.6. Software and Statistical Analyses

Figures were generated using PowerPoint 2019 (Microsoft Corporation, Redmond, WA, USA), AutoCAD 2018 (Autodesk Inc., San Rafael, CA, USA), and Origin 2018 (Origin-Lab Corporation., Northampton, MA, USA). Analyses of data were carried out by one-way ANOVA in SPSS 17.0 (SPSS Inc., Chicago, IL, USA). Difference significance among treatments was analyzed by Duncan's multiple range test. The letters "a", "b", and "c" in the Figures indicate statistically significant differences ($p < 0.05$).

3. Results

3.1. Vibration Transmissibility and Response Acceleration

Vibration transmissibility is used to describe the vibration response of packaged products caused by the transportation vehicle. It refers to the ratio of the external force of vibration transmitted to the product in the package through the buffer system to the external force of vibration. The force transferred to the product in the package is one of the main factors leading to the mechanical damage of the fruit. As shown in Figure 5, Packaging C had the lowest maximum transmissibility, whereas Packaging A had the highest maximum transmissibility. In the range of 3–28.69 Hz, the transmissibility of Packaging C was always lower than those of Packaging B and Packaging A. In the range of 28.69–30.56 Hz, the transmissibility of Packaging C was between Packaging A and Packaging B. In the high frequency range of 30.56–100 Hz, the transmissibility of Packaging B was the lowest.

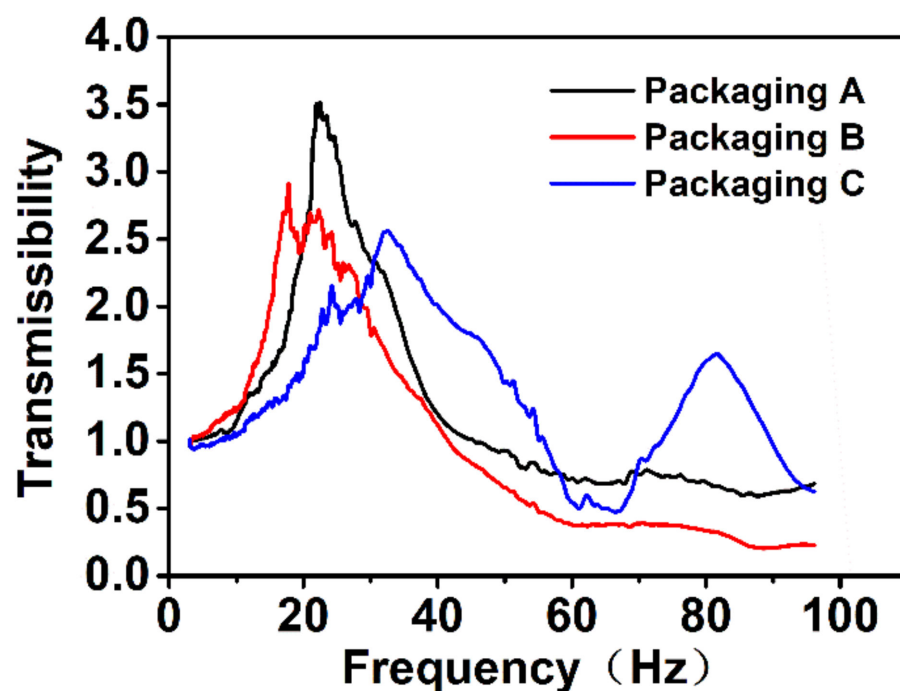


Figure 5. Vibration transmissibility–frequency curves of the three packaging formats.

As shown in Figure 5, Packaging B show a good vibration reduction capability in the high frequency range, but was poor in vibration reduction in the low frequency range. As the frequency of vehicle transportation is mainly concentrated in the low frequency range, Packaging B is not a good choice to achieve a good vibration reduction during the postharvest transportations for fruit. In contrast, although Packaging C could not achieve a good vibration reduction in the high frequency range, it had the best capability of reducing vibration in the low frequency range. Therefore, based on the results of vibration

transmissibility, Packaging C was more suitable than the other two packaging formats for protecting Hongmeiren orange fruit from transportation damage.

The natural frequency of the packaging system is defined as the frequency corresponding to the maximum vibration transmissibility. As shown in Table 3, the natural frequency of Packaging B and Packaging A was both in the low frequency band (<30 Hz), which is close to the frequency of vehicle transportation. Thus, during transportation, it would be easy to generate resonance, which damages the fruit. In contrast, the natural frequency of Packaging C was higher than 30 Hz. This means that Packaging C had the best capability of avoiding the frequency of vehicle transportation, resulting in avoiding resonance and protecting fruit effectively.

Table 3. Vibration transmission characteristics of three packaging formats.

Package Format	Natural Frequency (Hz)	Maximum Response Acceleration (g)	Maximum Vibration Transmissibility
Packaging A	21.96 ± 0.47 a	1.82 ± 0.01 a	3.62 ± 0.01 a
Packaging B	17.88 ± 1.31 a	1.70 ± 0.07 a	2.98 ± 0.12 b
Packaging C	32.67 ± 4.01 b	1.36 ± 0.04 b	2.64 ± 0.07 c

Values in the same column with different lowercase letters were significantly different ($p \leq 0.05$) according to Duncan's multiple range test.

Response acceleration is commonly used to assess the severity of impact damage to fruit, which sometimes causes more severe damage than vibration. The greater the response acceleration, the higher the possibility of fruit damage. As shown in Table 3, the maximum response accelerations of Packaging B and Packaging A were 1.82 g and 1.70 g, respectively, which were significantly higher than that of Packaging C (1.36 g), showing that Packaging C had the best capability of reducing response acceleration.

3.2. Protective Performance of Three Packaging Formats in Simulated Transportation with Two Distances

3.2.1. Simulated Transportation for 3 h

As shown in Figure 6a, after the simulated transportation for 3 h at 20 °C and 90% RH, the damage rates of Packaging A, B, and C were 85.56%, 6.67%, and 5.56%, respectively. The damage rate of Packaging A was significantly higher than the other two packaging formats. Thus, packaging formats using internal packages to separate each fruit, such as Packaging B and C, could protect Hongmeiren orange fruit from mechanical damage well, and the traditional way of using RPCs to transport most citrus varieties in bulk was not suitable for Hongmeiren, an orange fruit cultivar susceptible to mechanical damage, in the transportation within a short distance.

After the 3 h simulated transportation, the decay rates of fruit protected by Packaging B and Packaging C remained at a low level during the entire storage period (Figure 7a), showing that even the fruit protected by Packaging B and C suffered some damage after the 3 h simulated transportation; the fruit was not easily decayed during storage at 10 °C. In contrast, the decay rate of the fruit protected by Packaging A after simulated transportation increased quickly during the storage period (Figure 7a). These results indicated that the fruits protected by Packaging B and C were suitable for storage after 3 h transportation. For the fruit packed in Packaging A, not only did most fruits suffer mechanical damage during transportation, but they were also more prone to decay during storage.

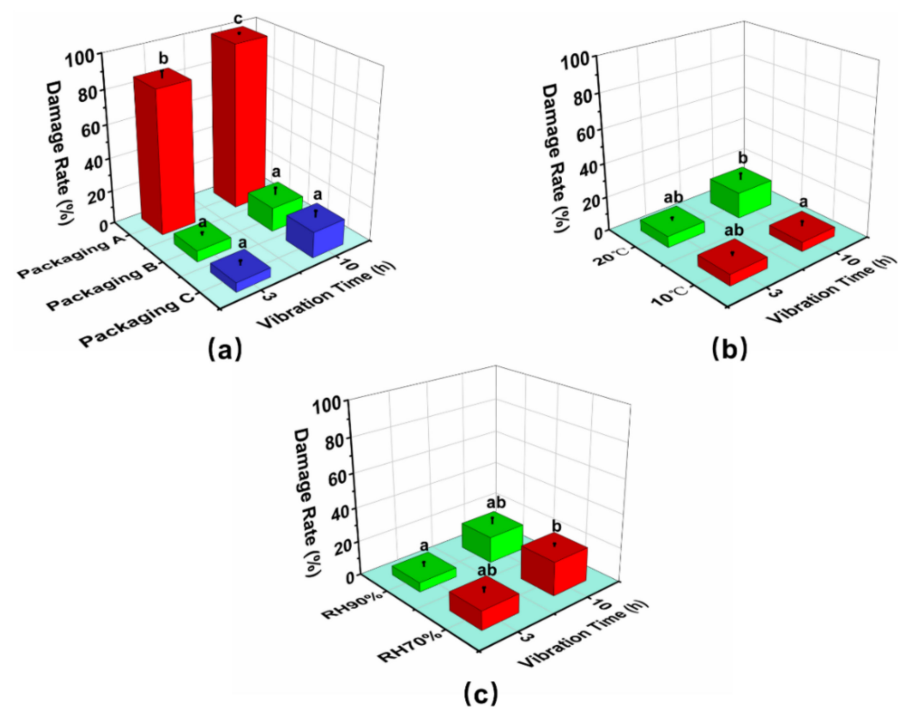


Figure 6. Damage rates after simulated transportation: (a) Three packaging formats vibrated at 20 °C and 90% RH for 3 and 10 h. (b) Packaging C vibrated at 10 and 20 °C and 90% RH for 3 and 10 h. (c) Packaging C vibrated at 20 °C and 70% RH and 90% RH for 3 and 10 h. Vertical bars represent standard error. Letters on columns indicate significant differences ($p < 0.05$).

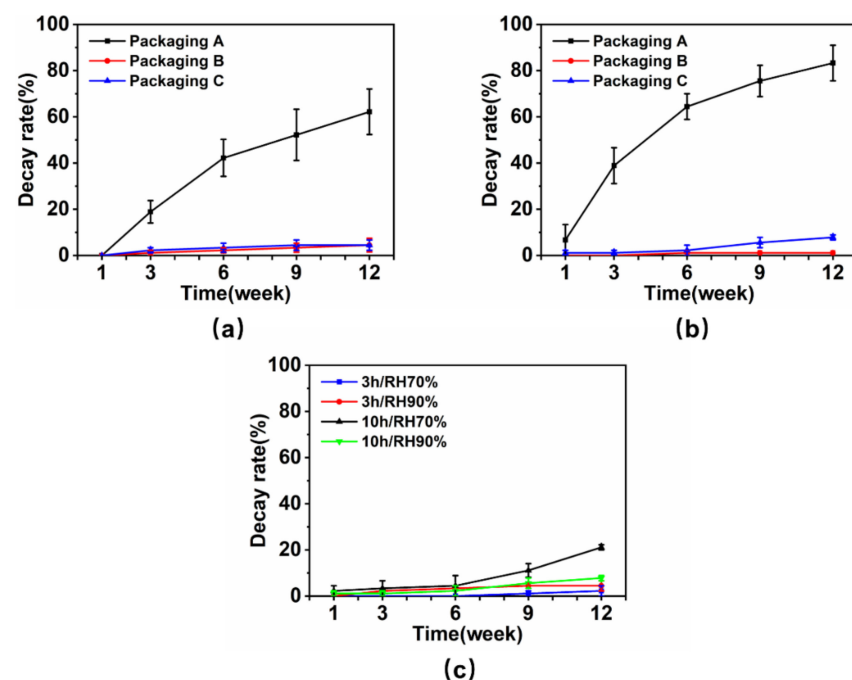


Figure 7. Decay rates during storage after simulated transportation: (a) Three packaging formats vibrated at 20 °C and 90% RH for 3 h. (b) Three packaging formats vibrated at 20 °C and 90% RH for 10 h. (c) Packaging C vibrated at 20 °C and 70% RH and 90% RH for 3 and 10 h. Vertical bars represent standard error.

3.2.2. Simulated Transportation for 10 h

Besides the short-distance transportation (3 h), long-distance transportation was also considered to compare the protection effect of three packaging formats, which were vibrated for 10 h under the condition of 20 °C and 90% RH. As shown in Figure 6a, the damage rates of Packaging A, Packaging B, and Packaging C were 98.89%, 14.44%, and 15.56%, respectively. The damage rate of Packaging A, which underwent 10 h of simulated transportation, was higher than that of the 3 h transportation. This illustrates that time is an important factor affecting damage.

Almost all fruits transported by Packaging A were cracked or bruised, indicating that Packaging A could also not be used for the long-distance transportation of Hongmeiren orange fruit. For both Packaging B and Packaging C, the damage rates increased 2–3 times as the vibration time increased from 3 h to 10 h. Nevertheless, compared to Packaging A, the damage rates of Packaging B and C were much lower, only around 15%, indicating their good protective performances in the 10 h simulated transportation. Similar to the storage results of the 3 h simulated transportation, the fruits protected by Packaging B and C maintained low decay rates during the storage after the 10 h simulated transportation (Figure 7b). After the fruits in Packaging A were vibrated for 10 h, their decay rate during storage increased faster than that of the 3 h simulated transportation. This further illustrates that Hongmeiren orange fruit was not suitable for storage after a long period of bulk transportation.

3.2.3. Analysis of Protective Capabilities of Packaging B and C

From the results of vibration transmissibility analysis, Packaging C had better performances than Packaging B on reducing vibration in the low frequency range, avoiding resonance, and reducing response acceleration. Nevertheless, the damage rates and decay rates of fruits in Packaging B and C were similar after both 3 and 10 h of simulated transportation and 12 d of storage, and this might be because the difference in vibration transmissibility between the two packages was not enough to cause significant damage differences. Besides there are many causes of fruit damage, and vibration transmissibility is only one of the factors. The exact cause needs to be further analyzed.

Packaging B is a packaging commonly used in the market for transporting Hongmeiren orange fruit. Although Packaging B can separate the fruits to avoid mechanical damage caused by the compression of each other as Packaging A does, it does not consider the existence of size differences between the fruits in practical applications. If the fruits are smaller than the size of the hole of Packaging B, they have high freedom of movement and will shake and roll inside Packaging B, thus causing impact and frictional damage to the fruit surface and vibration damage to the fruit flesh. If the fruits are larger than the size of the hole of Packaging B, it would cause dents in the pericarp of the fruit by the hard EPE sponge of Packaging B. The results of this study show that, after 3 h vibration, because of the short vibration time, the effect of Packaging B on the compression of large fruits was not obvious, whereas, after 10 h of vibration, due to the longer vibration time, Packaging B had obvious dents in the pericarp of some large fruits. These dents did not necessarily indicate that the fruit was cracked or bruised, but they would affect the appearance of fruit and in turn its market value. There is therefore a need for a packaging method that is compatible with different sizes of Hongmeiren orange fruit.

To overcome this problem, we proposed Packaging C, which used hard plastic partition boards to separate each layer into 24 units (Figure 2a,e), thereby avoiding compression and impact damages between fruits. The PU foam layer used to wrap the fruit in each unit in Packaging C was flexible, so it was suitable for wrapping and fixing fruits of different sizes without causing compression damage. Moreover, the combination of EPE and PU foam layers could absorb the energy of vibration and impact, so as to better protect the fruit from damage during transportation. Therefore, Packaging C is more suitable for transporting Hongmeiren orange fruit than Packaging B, and has promising applications in practice, especially when transporting over long distances.

3.3. Effect of Temperature and Humidity on Susceptibility to Mechanical Damage of Fruit Packaged by Packaging C during Simulated Transportation

3.3.1. Analysis of Different Transportation Temperatures

To compare the influence of different transportation temperatures on mechanical damage, besides the simulated transportation of Packaging C at 20 °C and 90% RH, the fruits in Packaging C were also vibrated at 10 °C and 90% RH, and the damage rates are shown in Figure 6b.

When Packaging C was vibrated for 3 h, there was no significant difference in the damage rates of fruit vibrated at 10 and 20 °C, and the decay rates were also similarly low during storage. When Packaging C was vibrated at 10 °C for 10 h, its damage rate was 5.56%, only 35.7% of that vibrated at 20 °C (where the damage rate was 15.56%), indicating that the low temperature of 10 °C reduced the mechanical damage of Hongmeiren orange fruit in long-distance transportation.

Nevertheless, the fruits vibrated at a low temperature had similar decay rates during storage compared to the fruits vibrated at room temperature (20 °C). This may be because the low-temperature storage environment caused the damaged fruit to decay without accelerating during storage. Even so, the mechanical damage caused during transportation could still cause a decline in the commercial value of fruit. Therefore, for long-distance transportation of Hongmeiren orange fruit, it is better to consider a low-temperature transportation environment when conditions permit it.

3.3.2. Analysis of Different Transportation Humidity

To evaluate the influence of humidity on the fruit susceptibility to mechanical damage, Packaging C was vibrated at 70 and 90% RH, and the damage rates are shown in Figure 6c. For the simulated transportation for both 3 and 10 h, the damage rates of fruits vibrated at 70% RH were higher than those at 90% RH. Moreover, in the humidity study, the longer the vibration time, the more serious the damage. The fruit vibrated at 70% RH for 10 h had the highest damage rate.

During the storage period, there was no significant difference in the decay rates of the fruit protected by Packaging C vibrated for 3 h under two humidity conditions (Figure 7c). When the fruit protected by Packaging C was vibrated for 10 h, the decay rates under two humidity conditions were similar in the first six weeks. In the ninth week, the decay rate of fruit vibrated at 70% RH was twice that vibrated at 90% RH. In the 12th week, the decay rate of fruit vibrated at 70% RH was almost three times that vibrated at 90% RH. The results show that, with the increase of transportation time, the influence of low humidity on mechanical damage was accordingly increased. It is recommended that the environment should be kept in a relatively high humidity condition when transporting Hongmeiren orange fruit, especially for long distances.

3.4. Road Transportation

3.4.1. Comparison of Packaging A and C in Road Test A

Long-distance transportation of fresh produce on, for example, interstate and international routes exacerbates the risk exposure of mechanical damage to the produce. Interstate supply chains in China often exceed hundreds or thousands of kilometers. In this work, a road transportation route of over 800 km (13 h) was carried out to further evaluate the protective capability of Packaging C for Hongmeiren orange fruit (Road Test A). The fruit packed in Packaging A was also transported as a control.

The results show that, when Hongmeiren orange fruit was packed in bulk, its damage rate was 51.33% when the fruits arrived at the destination. In contrast, only 8.67% of the fruit in Packaging C had mechanical damage upon arrival at the destination, indicating that the energy being transferred to the fruit in Packaging C was much less than the energy absorbed by the fruit in Packaging A. This further verified that the citrus cultivars that are susceptible to mechanical damage were not suitable to be transported in bulk. The higher damage obtained from the fruit in Packaging A suggested that there was fruit-to-fruit

contact due to the bulk arrangement of the citrus in the package as compared with the fruit in Packaging C, where individual citrus fruit was located in a separate unit, preventing fruit-to-fruit contact.

The fruit was stored at 10 °C after 13 h of Road Test A. As shown in Figure 8a, the decay rate of Packaging C remained below 5% in the first six weeks and was always lower than that of Packaging A during storage. In the later period of storage, the decay rate of Packaging C also increased rapidly. This indicates that, even if mechanical damage could be reduced by using suitable packaging, the postharvest fruit itself had a process of aging and decay, so it was hard to avoid fruit decay in the later stage, even for the fruit without mechanical damage. Therefore, not only is proper packaging protection needed to extend the storage period of the fruit, but other preservative measures should also be considered, such as low-temperature storage.

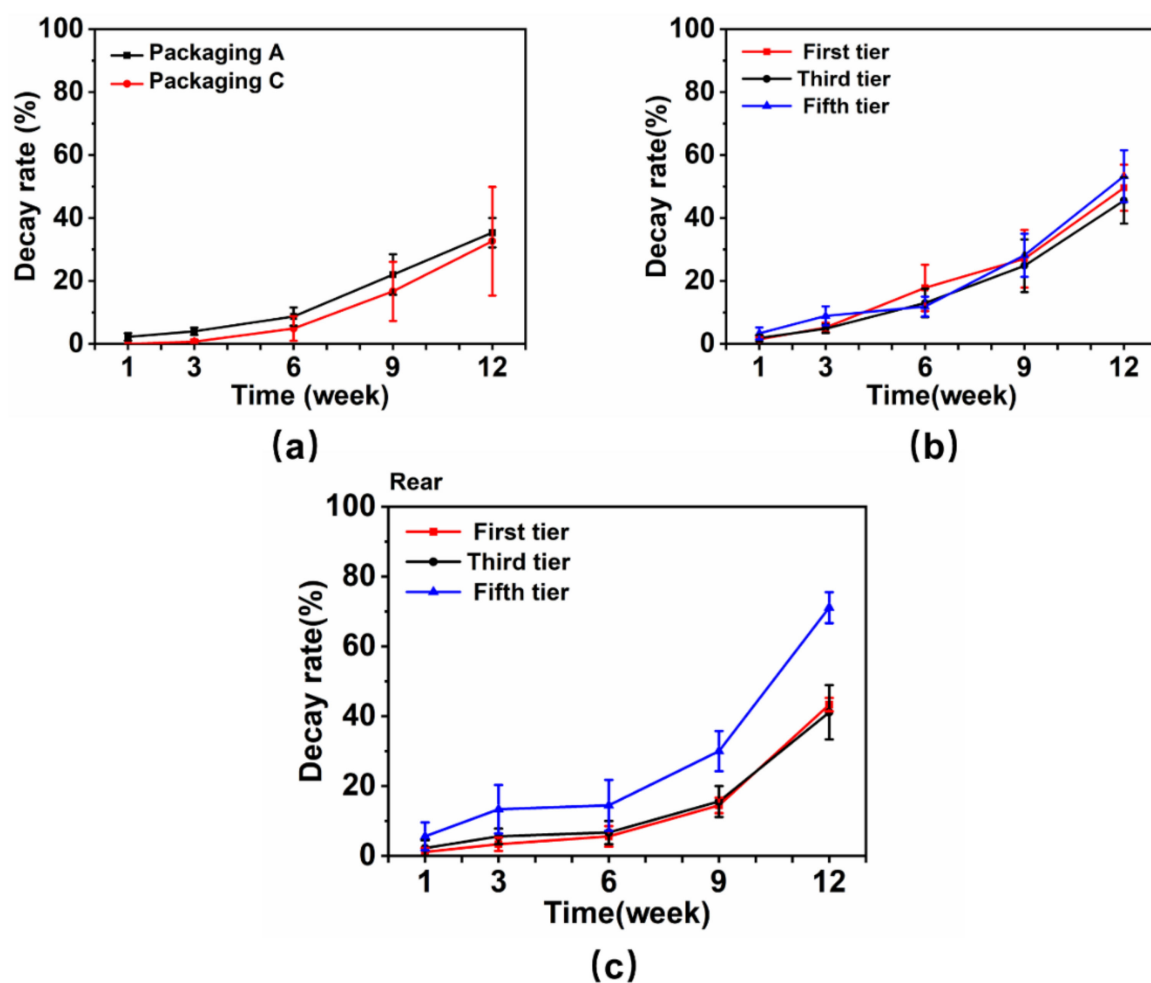


Figure 8. Decay rates during storage after road transportation: (a) Decay rates of Packaging A and C during storage after 13 h of Road Test A. (b) Average decay rates on Tiers 1, 3, and 5 for Packaging C after 30 h of Road Test B. (c) Decay rates of Packaging C at the rear position on Tiers 1, 3, and 5 after 30 h of Road Test B. Vertical bars represent standard error.

Packaging A is a kind of packaging commonly used for transporting citrus, which has the advantages of improving utilization efficiency and reducing costs, but the Hongmeiren orange fruit is relatively soft, and the above results show that the use of Packaging A could lead to the compression of fruits from each other, thus causing an increase in damage rate and decay rate. Therefore, Packaging A was not suitable for transporting citrus cultivars susceptible to mechanical damage.

Moreover, Hongmeiren orange fruit is harvested in winter in China, and is usually transported at a relatively low temperature. Therefore, in our study, the results for Road Test A were compared to the simulated transportation for 10 h at 10 °C. The results show that the damage rate was 5.56% for Packaging C with 10 h simulated vibration at 10 °C and 8.67% in Road Test A. The two results are similar, showing that the result of the simulated transportation study was reliable. The slight increase in damage rate may be due to the fact that the time of Road Test A was 3 h longer than the simulated transportation. In addition, road transportation was more complex than simulated transportation, e.g., the fruit would be subjected to more mechanical forces at the same time and there may be careless handling, all of which could lead to an increased damage rate.

3.4.2. Effect of Packaging C at Different Stack Positions and Heights on A Lorry in Road Test B

As shown in Figure 9a, the damage rate of fruit at the rear position on the lorry was higher than those at the front and middle of the carriage, and that at the front position on the lorry was the lowest. For the stack heights of the fruit located, there was no significant difference in the damage rates between the first, third, and fifth tiers (Figure 9b), showing that the stack heights did not have much influence on the damage rate of Hongmeiren orange fruit during road transportation.

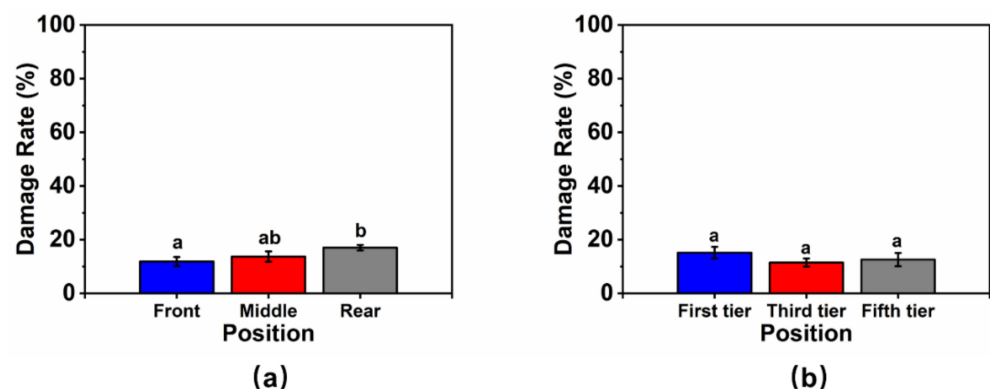


Figure 9. Damage rates of different positions in a lorry after road transportation (Road Test B): (a) Damage rates of fruit at the front, middle, and rear of the lorry. (b) Damage rates of fruit at the first, third and fifth tiers. Vertical bars represent standard error. Letters on columns indicate significant differences ($p < 0.05$).

On the other hand, Figure 8b shows the average decay rates of Packaging C on Tiers 1, 3, and 5 during storage after 30 h of Road Test B. There was no significant difference in decay rates among the three tiers during storage. Nevertheless, as shown in Figure 8c, particularly for the rear position, the decay rate of the fifth tier was higher than those of the first and third tiers throughout the storage period, while there was no significant difference in decay rate between the first and third tiers.

3.4.3. Results of Acceleration Measurements in Road Test C

Road Test C was carried out to record acceleration data on the road from Quzhou to Beijing, and a total of 102,411 acceleration data sample points were collected. The collected time-domain acceleration data were converted into frequency-dependent PSD diagrams. The level of density values corresponding to different frequencies in the PSD diagrams can reflect the level of vibration during vehicle transportation. The experimental results show that two peaks at 3 Hz and 16 Hz were found in the vehicle vibration spectra in Road Test C. This was consistent with the composite truck spectrum in the ASTM D4169-16 Assurance Level II used for the simulation transportation, whose highest value was in the range of 4–16 Hz [24]. Therefore, the simulation transportation of Hongmeiren orange fruit

based on the composite truck spectrum data in the ASTM D4169-16 Assurance Level II could be used to reflect the actual road transportation. Moreover, the vibration peaks in the vehicle vibration spectra obtained from the Road Test C were mainly concentrated in the low frequency range of 3–16 Hz. This was similar to the results of some previous studies. Böröcz and Singh [26] studied that the highest density values in truck traffic occurred at 2–3 Hz and 13–16 Hz, and in the study by Chonhenchob et al. [27], the highest density values were 2 Hz for trucks and 3 Hz for both small trucks and large tractors. In another study, Jarimopas et al. [28] found that the average power spectral density (PSD) for all measurements of truck transport was in the range of 0.1 to 5 Hz. It should be noted that there are differences between the vibration spectra of different vehicles, and the reason for this may be due to the speed of the truck, the type of suspension, the tires used, and the stiffness and load capacity of the vehicle [29–31]. On the other hand, the vibration frequencies that affect the susceptibility of fruit to mechanical damage generally occur in the lower range. Vursavuş and Özgüven [32] found that the frequency range between 0 and 10 Hz was most disruptive to the apple. Therefore, attention to lower frequencies is critical for reducing mechanical damage to transported fresh produce, and it is suggested to select packaging that can reduce the impact of vibration in the low frequency range, as well as to select vehicles that do not vibrate significantly in the low frequency range for transporting fruits. In our study, through simulated vibration experiments, we found that Packaging C specifically designed for Hongmeiren orange fruit obtained the lowest vibration transmission rate and the lowest maximum response acceleration in the low frequency range compared to the other two packaging formats. Moreover, in future works, the vehicle vibration spectra on the road along the actual transportation route should be imported into the simulated vibration platform, so that the packaging suitable for Hongmeiren orange fruit transportation can be better studied and produced.

4. Discussion

4.1. Discussion on Packaging for Transportation of the Citrus Susceptible to Mechanical Damage

Transportation of fruit in bulk is a method of packing with a high cargo density. For citrus cultivars that are less susceptible to mechanical damage, they are suitable for direct bulk transportation without internal packaging. RPCs are commonly used as containers for bulk transportation of citrus from origin to destination on the basis that such containers are reusable, stackable, and collapsible. Different to many citrus cultivars that can resist mechanical damage and can be transported in bulk, the results of this work show that Hongmeiren orange fruit was more susceptible to mechanical damage during transportation and should not be transported in bulk.

In this work, a protective packaging format (Packaging C) was designed according to the thin pericarp and vulnerable body of Hongmeiren orange fruit, and its positive performance was proved by simulated transportation and road transportation. The main difference from bulk transportation was that, in order to avoid compressing the citrus from each other in the front, back, left, and right directions, the inside of Packaging C was divided by hard plastic partition boards into 24 units (Figure 2a,e). The hard plastic partition boards could also support the hard PP board to divide the folding plastic basket into two layers. In addition, by adjusting the hard plastic partition boards, the size of the unit space can be changed to fit other round or round-like fruits. Therefore, Packaging C is also expected to be used to transport other fruits susceptible to mechanical damage. However, Packaging C is currently not very convenient to use and is limited to laboratory research. In future work, Packaging C needs to be improved in structure to facilitate quantity production.

Moreover, since citrus transportation in China is often done across long distances, different from previous works of citrus vibration in which the authors only considered only 1 h or 30 min [28,33], simulated transportation of 3 and 10 h and road transportation of 13 h were carried out in this study, and the results show that, even for the long-distance trans-

portation of Hongmeiren orange fruit, instead of bulk transportation, suitable packaging with suitable temperature and humidity could obtain a low damage rate and decay rate.

4.2. Discussion on the Delicate Balance between Fruit Decay and Internal Packaging Waste

Foam packaging material can absorb or attenuate the impact of strength and vibration acceleration to the utmost extent. Moreover, the shape of the foam packing material can be customized to precisely fit the item to be transported. In this work, Packaging C, with its combination of EPE and PU foam layers, obtained better performance in terms of vibration transmissibility, maximum response acceleration, and natural frequency than the other two packaging formats. Improved packaging and a decrease in the freedom of movement of fruit are important to reduce damage [34].

Most fruit are sensitive to mechanical damage throughout the postharvest supply chain. As a result of postharvest damage, growers, distributors, retailers, and exporters in the fruit industry may suffer severe economic losses. Specifically, Hongmeiren orange fruit, as a fruit susceptible to mechanical damage, can lead to serious damage and decay if not well protected during transportation, thus seriously affecting the commercial value. If the fruit cannot be transported intact to the consumer, all efforts to obtain the fruit, including the resources used to grow and transport it, such as land, water, labor, vehicles, fuel, and time, are wasted, and the spoiled fruit causes environmental pollution. Therefore, although the use of excessive packaging would cause environmental pollution and increase the cost, it is worthwhile to transport some fragile and high-value fruits, such as Hongmeiren orange fruit, with proper packaging. It is also necessary to consider the cost of packaging and the impact of excessive packaging on the environment. Therefore, in practical application, it is necessary to consider the balance between the cost of packaging and the resulting environmental pollution, the balance between fruit waste and packaging waste, as well as the relationship between the waste of fruit due to damage and the decline in commodity value [35].

The experimental results show that Packaging C could mitigate the mechanical damage suffered by Hongmeiren orange fruit during the actual road transportation. Then, the environmental friendliness of Packaging C was evaluated. Among the materials used in the manufacture of packaging C, the folding plastic basket, PP, and EPE were reusable. Nevertheless, for PU, it was susceptible to biodegradation under particular conditions [36], but others considered that their recycling is a problem that has not yet been solved on a large scale. However, considering that the focus of this study was to develop a packaging that could better protect Hongmeiren orange fruit, a citrus cultivar susceptible to mechanical damage, the degradability of the packaging, although needing to be considered, is not the focus of this study.

This study found that although Packaging C used internal packaging compared with Packaging A (bulk), the protection effect of Packaging C was significantly better than that of Packaging A. Using Packaging C to transport fruits could reduce the damage and maintain the quality. This can thus bring consumers a high-quality fruit consumption experience and can assist in the establishment of new markets. Currently, the economic value of Hongmeiren orange fruit is higher than many citrus fruit in China, if they are not packed properly with suitable packaging, it will cause a great deal of waste and will thus pollute the environment, so proper packaging is cost-effective. Certainly, we will also focus on finding new biodegradable and well-cushioned materials that can replace PU and EPE, and use them in future research.

4.3. Discussion on the Effect of Transport Environment on the Susceptibility of Fruits to Mechanical Damage

Temperature is one of the most important environmental factors in the fruit supply chain. However, there are few studies on the influence of transportation temperature on the ability of fruit to resist mechanical damage [37,38]. Our study found that, when the temperature of the simulated transportation for 10 h dropped from 20 to 10 °C, the

damage rate of the fruit dropped over 60%. Nevertheless, previous studies also found that better results are not always obtained at low temperature [39,40]. The above results show that some fruits are more suitable for low temperature transportation, and some fruits need to be transported at a higher temperature. Therefore, it is suggested that the optimal transportation temperatures of fruits in the same container should be similar during cold chain transportation, and the fruits with a large difference in the optimal transportation temperature against mechanical damage should not be transported together. Further studies are required to explore the optimum transportation temperatures against mechanical damage for different fruits. In addition, the reason why temperatures can influence the ability of fruit against mechanical damage should be explored. Lu et al. [41] found that the respiration rate, ethylene production, and the relative expression of MdACS1 and MdACO1 of mature apples (*Malus domestica* Borkh. cv. Fuji) vibrated for 0–12 h at 4 °C were always lower than those at 20 °C.

4.4. Discussion on the Effect of Position and Height of Fruits in the Truck to the Susceptibility to Mechanical Damage

Previous works show that the stacked position of fruit on the truck and the stack height of fruit during transportation affect the damage level to fresh produce [18,34,42,43]. Many works focus on studying the effect of the stack position and/or height of the fruit packages in a semi-trailer truck [34], such as apples [43], pears [44–46], loquats [18], tangerines [28], and watermelons [47].

However, there are no studies on the effect of different positions and heights of citrus cultivars susceptible to mechanical damage, such as Hongmeiren orange fruit on a lorry. The results of this study show that the fruit in the rear position on the lorry was more seriously damaged than that in the front position. Zhou, Su, Yan and Li [44] reported that the damage levels were significantly different among the pears loaded on different positions in a semi-truck. Fernando, Fei and Stanley [34] found that there were significant differences ($p < 0.01$) in mechanical damage between bananas stacked on pallets at different positions of a road train with two trailers. However, the differences in the damage of different positions in our study are not as obvious as in previous studies. This may be because a lorry with space for cargo and cab all attached together was used for the road transportation in our study, whereas previous studies used a semi-truck or a road train with two trailers. For the fruits at different heights, there was no significant difference in the damage rates and decay rates, which may be because the altitude difference of the first, third and fifth tiers was not enough to make a difference.

5. Conclusions

This study evaluated the protective performance of three packaging formats for transporting Hongmeiren orange fruit, a citrus cultivar susceptible to mechanical damage. As a common packaging format for transporting citrus, Packaging A used a reusable plastic container for transporting fruit in bulk and tended to cause compression damage between fruits. Besides, as a gift packaging format, Packaging B is a cardboard box with expandable polyethylene (EPE) inside and was not well suitable for the transportation of fruits of different sizes. To address these deficiencies, Packaging C was designed in this study, which had dividers to avoid the fruits from crushing each other and placed an EPE foam layer in each divider and a PU layer inside the EPE layer to suit different sizes of fruits. The results of the simulated and road transportation tests, and the vibration transmissibility analysis, show that the proposed Packaging C was more suitable for transporting Hongmeiren orange fruit than Packaging A and Packaging B. Although Packaging C uses more packaging materials compared to Packaging A, which may cause some environmental problems, considering the high value of Hongmeiren orange fruit, the resulting fruit decay can also cause environmental problems if not protected, and cause waste of cultivation and transportation resources, such as fertilizer application and vehicle oil. The results also showed that a temperature of 10 °C and a humidity of 90% RH during transportation reduced the mechanical damage,

especially for long-distance transportation. The road transportation tests further show that the damage rate of fruit at the rear position on the lorry was significantly higher than those at the front position, and the stack heights had little influence on the damage rate. Future research should be carried out on how to optimize the structure of Packaging C to make it easier to produce and use in practice. Moreover, the performance of Packaging C on the protection of other fruits susceptible to mechanical damage can be studied in the future.

Author Contributions: Conceptualization: D.Z., J.C. (Jiahui Chen), D.W. (Di Wu) and K.C.; methodology: M.L., D.W. (Di Wu) and J.W.; software: M.L.; validation: J.C. (Jiahui Chen), M.L., D.W. (Da Wang), Q.L. and J.C. (Jingping Cao); formal analysis: D.Z., J.C. (Jiahui Chen), M.L., X.Y. (Xiangzheng Yang) and Y.D.; investigation: D.Z., J.C. (Jiahui Chen), M.L., D.W. (Da Wang), Q.L., J.C. (Jingping Cao) and X.Y. (Xianming Ye); resources: X.Y. (Xiangzheng Yang), Y.D., X.Y. (Xianming Ye) and C.S.; data curation: D.Z., J.C. (Jiahui Chen), D.W. (Da Wang), Q.L. and J.C. (Jingping Cao); writing—original draft preparation: D.Z. and J.C. (Jiahui Chen); writing—review and editing: D.W. (Di Wu) and K.C.; visualization: D.Z., J.C. (Jiahui Chen) and D.W. (Di Wu); supervision: C.S., D.W. (Di Wu), J.W. and K.C.; funding acquisition: C.S., D.W. (Di Wu) and K.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Zhejiang Provincial Key R&D Program of China (2019C02074), Fundamental Research Funds for the Central Universities (K20210202).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Porat, R.; Lichter, A.; Terry, L.A.; Harker, R.; Buzby, J. Postharvest losses of fruit and vegetables during retail and in consumers' homes: Quantifications, causes, and means of prevention. *Postharvest Biol. Technol.* **2018**, *139*, 135–149. [\[CrossRef\]](#)
2. Nattaporn, J.; Krittika, T. Effect of storage time and relative humidity on transportability of sweet tamarind. *Acta Hortic.* **2010**, 151–156. [\[CrossRef\]](#)
3. Golombek, S.D.; Blanke, M.M. Orchard management strategies to reduce bruises on apples in India: A review. *Vegetos* **2022**. [\[CrossRef\]](#)
4. Opara, U.L.; Pathare, P.B. Bruise damage measurement and analysis of fresh horticultural produce—A review. *Postharvest Biol. Technol.* **2014**, *91*, 9–24. [\[CrossRef\]](#)
5. Fernando, I.; Fei, J.; Stanley, R.; Enshaei, H.; Eyles, A. Quality deterioration of bananas in the post-harvest supply chain—An empirical study. *Mod. Supply Chain Res. Appl.* **2019**, *1*, 135–154. [\[CrossRef\]](#)
6. Chonhenchob, V.; Singh, S.P.; Singh, J.J.; Sittipod, S.; Swasdee, D.; Pratheepthinthong, S. Measurement and analysis of truck and rail vibration levels in Thailand. *Packag. Technol. Sci.* **2010**, *23*, 91–100. [\[CrossRef\]](#)
7. Shigematsu, Y.; Kita, K.; Yakushiji, H.; Ishikawa, K.; Inoue, H. The new citrus cultivar 'Ehime Kashi No. 28'. *Bull. Ehime Fruit Tree Exp. Stn. (Jpn.)* **2005**, *19*, 1–6.
8. Hurst, P.; Termine, P.; Karl, M. *Agricultural Workers and Their Contribution to Sustainable Agriculture and Rural Development*; International Labour Organization (ILO), Food and Agriculture Organization of the United Nations (FAO), International Union of Food, Agricultural, Hotel, Restaurant, Catering, Tobacco and Allied Workers' Associations (IUF): Genève, Switzerland, 2007.
9. Okudai, N.; Matsumoto, R.; Oiyama, I.; Takahara, T.; Ishiuchi, D.; Asada, K.; Murata, H. New citrus [*Citrus reticulata*] cultivar "Nankou" [Japan]. *Bull. Fruit Tree Res. Stn. (Jpn.)* **1991**, *20*, 71–77.
10. Chen, X.; Chen, M.; Xu, C.; Yam, K.L. Critical review of controlled release packaging to improve food safety and quality. *Crit. Rev. Food Sci. Nutr.* **2019**, *59*, 2386–2399. [\[CrossRef\]](#)
11. Fernando, I.; Fei, J.; Stanley, R.; Enshaei, H. Measurement and evaluation of the effect of vibration on fruits in transit—Review. *Packag. Technol. Sci.* **2018**, *31*, 723–738. [\[CrossRef\]](#)
12. Ge, C. Theory and practice of cushion curve: A supplementary discussion. *Packag. Technol. Sci.* **2019**, *32*, 185–197. [\[CrossRef\]](#)
13. Ge, C.; Pan, L. Vibration damage rate curves for quantifying abrasion of printed packaging in accelerated random vibration test. *Packag. Technol. Sci.* **2018**, *31*, 71–81. [\[CrossRef\]](#)
14. Saade, C.; Annous, B.A.; Gualtieri, A.J.; Schaich, K.M.; Liu, L.; Yam, K.L. System feasibility: Designing a chlorine dioxide self-generating package label to improve fresh produce safety part I: Extrusion approach. *Innov. Food Sci. Emerg. Technol.* **2017**, *43*, 102–111. [\[CrossRef\]](#)
15. Saade, C.; Annous, B.A.; Gualtieri, A.J.; Schaich, K.M.; Liu, L.; Yam, K.L. System feasibility: Designing a chlorine dioxide self-generating package label to improve fresh produce safety part II: Solution casting approach. *Innov. Food Sci. Emerg. Technol.* **2018**, *47*, 110–119. [\[CrossRef\]](#)

16. Chonhenchob, V.; Singh, S.P. Testing and comparison of various packages for mango distribution. *J. Test. Eval.* **2004**, *32*, 69–72. [\[CrossRef\]](#)
17. Chonhenchob, V.; Sittipod, S.; Swasdee, D.; Rachtanapun, P.; Singh, S.P.; Singh, J.A. Effect of truck vibration during transport on damage to fresh produce shipments in Thailand. *J. Appl. Packag. Res.* **2009**, *3*, 27–38.
18. Barchi, G.L.; Berardinelli, A.; Guarnieri, A.; Ragni, L.; Fila, C.T. PH—Postharvest Technology: Damage to loquats by vibration-simulating intra-state transport. *Biosyst. Eng.* **2002**, *82*, 305–312. [\[CrossRef\]](#)
19. Chonhenchob, V.; Singh, S.P. Packaging performance comparison for distribution and export of papaya fruit. *Packag. Technol. Sci.* **2005**, *18*, 125–131. [\[CrossRef\]](#)
20. Zhou, R.; Su, S.; Li, Y. Effects of cushioning materials on the firmness of Huanghua pears (*Pyrus pyrifolia* Nakai cv. Huanghua) during distribution and storage. *Packag. Technol. Sci.* **2008**, *21*, 1–11. [\[CrossRef\]](#)
21. Fadiji, T.; Coetzee, C.; Chen, L.; Chukwu, O.; Opara, U.L. Susceptibility of apples to bruising inside ventilated corrugated paperboard packages during simulated transport damage. *Postharvest Biol. Technol.* **2016**, *118*, 111–119. [\[CrossRef\]](#)
22. Chonhenchob, V.; Kamhangwong, D.; Singh, S.P. Comparison of reusable and single-use plastic and paper shipping containers for distribution of fresh pineapples. *Packag. Technol. Sci.* **2008**, *21*, 73–83. [\[CrossRef\]](#)
23. Lin, M.; Chen, J.; Chen, F.; Zhu, C.; Wu, D.; Wang, J.; Chen, K. Effects of cushioning materials and temperature on quality damage of ripe peaches according to the vibration test. *Food Packag. Shelf Life* **2020**, *25*, 100518. [\[CrossRef\]](#)
24. ASTM (ASTM D4169-2016); Standard Practice for Performance Testing of Shipping Containers and Systems. ASTM International: West Conshohocken, PA, USA. [\[CrossRef\]](#)
25. Zhang, L.; Yang, C.; Wang, Y.; Pan, D.; Meng, X.; Tong, T. Vibration and impact performance tests of cherry tomato transport packages. *Trans. Chin. Soc. Agric. Mach.* **2011**, *42*, 125–130, 155.
26. Böröcz, P.; Singh, S.P. Measurement and analysis of delivery van vibration levels to simulate package testing for parcel delivery in Hungary. *Packag. Technol. Sci.* **2018**, *31*, 342–352. [\[CrossRef\]](#)
27. Chonhenchob, V.; Singh, S.P.; Singh, J.J.; Stallings, J.; Grewal, G. Measurement and analysis of vehicle vibration for delivering packages in small-sized and medium-sized trucks and automobiles. *Packag. Technol. Sci.* **2012**, *25*, 31–38. [\[CrossRef\]](#)
28. Jarimopas, B.; Singh, S.P.; Saengnil, W. Measurement and analysis of truck transport vibration levels and damage to packaged tangerines during transit. *Packag. Technol. Sci.* **2005**, *18*, 179–188. [\[CrossRef\]](#)
29. Yam, K.L. *Encyclopedia of Packaging Technology*; John Wiley & Sons Inc.: Hoboken, NJ, USA, 2009.
30. CPP Soroka, W. *Fundamentals of Packaging Technology*; DEStech Publications Inc.: Lancaster, PA, USA, 2009.
31. Rouillard, V.; Lamb, M. On the effects of sampling parameters when surveying distribution vibrations. *Packag. Technol. Sci.* **2008**, *21*, 467–477. [\[CrossRef\]](#)
32. Vursavuş, K.K.; Özgüven, F. Determining the effects of vibration parameters and packaging method on mechanical damage in golden delicious apples. *Turk. J. Agric. For.* **2004**, *28*, 311–320. [\[CrossRef\]](#)
33. Chen, H.; Yin, Y.; Pan, H.; Bao, X.; Li, S.; Xu, Q.; Xu, X. Loss factor analysis of mechanical damage and cushioning protection measure for Citrus reticulata Blanco. *Trans. Chin. Soc. Agric. Eng.* **2018**, *34*, 258–266. [\[CrossRef\]](#)
34. Fernando, I.; Fei, J.; Stanley, R. Measurement and analysis of vibration and mechanical damage to bananas during long-distance interstate transport by multi-trailer road trains. *Postharvest Biol. Technol.* **2019**, *158*, 110977. [\[CrossRef\]](#)
35. Verghese, K.; Lewis, H.; Lockrey, S.; Williams, H. Packaging's role in minimizing food loss and waste across the supply chain. *Packag. Technol. Sci.* **2015**, *28*, 603–620. [\[CrossRef\]](#)
36. Vroman, I.; Tighzert, L. Biodegradable polymers. *Materials* **2009**, *2*, 307–344. [\[CrossRef\]](#)
37. Zoffoli, J.P.; Rodriguez, J. Fruit temperature affects physical injury sensitivity of sweet cherry during postharvest handling. *Acta Hortic.* **2014**, *1020*, 111–114. [\[CrossRef\]](#)
38. DeMartino, G.; Massantini, R.; Botondi, R.; Mencarelli, F. Temperature affects impact injury on apricot fruit. *Postharvest Biol. Technol.* **2002**, *25*, 145–149. [\[CrossRef\]](#)
39. Crisosto, C.H.; Garner, D.; Doyle, J.; Day, K.R. Relationship between fruit respiration, bruising susceptibility, and temperature in sweet cherries. *Hortscience* **1993**, *28*, 132–135. [\[CrossRef\]](#)
40. Mohammad Shafie, M.; Rajabipour, A.; Castro-García, S.; Jiménez-Jiménez, F.; Mobli, H. Effect of fruit properties on pomegranate bruising. *Int. J. Food Prop.* **2015**, *18*, 1837–1846. [\[CrossRef\]](#)
41. Lu, F.; Xu, F.; Li, Z.; Liu, Y.; Wang, J.; Zhang, L. Effect of vibration on storage quality and ethylene biosynthesis-related enzyme genes expression in harvested apple fruit. *Sci. Hortic.* **2019**, *249*, 1–6. [\[CrossRef\]](#)
42. Berardinelli, A.; Donati, V.; Giunchi, A.; Guarnieri, A.; Ragni, L. Effects of transport vibrations on quality indices of shell eggs. *Biosyst. Eng.* **2003**, *86*, 495–502. [\[CrossRef\]](#)
43. Soleimani, B.; Ahmadi, E. Measurement and analysis of truck vibration levels as a function of packages locations in truck bed and suspension. *Comput. Electron. Agric.* **2014**, *109*, 141–147. [\[CrossRef\]](#)
44. Zhou, R.; Su, S.; Yan, L.; Li, Y. Effect of transport vibration levels on mechanical damage and physiological responses of huanghua pears (*Pyrus pyrifolia* Nakai cv. Huanghua). *Postharvest Biol. Technol.* **2007**, *46*, 20–28. [\[CrossRef\]](#)
45. Berardinelli, A.; Donati, V.; Giunchi, A.; Guarnieri, A.; Ragni, L. Damage to pears caused by simulated transport. *J. Food Eng.* **2005**, *66*, 219–226. [\[CrossRef\]](#)

-
46. Slaughter, D.C.; Thompson, J.F.; Hinsch, R.T. Packaging Bartlett pears in polyethylene film bags to reduce vibration injury in transit. *Trans. Am. Soc. Agric. Eng.* **1998**, *41*, 107–114. [[CrossRef](#)]
 47. Shahbazi, F.; Rajabipour, A.; Mohtasebi, S.; Rafie, S. Simulated in-transit vibration damage to watermelons. *J. Agric. Sci. Technol.* **2010**, *12*, 23–34. [[CrossRef](#)]