Mechanical damages and packaging methods along the fresh fruit supply chain: a review

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Highlights

Mathematical modeling has been increasingly used to calculate damage to fruit

Cell and molecular mechanisms response to fruit damage is an under-explored area

Susceptibility measurement of different mechanical forces has received attention

Customized design of reusable and biodegradable packaging is a hot topic of research

Abstract

Mechanical damage of fresh fruit occurs throughout the postharvest supply chain leading to poor consumer acceptance and marketability. In this review, the mechanisms of damage development are discussed firstly. Mathematical modeling provides advanced ways to describe and predict the deformation of fruit with arbitrary geometry, which is important to understand their mechanical responses to external forces. Also, the effects of damage at the cellular and molecular levels are discussed as this provides insight into fruit physiological responses to damage. Next, direct measurement methods for damage including manual evaluation, optical detection, magnetic resonance imaging, and X-ray computed tomography are examined, as well as indirect methods based on physiochemical indexes. Also, methods to measure fruit susceptibility to mechanical damage based on the bruise threshold and the amount of damage per unit of impact energy are reviewed. Further, commonly used external and interior packaging and their applications in reducing damage are summarized, and a recent biomimetic approach for designing novel lightweight packaging inspired by the fruit pericarp. Finally, future research directions are provided.

Keywords

Mechanical response, mathematical modeling, physiological response, fruit susceptibility, packaging, postharvest handling

1 Introduction

Fruit are rich sources of nutrients, presenting a variety of appealing sensory characteristics to consumers. With the continuous improvement in living standards, consumers have come to expect premium fruit that is free of bruises, cuts, punctures, physiological disorders, and pathogenic spoilage (Eissa & Gomaa, 2012). The cosmetic appearance of fruit influences consumers' purchase decisions. Harker (2009) reported that cosmetic damage in fruit was a more important barrier to purchase than price. Fruit without bruises or abrasions has a better appearance than bruised or abraded fruit, which leads to higher perceived quality and marketability values (Sablani et al., 2006; Li & Thomas, 2014; Opara & Pathare, 2014). Unfortunately, most fruit is 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. Losses due to mechanical damage in the postharvest supply of fruit remain a major problem in the fruit industry (Opara, 2007; Fadiji et al., 2016b).

Impact, vibration, compression, friction, and puncture forces are the main factors that cause mechanical damage to fruit after harvest, causing physiological changes and quality deterioration (Jedermann et al., 2013; Opara & Fadiji, 2018; Lu et al., 2019; Xu et al., 2020; Al-Dairi et al., 2022). Careful handling and proper packaging are essential to reduce mechanical damage to the fruit (Fernando et al., 2020; Berry et al., 2022). The increasing trade of agricultural products in the modern global economy has also placed higher demands on packaging performance. Besides, timely detection of mechanical damage to fruit is key to improving information transparency and changing transportation strategies throughout the fruit supply chain (Rao et al., 2020; Yang et al., 2020; Al-Dairi et al., 2022). Therefore, understanding the mechanism of damage development and the measurement of mechanical damage, and putting forward effective packaging methods are important to reduce mechanical damage and economic losses of postharvest fruit, and many studies have focused on these aspects in recent years, which have not been reviewed yet.

Consequently, the present review synthesizes the findings of previous studies and aims to provide a reference for reducing fruit damage and loss in postharvest supply chains. In order to focus on recent advances, the present review provides knowledge on recent advances in the mechanical damage and protective packaging for fruit, mainly with greater attention to studies conducted since 2005. Besides, some classic and ground-breaking literatures published before 2005 were also cited. The focus of this review was on (1) mechanisms of damage development, including mechanical and physiological responses of fruit to external forces, which help to provide a theoretical basis for reducing fruit damage and economic losses in the fruit industry; (2) measurement of fruit damage, including direct, indirect, and susceptibility measurement methods, which is important for developing remedial actions and optimizing management strategies to reduce fruit damage and losses; and (3) packaging methods for protecting fruit against mechanical damage, including external, interior, and biomimetic packaging designs, which fulfills an important role in ensuring product integrity and extending shelf life by absorbing the energy loaded on the fruit. In addition, future research directions are put forward. To provide readers with a better understanding, a diagrammatic illustration of the structure of the present review is shown in Fig. 1.

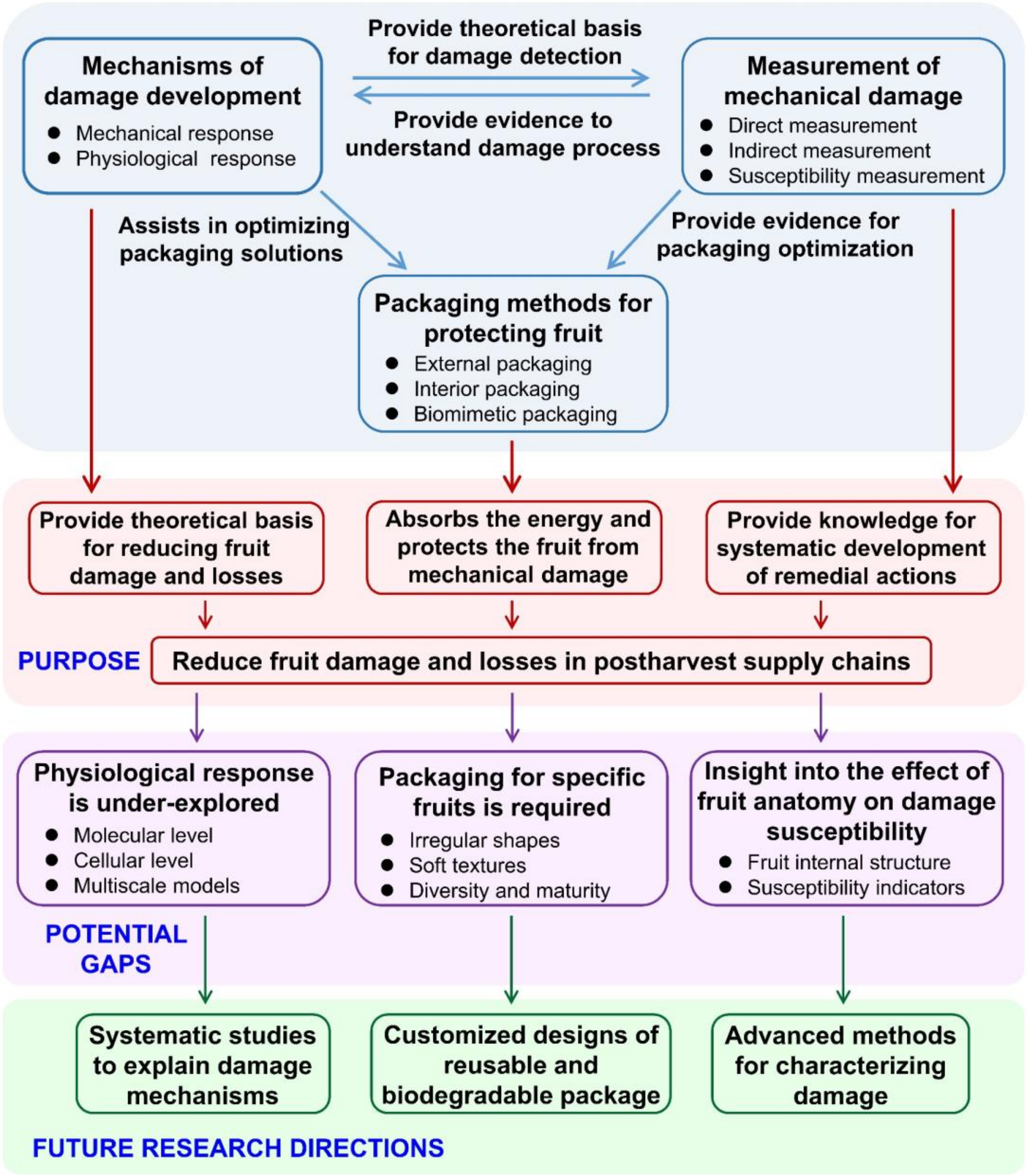

Figure 1. Diagrammatic illustration of the structure of present review.

2 Mechanisms of damage development

Given the rising demand for mitigating the incidence of mechanical damage and improving the quality of fruit, understanding the related mechanisms of damage development has become of considerable interest to researchers. In particular, the studies on mechanical responses of fruit to external forces and the study of the related physiological responses are the focus of attention of this review (Fig. 2).

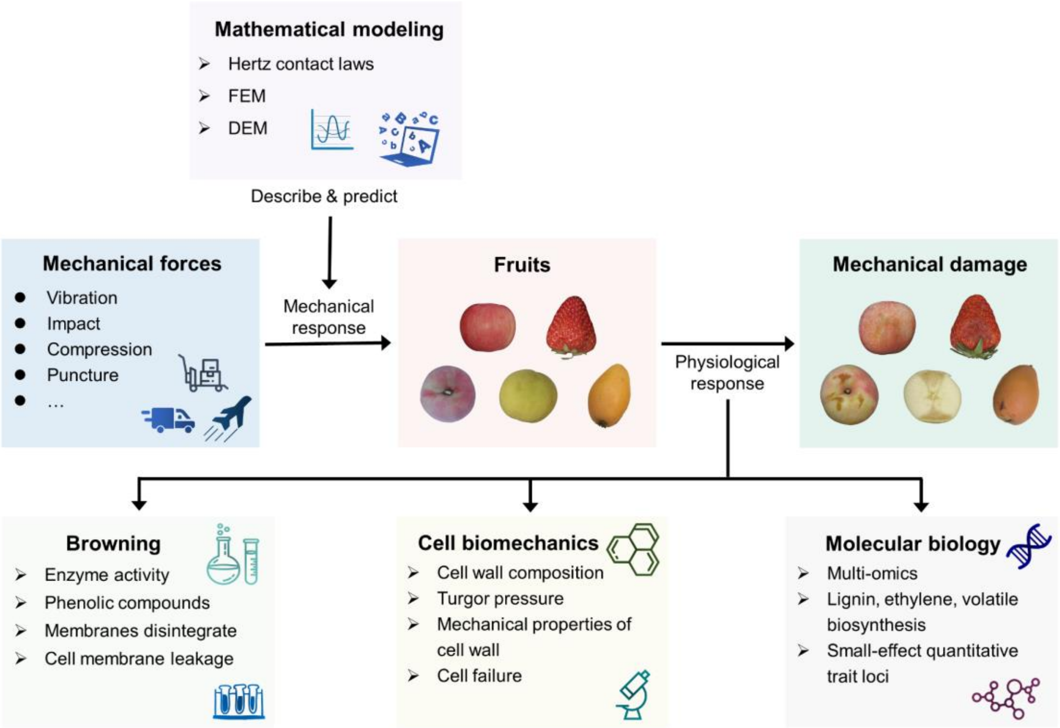

Figure 2. Mechanisms of damage development include the mechanical responses and the physiological responses of fruit to external forces. Vibration, impact, compression, and puncture damage are mainly consequential of mechanical stresses. The mechanical damage of fruit can be described and predicted by mathematical models. Fruit subjected to mechanical damage exhibit a variety of physiological responses at the cellular and molecular levels. FEM: finite element method. DEM: discrete element method.

2.1 Mechanical response of fruit to external forces

Mechanical damage occurs when the force per surface area, or stress, exceeds a certain threshold (Rudnicki, 2014). Every force can be expressed as the sum of a force perpendicular to a surface and a force parallel to the surface (Rudnicki, 2014). Perpendicular forces per unit area are called normal stresses, while parallel forces per unit area are called shear stresses (Rudnicki, 2014). Vibration, impact, compression, and puncture damage are mainly consequential of normal stresses. Compression is a consequence of a static load, impact and puncture damage are both caused by dynamic loads, and vibration damage is a result of repetitive impact loads. Friction is caused by shear stresses. In practice, all loads have both a normal and a shear component. The study of mechanical damage can, thus, be reduced to investigating how fruit responds to (static and dynamic) normal and shear stresses.

Mathematical modeling can be used to describe and predict the mechanical damage to fruit. Early models were based on Hertz contact laws for elastic solids with simple geometries (Dintwa et al., 2008). These equations allow us to calculate local stresses and deformations due to static loads. By comparing the computed local stresses with experimentally determined failure criteria (e.g., the rupture stress of tissue), the consequent damage can be predicted. These equations can also be extended to account for dynamic forces.

The finite element method (FEM) is a more advanced method to calculate the deformation due to static (as well as dynamic) forces applied to the fruit of arbitrary geometry. This numerical procedure solves the governing partial differential equations of deformation (Yousefi et al., 2016). The mechanical properties (elasticity modulus, visco-elastic properties) need to be known, and a digital representation of the shape of the fruit is required. The former can be measured by mechanical tests, while the latter is typically constructed from images acquired by computer vision systems (Jancsók et al., 2001), MRI, or X-ray tomography (Piovesan et al., 2021). Rogge et al. (2014, 2015) developed software to generate random fruit shapes to cope with the variability in fruit shapes. The computed local stresses can then be compared to failure criteria. The FEM has been used to calculate the mechanical deformation of apples (Celik et al., 2011; Ahmadi et al., 2016), pomelo (Miraei Ashtiani et al., 2019), oranges (Gharaghani & Maghsoudi, 2018), pear (Yousefi et al., 2016; Celik, 2017), tomato (Li et al., 2013; Li et al., 2017), kiwifruit (Du et al., 2019), and *Lycium barbarum* L. (Zhao et al., 2019). A review of the FEM for fruit stress analysis can be found in the literature (Zulkifli et al., 2020). However, fruit are complex materials and the constitutive laws that govern their mechanical behavior have not received much attention. More research in this area is, hence, required. Recent research has included the construction of cell models as a building block for a multiscale mechanical model for fruit deformation (Dintwa et al., 2011; Li & Thomas, 2016; Diels et al., 2019). This research area will lead to a much better understanding of the effect of external macroscopic forces on stresses at the cellular level.

The effect of multiple fruit impacting each other in a sorting line or a vibrating box can be computed using the discrete element method (DEM). In this method, Newton's equations of motion are numerically solved for every fruit, and impacts between a fruit and a wall or another fruit are modeled using an appropriate contact law. Van Zeebroeck et al. (2006) simulated the effect of vibration on apples using the DEM. Their results showed that it was possible to predict bruise damage (bruise depth) of 'Jonagold' apples (Van Zeebroeck et al., 2006). Furthermore, Van Zeebroeck et al. (2008) used the DEM to simulate the impact damage to apples when a truck passes over a speed bump. The dynamic response of the stacked apples clearly illustrated the influence of suspension type, load capacity, driving speed, and the position of the bulk bin on the impact damage of apples caused by the truck passing over the speed bump (Van Zeebroeck et al., 2008). However, knowledge on contact laws is scarce and more research is required in this area. Furthermore, the aforementioned multiscale mechanical models for fruit deformation need to be incorporated into these DEMs, in order to understand the effect of impacts on cell deformation and rupture. Such models can, then, be used for designing fruit packages and handling equipment with the aim of minimizing mechanical damage.

2.2 Physiological response

Fruit cells are usually turgid and brittle; local excessive stresses may cause cell wall rupture and cause brittle failure of the cell (Ferreira et al., 2009). Cells respond differently to static and dynamic stresses. This is due to the fact that cells may expel water to alleviate the effects of static stresses, while dynamic stresses (impacts) occur over short periods, such that the cells cannot respond quickly enough and fail easier. This contributes to the viscoelastic character of fruit tissue; that is, they have the mechanical properties of a viscous liquid and an elastic solid. To understand the fracture strength, Singh et al. (2014) studied the compressive stiffness and turgor pressure in the cell walls of apple and potato tissues and developed a relationship between the elastic modulus and turgor pressure, confirming a relationship discovered much earlier by Falk et al. (1958). In another study, to determine cell wall material properties, a groundbreaking micromanipulation method was proposed by Wang et al. (2004). In this method, a single tomato cell in suspension was compressed between two parallel flat surfaces — the flat end of optic fiber and a glass surface — to obtain the corresponding force-deformation curve. The results showed that Young's modulus of the wall of single tomato cells could be estimated using a linear elastic model. Recently, Li et al. (2016b) used high-speed compression-holding tests to investigate the microscale viscoelastic-plastic behavior of tomato mesocarp cells and proposed that mechanical damage of fruit was, indeed, ultimately caused by the failure of cells. Nevertheless, quantitative understanding of the physiological effects of mechanical stresses is hindered by the difficulty of measuring mechanical properties of cell walls *in vivo*.

During cell failure, the membranes disintegrate and the resulting de-compartmentalization may cause the phenolic substrates to merge with the polyphenol oxidases, which are normally located in the plastids. This results in browning (Li & Thomas, 2014). Other processes that have been associated with mechanical damage are cell membrane leakage, enzyme activity, and cell wall constituent losses (Zhou et al., 2015). Another study found that the increased firmness of mangosteen pericarp after impact was related to the increased enzyme activity required for lignin biosynthesis and was not correlated to the biosynthesis of phenolic compounds (Bunsiri et al., 2012). The enzymes involved in lignin biosynthesis include phenylalanine ammonia-lyase, peroxidase, and cinnamyl alcohol dehydrogenase. Their activity increased 15 minutes after impact and then decreased (Bunsiri et al., 2012).

Mechanical damage causes a series of molecular events in fruit. Omics research is a new approach in determining fruit constituents at the molecular level. The use of advanced analytical techniques in omics research allows scientists to look into plant physiology from a broad perspective. Recently, studies have been conducted to illustrate the damage development of fruit through different omics disciplines such as genomics, transcriptomics, proteomics, and metabolomics (Saeed et al., 2014). At the genomic level, Saeed et al. (2014) found that postharvest friction discoloration was controlled by multiple small-effect quantitative trait loci and that genomic selection could be used to select superior genotypes with lower or no friction discoloration sensitivity early in the breeding cycle. For transcription levels, Kamdee et al. (2014) demonstrated that pericarp hardening of mangosteen after impact was due to rapid transcriptional activation of the late steps of the lignin biosynthetic pathway, potentially by upregulation of transcription factors such as R2R3 MYBs. In another study, Xu et al. (2020) reported that gene expression of ethylene biosynthesis-related enzyme genes in damaged apples was significantly higher than that in healthy apples after an impact test. Similar results of gene expression were found in apples subjected to vibration damage (Lu et al., 2019). Lately, Lin et al. (2021) indicated that transcription factors may contribute to the accumulation of hexanal and ethyl acetate in compression-damaged apples by regulating the expression of genes related to the lipoxygenase pathway (*MdLOX-like*, *MdLOX3b*, *MdLOX7b*, *MdLOX7c*, *MdLOX2a*, and *MdAAT*). At proteomic levels, Buron-Moles et al. (2014) analyzed changes in protein abundance after wounding ‘Golden Delicious’ apples and speculated that the abundance of appropriate proteins was modulated to respond to wound stress, while a broad range of pathogenesis-related proteins was synthesized against mechanical damage. Moreover, Han et al. (2018) explored the underlying mechanism of abscisic acid (ABA) stimulation in kiwifruit after wound suberization through proteomic and transcriptomic assays. The results showed that antioxidant system, lipid metabolism, and phenylpropanoid metabolism were involved in the response of ABA to stimulate wound suberization (Han et al., 2018). Also, ABA significantly up-regulated the gene expression of *KCS11*, *POD*, *GSH-Px*, *CCR*, *CYP86B1*, and *DGGT*, thereby promoting wound-induced suberization in kiwifruit (Han et al., 2018). While all these studies indicate that the physiological response to damage happens at multiple organizational levels and involves signaling and stress response pathways, the regulatory mechanisms of physiological degradation of fruit caused by mechanical damage are less studied. Further systematic studies (multi-omics) are needed to identify and validate key gene functions to explain the molecular mechanisms in fruit subjected to mechanical damage.

3 Measurement of mechanical damage

The availability of techniques to measure fruit damage is important for the systematic development of remedial actions. Accurate evaluation of the mechanical damage of fruit provides direct evidence to understand the damage process during transportation and other postharvest processes. Once damage occurs, it is necessary to measure the damage degree objectively and quantitatively in order to grade the damaged fruit and calculate postharvest fruit losses, thereby minimizing economic losses. Currently, the damage detection of fruit is typically based on direct methods, such as manual evaluation and optical detection, and some reviews have been published in this area (Li & Thomas, 2014; Opara & Pathare, 2014). Besides direct measurement, mechanical damage may induce physiochemical responses in fruit, resulting in deterioration of fruit quality. Therefore, mechanical damage can also be evaluated by detecting physiochemical indexes. Consequently, in addition to briefly introducing direct detection methods, indirect methods based on physiochemical indexes for damage detection are also presented in this review. Moreover, the measurement of fruit susceptibility to mechanical damage is important to reduce the incidence of fruit damage, which is also specifically reviewed.

3.1 Direct methods for damage detection

Bruising is the most common type of mechanical damage in fresh horticultural produce (Boydas et al., 2014; Li et al., 2016a). There are generally two ways to directly detect bruise damage: manual evaluation and optical detection. The most classic method for evaluating bruise damage is manual evaluation, which mainly measures bruise area, bruise volume (BV), bruise number, bruise diameter, bruise depth, bruise proportion, and bruise index (Li & Thomas, 2014; Opara & Pathare, 2014). However, some manual evaluation methods are destructive, resulting in the fruit being no longer available for further storage and sale after measurement. In addition, the efficiency and objectivity of bruise detection are low when using manual evaluation. Therefore, rapid and non-invasive methods are required for damage determination in mass-produced fruit. Optical detection techniques are commonly used to non-destructively detect damaged fruit (Du et al., 2020). Among them, computer vision, visible and near-infrared (Vis/NIR) spectroscopy, multispectral imaging, and hyperspectral imaging techniques are commonly used to non-destructively detect damaged pericarps and parts of mesocarps of fruit (He et al., 2021; Li et al., 2021; Sun et al., 2021; Zhang et al., 2021). Keresztes et al. (2017) summarized a four-step experimental procedure, including sample supply (such as stored apple fruit, in this work), bruising experiment (optimal design of experiment), hyperspectral model building (step-wise/multi-class bruise prediction), and non-destructive bruise monitoring (monitor browning evolution for prediction accuracy); which is typical for a study of fruit bruise detection using hyperspectral imaging techniques. On the other hand, X-ray computed tomography (CT) and magnetic resonance imaging (MRI) are more suitable for measuring damage inside fruit. Diels et al. (2017) developed a method to automatically detect and quantify bruise volumes in the equatorial region of apples using X-ray CT images. Zhou et al. (2015) used MRI to non-destructively assess the changes in the internal morphological characteristics of Hami melons caused by simulated vibration. In the obtained MRI images, the necrosis inside the damaged melons was clearly distinguishable (Zhou et al., 2015). Optical coherence tomography (OCT) has also been recently introduced to assess horticultural produce due to its high speed and sensitivity. OCT is a non-invasive and contactless optical imaging method that can acquire three-dimensional (3D) resolved images of plant tissues with a depth of up to 2 mm and a resolution of 5–20 μm (Li et al., 2019a). For the detection of mechanical damage in fruit, Zhou et al. (2018) measured the cellular morphology changes of loquat using OCT and found that the total cell surface area and cell amount were good indicators for bruise identification in loquat fruit. In another study, they extracted attenuation coefficients (μ_t) from the regions of interest in the OCT images and found that the μ_t values of intact and bruised tissues of loquat fruit were different (Zhou et al., 2017).

3.2 Indirect methods for damage detection

Several indexes have been found to be related to mechanical damage, such as micro-organism invasion and changes in firmness, respiration rate, and ethylene production. These indexes have been considered good candidates to evaluate fruit damage indirectly. The invasion of micro-organisms is one of the most significant consequences of mechanical damage. Scalia et al. (2015) analyzed the microbiological changes of two strawberry cultivars subjected to a simulated vibration test. The authors showed that the volatile organic compounds of dominant micro-organisms could indirectly indicate bruise damage (Scalia et al., 2015). Besides micro-organisms, Bunsiri et al. (2012) found that the firmness of mangosteen increased within 15 minutes after impact, whereas no increase was found in non-impacted pericarp tissue. The respiration rate and ethylene production of damaged apples were also shown to be significantly increased compared to those of controlled apples (Lu et al., 2019). In addition, other measured physicochemical indexes of fruit relating to their mechanical damage include weight loss, color, total soluble solids and acidity, ascorbic acid concentration, total phenolic content, electrical impedance value, and electrical conductivity (Eissa & Gomaa, 2012; Dhital et al., 2017; Watanabe et al., 2018; Hussein et al., 2019b; Wei et al., 2019; Hussein et al., 2020; Xu et al., 2020).

3.3 Measurement of fruit susceptibility to mechanical damage

Fruit susceptibility to mechanical damage expresses the ability of the fruit to withstand external loads. Susceptibility to mechanical damage and its measurement during postharvest handling of fruit is an important research area, which has received increasing attention (Opara, 2007; Bugaud et al., 2014). Knowledge of the factors affecting fruit susceptibility is essential for growers and operators in the postharvest supply chain. Studies on the measurement of bruise thresholds will provide new insights into the mechanisms of bruising. The measurement of fruit susceptibility to mechanical damage can provide useful information for postharvest handling in order to take preventive measures to minimize the occurrence of fruit damage.

3.3.1. Fruit susceptibility to impact force and its measurement

Fruit susceptibility to impact damage has been studied using several impact tests, including drop tests, pendulum impactor tests, and spherical impactor tests. Several factors affect the susceptibility of fruit to impact damage, of which cultivar is an important one. Jiménez-Jiménez et al. (2013) carried out a drop test to measure the susceptibility of olives to impact damage and reported that the cultivar was a critical determinant. They found that, among the three most internationally important olive cultivars, the bruise susceptibility of the 'Manzanilla cultivar' was higher, followed by the 'Hojiblanca' and 'Gordal Sevillana' cultivars (Jiménez-Jiménez et al., 2013). Bugaud et al. (2014) also found that, among five banana cultivars, 'French Corne' had the highest sensitivity, followed by 'Fougamou', then the hybrid 'Flhorban916', whereas 'Grande Naine' and the hybrid 'Flhorban925' did not develop bruises, even at the maximum impact energy (E_i; 200 mJ). Van Linden et al. (2006) developed a pendulum instrument to control E_i in fruit and found that the cultivar of tomato and the location of impact affected the susceptibility to bruise damage. Recently, Wang et al.

(2020) designed an experimental system to study the effect of impact force on the damage susceptibility of litchi fruit and found that the ‘Nuomici’ cultivar had a lower damage susceptibility than the ‘Guiwei’ cultivar (Fig. 3D). Besides cultivar, the susceptibility of impact damage was also found to increase with the ripening degree of fruit such as banana (Bugaud et al., 2014) and loquat (Cañete et al., 2015). Fruit temperature is another factor that affects the susceptibility to impact damage. Bruise susceptibility was higher for bananas stored at 18 °C throughout ripening than those at 13 °C between the 2nd and 6th day (Bugaud et al., 2014). Furthermore, the authors found that the susceptibility of bananas to impact damage was positively correlated to peel electrolyte leakage ($R = 0.78$) and negatively correlated to peel firmness ($R = -0.45$); however, no correlation was found to total polyphenolic content (Bugaud et al., 2014). Recently, packaging designs have also been found to have an influence on damage susceptibility. Fadiji et al. (2016b) used a drop tester to produce impact damage by dropping fruit packages from specific heights onto a steel surface. Higher bruise susceptibility was found in apples packed inside polyethylene plastic bags than in apples on trays. In addition to the aforementioned postharvest factors, management practices and harvest date may also affect fruit susceptibility to impact damage. According to Opara (2007), reducing the frequency of irrigation and selectively and timely picking mature fruit may reduce the susceptibility of apples to impact damage. The bruise susceptibility in mid-season apples was increased significantly, compared to early-season apples; however, in late apples, bruise susceptibility again decreased (Opara, 2007).

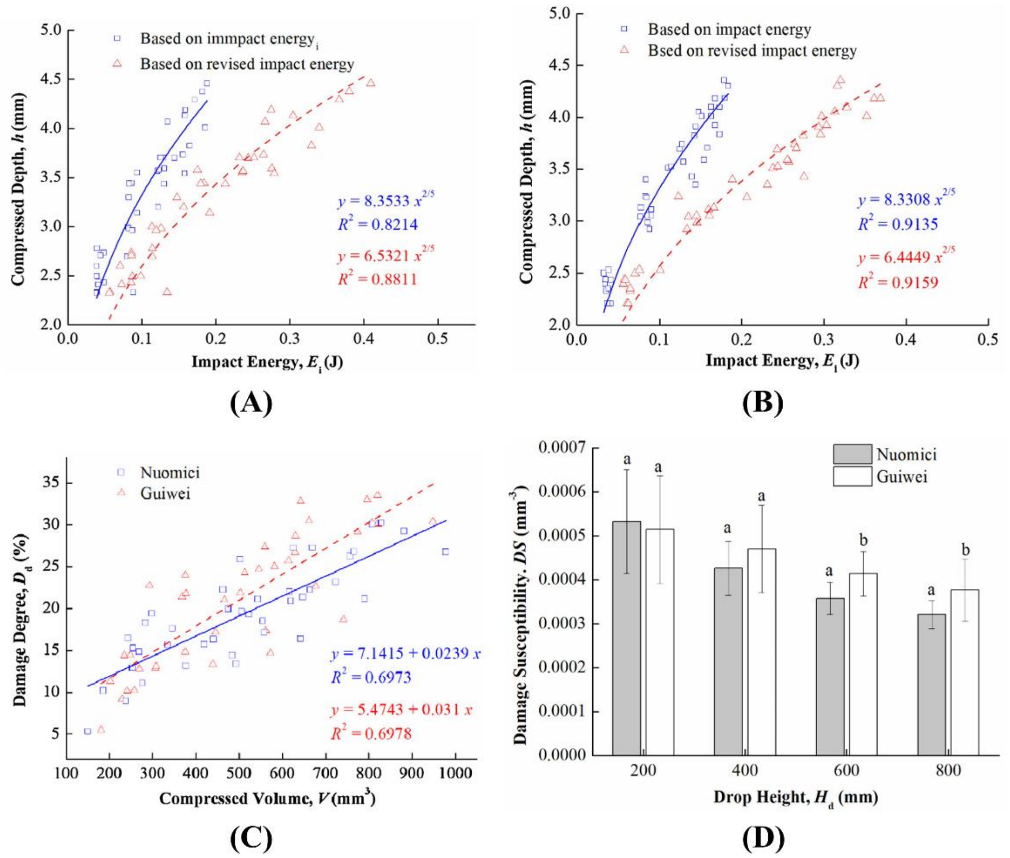

Figure 3. Compressed volume for assessing litchi damage (Wang et al., 2020). (A) relationship between compressed depth and impact energy of ‘Guiwei’; (B) relationship between compressed depth and impact energy of ‘Nuomici’; (C) relationship between damage degree and compressed volume for the two cultivars; and (D) damage susceptibility of the two cultivars at four different drop heights.

Bruise threshold and the amount of damage per unit of E_i can be used to measure the fruit susceptibility to bruise during impact loading (Bajema & Hyde, 1998). The bruise threshold for impact force commonly refers to the energy, velocity, or height thresholds at which fruit bruising begins to occur. Kitthawee et al. (2011) dropped a 96 g spherical impactor onto overmatured coconuts and found that the energy threshold level was 0.207 J and the corresponding thresholds of drop height and velocity were 0.22 m and 2.078 ms^{-1}, respectively. Stropek and Gołacki (2013) dropped apples from eight different heights to obtain different impact velocities and suggested that the maximum safe velocity for the fruit not to develop bruising was 0.25 ms^{-1}. In another study, Hussein et al. (2019a) dropped pomegranates from three different heights (0.1, 0.15, and 0.2 m) against a rigid flat ceramic floor using laboratory-fabricated equipment. The study results indicated that the impact threshold energy for bruising of 'Wonderful' pomegranates was 371.87 MJ when dropped below 0.1 m (Hussein et al., 2019a). For the amount of damage per unit of E_i, Stropek and Gołacki (2020) used BV/E_i (mm^3 J^{-1}) to measure the susceptibility of pears and found that their susceptibility increased with increasing impact velocity, amounting to around 3 cm^3 J^{-1} at velocities of 1–1.5 m s^{-1}. In another study, Zhu et al. (2016) carried out an impact test by rotating a wooden-ball (164.8 g) pendulum at three levels of Ei (1.11, 0.66, and 0.33 J) onto apples and evaluated the susceptibility using BV/Ei. They determined that the susceptibility of the test apple to impact stress ranged between 353 and 881 mm^3 J^{-1} (Zhu et al., 2016). Furthermore, according to Opara (2007), fruit size also affects fruit susceptibility. Therefore, to reduce the potential influences of fruit mass on measured bruise susceptibility, they proposed a new indicator as a function of fruit mass — called specific bruise susceptibility (mm^3 J^{-1} g^{-1}) — to quantify the potential of fruit to experience bruise damage after induced impact damage (Opara, 2007). Recently, as the determination of the BV of irregular fruit such as litchi is difficult due to the difficulty of observing bruise area, Wang et al. (2020) introduced the compressed volume to assess fruit damage. As shown in Figs. 3A and 3B, a good correlation between E_i and compressed depth was observed for both litchi cultivars. Therefore, the compressed depth can be predicted with E_i, according to elastic theory. The compressed volume can then be determined, based on the compressed depth. On the other hand, as shown in Fig. 3C, damage degree has a good linear relationship with compressed volume. Therefore, the damage degree can be calculated based on Figs. 3A, 3B, and 3C with E_i. Wang et al. (2020) defined the susceptibility of litchi fruit to impact damage as the ratio of the damage degree (change rate of the elastic modulus) to the compressed volume (volume of a spherical cap). Fig. 3D shows the calculated damage susceptibilities of two cultivars at four different drop heights.

3.3.2. Fruit susceptibility to vibration and other forces and its measurement

Fruit susceptibility to vibration damage is a function of several factors and is commonly studied using of in-transit experiments, simulation experiments, and transit-simulation experiments (Fernando et al., 2018). Çakmak et al. (2010) examined the effects of vibration on three fig cultivars (‘Sarilop’, ‘Yediveren’, and ‘Bursa Black’) based on a transit-simulation study. The results showed that the ‘Sarilop’ cultivar was more susceptible to vibration damage under off-road conditions, while the ‘Bursa Black’ cultivar was more sensitive under long highway road conditions (Çakmak et al., 2010). Thompson et al. (2008) revealed that fruit maturity might also affect fruit susceptibility; it was evident, during damage inspections, that the susceptibility of ‘Bartlett’ pears and ‘Hass’ avocados to vibration damage increased as the fruit softened during ripening after being subjected to a simulated vibration experiment. Furthermore, package layers have been shown to influence the vibration damage susceptibility of fruit. Fadiji et al. (2016a) found that apples packed on the top layer were more susceptible to vibration damage based on a simulated vibration test. In another study, based on a transit-simulation study, the bananas in the top two layers inside the package were found to be more susceptible to vibration damage than the bottom-layer fruit (Fernando et al., 2020). This result indicated that the freedom of movement of bananas further affected their damage levels (Fernando et al., 2020). In addition, the susceptibility of fruit to vibration is also affected by the frequency, acceleration, and duration of vibration. A simulation experiment indicated that watermelon flesh was susceptible to vibration with an acceleration of 0.7 g, frequency of 7.5 Hz, and duration of 60 minutes (Shahbazi et al., 2010).

Only a few works have focused on fruit susceptibility to other forces, such as compression, friction and puncture. Opara and Fadiji (2018) found that packaging design significantly affected the susceptibility of apples to compression damage. In another study, Kitthawee et al. (2011) revealed that fruit maturity and compression energy level influenced the susceptibility of coconuts and concluded that young coconuts were more susceptible to impact damage than to compression damage. For friction, Saeed et al. (2014) rubbed pears twice against the surface of a fiber tray cup to obtain their friction discoloration and found that genetic factors were related to friction discoloration susceptibility. The authors mentioned that their results could be applied to the selection of elite genotypes with lower or no susceptibility to friction early in the breeding cycle (Saeed et al., 2014). Desmet et al. (2004a, b) investigated puncture damage of tomato by means of pendulum measurements. They developed a method to predict puncture injury of tomatoes during grading based on impact measurements obtained with an electronic sphere. Studies on fruit susceptibility to mechanical damage caused by different mechanical forces are summarized in Table 1.

4 Packaging methods for protecting fruit against mechanical damage

A wide range of packaging designs and packing methods are used in postharvest handling and logistics of fresh fruit (Berry et al., 2015). Studies on the occurrence and quantification of mechanical damage to fruit can help to understand the damage mechanisms better and assist in optimizing packaging solutions (Fig. 4). Packaging absorbs the energy generated by mechanical forces and fulfills an important role in ensuring product integrity and extending the shelf life of fruit, thus comprising a key element in protecting the fruit from mechanical damage in the supply chain (Jarimopas et al., 2008; Thompson et al., 2008). Fruit packaging commonly consists of external packaging and interior packaging. Among the reported studies, the protection properties of packaging were focused on external packaging, including cartons and plastic containers, and interior packaging, including paper-based materials and foam materials. In addition, a biomimetic approach for designing novel lightweight packaging inspired by the pericarp structure is also specifically reviewed.

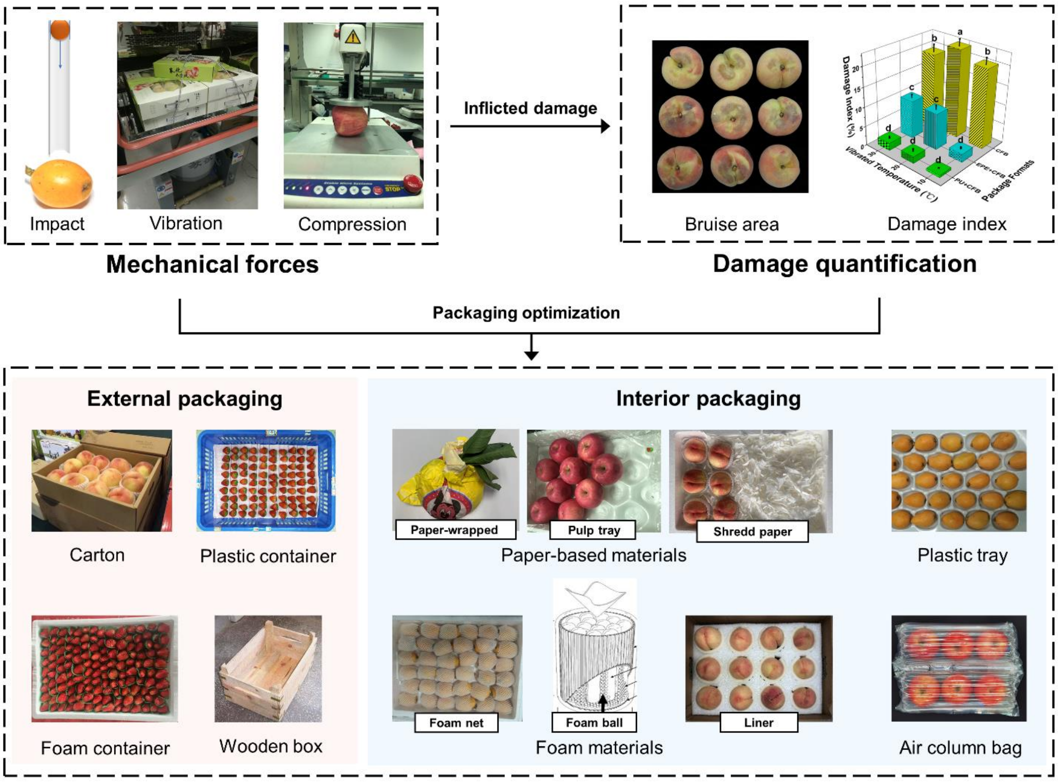

Figure 4. Studies on the occurrence and quantification of mechanical damage to fruit help to determine and optimize packaging solutions. (A) different types of mechanical forces; (B) quantification of mechanical damage; (C) external and interior packaging applications (Acıcan et al., 2007; Jarimopas et al., 2008; Lin et al., 2020).

4.1 Protective performance of external packaging

4.1.1 Paperboard carton packaging

Cartons have sufficient structural strength to protect fruit from mechanical damage and, thus, pose an ideal choice for fruit packaging. There are several advantages to using cartons to protect fruit, including lightweight, low cost, environmental friendliness, recyclability, and availability, and they can be adequately designed as needed (Pathare & Opara, 2014). Furthermore, empty cartons can be compactly folded up for convenient transportation (Pathare & Opara, 2014). The compression strength is an important factor in evaluating cartons, which mainly depends on moisture absorption, long-term compression load, and the fatigue caused by impact and vibration loads. A disadvantage of using cartons to package fruit is that, as the storage period increases, the cartons typically absorb moisture from the storage atmosphere and fruit, decreasing their compression and stacking strength (Defraeye et al., 2015; Jalali et al., 2019). Fernando et al. (2019b) revealed that the high relative humidity within the banana ripening environment contributes to weakening the structural integrity of paperboard cartons. Coated cartons are commercially available that absorb considerably less moisture.

Due to the respiration of horticultural products, cartons are usually vented in order to precool the packaged products and provide sufficient air circulation within the package, resulting in better storability and less physiological loss of the products (Pathare et al., 2012; Gruyters et al., 2018). The presence of vents can reduce the mechanical strength of the carton and increase the likelihood of package failure. Therefore, ventilation holes must be carefully added to allow air circulation through the product while providing proper structural strength (Fadiji et al., 2019). Berry et al. (2017) used computational fluid dynamics to simulate horizontal airflow through different types of boxes with ventilated holes. By comparing the values of convective heat transfer coefficient over apple surfaces for four vent hole configurations and three vent hole areas, they found that the appropriate design of vent holes may provide ventilation inside the package while maintaining the compression strength of the carton, thus avoiding compression damage of the apples in the carton (Berry et al., 2017). In addition to the structural strength of the carton, the placement of the fruit within the cartons can also affect the damage degree to fruit. The study by Lin et al. (2020) showed that packing peaches with polyurethane cushions inside cartons had better protective performance than packing with expandable polyethylene cushions inside cartons. The way the cartons are stacked on the pallet can influence the fruit damage too (Delele et al., 2013; Opara et al., 2018). Fernando et al. (2021) studied the stacking ways of packaged bananas on a pallet and found that cross-stacking of the pallet resulted in increased vibration damage to fruit, and the column-stacking of packages reduced the level of vibration.

Corrugated fiberboard boxes (CFBs), which are made up of fluted corrugated cardboard with one or two flat linerboards, are the most popular carton for fruit packaging. Specifically, the corrugated board has an orthotropic sandwich structure with a central, corrugation-shaped paper (flute) on one or two flat papers (liners) (Pathare & Opara, 2014). The combination and properties of the flute and liners determine the strength of the carton. CFBs can protect fruit from impact, vibration, friction, and compression damages, thereby providing less damage and better quality and keeping the fruit stored for a long time after transportation (Mukama et al., 2020a). The corrugated paper layers, flute type, and structure of CFB have been shown to influence the package's protective performance based on vibration tests (Jin et al., 2013) and compression tests (Frank, 2014). By using pressure-sensitive films, the pressurized areas and average pressures of apples in a single-wall CFB were determined to be larger than those in double-wall boxes (Fei et al., 2010). Fadiji et al. (2016a) and Opara and

Fadiji (2018) carried out vibration and compression tests to compare two packages with respect to damage. They found that the MK4 package, which has a higher length-to-height ratio, longer trays, and higher ventilation areas than the MK6 package, suffered less fruit damage than the MK6 package during apple transportation. Therefore, the MK4 package exhibited better protective performance than the MK6 package for apple transportation (Fadiji et al., 2016a; Opara & Fadiji, 2018).

4.1.2 Plastic container

Plastic containers are another commonly used external package. Plastic containers have been increasingly applied for the distribution of fresh products due to the potential cost-advantages obtained by the attributes of reusability and environmental friendliness, compared to single-use corrugated boxes (Fernando et al., 2020). Reusable plastic containers (RPCs) provide an integrated solution for bulk packaging, linking growers, retailers, and customers. Magda and Rahman (2006) found that the transportation losses of breaker-stage tomatoes increased by 3.13 % when using RPCs and 2.75 % when using ventilated cardboard boxes when the transport distance increased by 100 km. Although the losses of ventilated cardboard boxes were slightly lower than RPCs, the latter were still recommended for local marketing and export due to their durability and reusability (Magda & Rahman, 2006). However, it should be noted that there is an industrial concern that the rigid surfaces of the RPCs might cause fruit damage (Fernando et al., 2020). RPCs also require an (often large) washing installation in between uses. Further, RPCs may deteriorate due to brittle fracture, and the containers will eventually be unusable if exposed to sunlight for a long period of time. In addition, RPCs are typically fossil oil-based and may create substantial environmental pollution when disposed or incinerated.

4.1.3 Trade-off between CFBs and RPCs

CFBs have been demonstrated to have a better protection performance than RPCs (Chonhenchob et al., 2008; More et al., 2015; Patrignani et al., 2016; Fernando et al., 2020). By comparing different packaging designs based on simulated vibration tests of pineapples, CFBs were found to have better protective performance than RPCs and plastic foam containers (Chonhenchob et al., 2008). Patrignani et al. (2016) found that, compared to RPCs, CFBs significantly decrease microbial contamination by reducing the possibility of microbial transfer from the packaging to the fruit. Therefore, the authors suggested using CFBs as the preferred packaging option for the supply chain of peaches (Patrignani et al., 2016).

Several comparative studies have been carried out on the environmental burdens of both CFB and RPC packaging for agricultural products (Zabaniotou & Kassidi, 2003; Lai et al., 2008; Levi et al., 2011). In these studies, RPCs were found to generate lower impact than CFBs. The authors emphasized that the results depend heavily on the different logistic scenarios. By comparing 10 different agricultural products, including apples, grapes, strawberries, oranges, tomatoes, carrots, and onions, Singh et al. (2006) reported that RPCs require 39 % less total energy, generate 95 % less total solid waste, and produce 29 % less total greenhouse gas emissions compared to CFBs. Singh et al. (2016) conducted an empirical investigation to explore the economic and social sustainability impacts of standardized bulk packaging (RPCs) on the transportation of fresh produce in North America. The author demonstrated that the increased use of RPCs leads to lower costs and reduced waste. The number of uses of RPCs is a feature that leads to a strong reduction in the impact of the production phase. However, there is an asymptotic behavior when considering more than 50 uses (Lai et al., 2008).

Life cycle assessment (LCA) and life cycle costing (LCC) methodologies are often used to analysis package systems. Accorsi et al. (2014) suggested that the adoption of an RPC packaging system was preferable throughout the fruit (and other food) supply chain based on LCA and LCC analyses. In another study, Albrecht et al. (2013) applied LCA and LCC principles to analyze and compare different packages and proposed an optimized transportation system for RPCs; the results indicated that RPCs and single-use wooden boxes are more sustainable than cardboard boxes. This has been taken up by companies such as Euro Pool Systems (https://www.europoolsystem.com/), which use standard RPCs of standardized dimensions all over Europe.

Packaging is a delicate topic for strategic logistics decisions in various research fields, as it usually implies choosing between one-way transport packaging (CFBs) and reusable packaging (RPCs) (Levi et al., 2011). CFBs are generally considered to generate a higher impact on the environment than RPCs, mainly because they are typically single use. Alternatively, recyclable CFBs may increase their sustainability. Koskela et al. (2014) compared two delivery systems and concluded that the recyclable CFB system was more environmentally friendly than the reusable RPC system. Nevertheless, recyclable CFBs required a profitable and efficient recycling system (Koskela et al., 2014).

In conclusion, conflicting requirements for protection performance of packaging and economic and environmental impact in the fruit supply chain necessitates trade-offs. In general, CFBs provide better protection for fruit, while RPCs are preferable from an environmental and economic perspective. Recycling systems for CFBs should therefore be implemented and contact forces between fruit and plastic container wall should be minimized in RPC packages by, e.g., using protective materials. Finally, an optimized transportation system for the use of CFB and RPC packaging is needed throughout the fruit supply chain. It is suggested that CFBs are more suitable for situations where they are used less often or only once, while RPCs are more suitable for situations where they are often used, and this may be a potential trade-off packaging solution in the postharvest supply chain (Fig. 5).

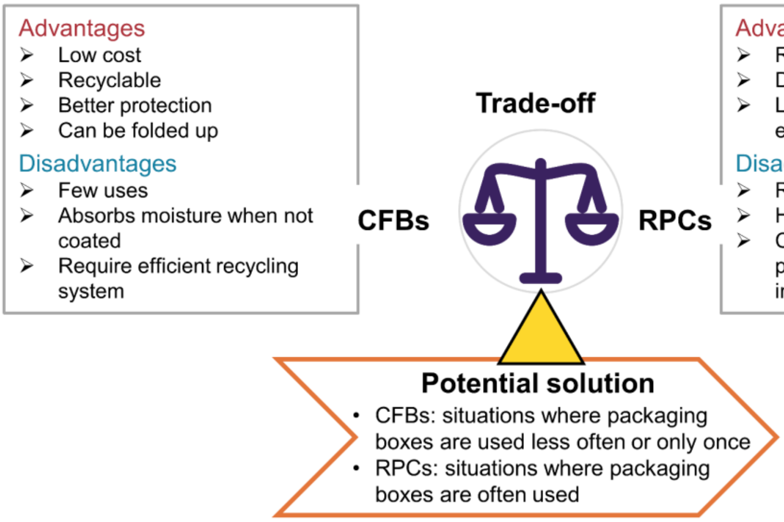

Figure 5. A potential trade-off packaging solution for fruit transportation. CFBs: Corrugated fiberboard boxes. RPCs: reusable plastic containers.

4.2 Protective performance of interior packaging

As an effective supplement to the external packaging, interior packaging provides a better cushioning effect and can further slow down or prevent external mechanical forces from being transmitted to the fruit. Therefore, interior packaging is commonly considered in the fruit supply chain to protect against fruit damage effectively. Paper-based materials and foam materials used as interior packaging are commonly used.

Paper-based materials can be fabricated into a variety of shapes and sizes, such as partitions, pads, and paper pulp molds. Opara and Fadiji (2018) found that the pulp tray inside the apple packaging was cracked after compression tests, indicating that the pulp tray absorbed the energy generated by compression loads. A similar situation of tray cracking was observed when the packages were subjected to impact (Fadiji et al., 2016b) and vibration tests (Fadiji et al., 2016a). The thickness of the paper can affect its protective performance. Cui (2012) concluded that the repeated impact strengths of transporting packages for ‘Crown’ pears increased with an increasing number of corrugated paper walls. Furthermore, the contact orientation of paper to fruit also plays an important role. Jarimopas et al. (2007) illustrated that single-face corrugated board with flutes on the outside achieved the best buffering performance for apples.

Foam materials can be designed as foam nets, foam balls, foam trays, and other forms, depending on the different demands of the fruit industry. More et al. (2015) showed that a foam sheet was a better cushioning material than banana leaves for interior packaging. In another study, Jarimopas et al. (2008) proposed a new sleeve-design foam package containing a 5 mm foam balls mixture, with sweet tamarinds inserted vertically. The foam balls mixed with the sweet tamarinds absorbed impact energy, thus diminishing the severity of the energy transmitted to sweet tamarinds and resulting in less damage to the fruit (Jarimopas et al., 2008).

Some studies have compared the protective performance of both paper-based and foam materials. Zhou et al. (2008) found that, compared with paper-wrapped packages, foam net packages better damped vibrations in transit and, therefore, provided better protective effects with respect to the firmness, hydrolase activity, and cell wall constituents of Huanghua pears. Eissa and Gomaa (2012) revealed that foam net packaging (single apple wrapping) decreased the percentage of apple damage by 50–63 % and was more effective than paper-wrapped packaging or no packaging. On the contrary, Wongsuriyasak and Srichandr (2012) demonstrated that paper pulp molds exhibited better performance than foam nets for mango transportation in firmness, weight loss, and color changes. Also, it should be noted that foam materials are plastic and are, therefore, a potential environmental burden.

Vacuum packaging can restrict fruit movement and is, therefore, a promising method to reduce damage for some fresh fruits. Fernando et al. (2020) evaluated the protective performance of vacuum tightening packaging for bananas and found that it was effective in reducing vibration damage, especially in the bottom and top layers, by more than 70%. In another study, Othman et al. (2021) also proposed that vacuum packaging holds promise for extending the shelf life of bananas. Besides, Jiang et al. (2021) analyzed vibrations, impacts and quality changes of Chinese bayberry during the actual express delivery process, and indicated that semi-vacuum packaging can reduce the amplitude of vibrations inside the package.

4.3 Protective packaging designs inspired by the structures of pericarps

Alternative fruit packaging materials that meet better protection and more environmentally friendly standards have attracted widespread attention. In nature, plants provide many excellent structures with high strength, low density, and high energy absorption capacity that can be inspiring to design novel structures. Bio-inspired structures have been proven to have better energy absorption capabilities than conventional structures (Ha & Lu, 2020). The use of a biomimetic approach for designing novel lightweight structures with excellent energy absorption capacity has been increasing in engineering fields in recent years (Ha & Lu, 2020; Lazarus et al., 2020). Particularly, some fruit pericarps already provide good protective packaging, such as pomelo, coconut, and durian. The structural characteristics of these fruit pericarps show good energy absorption capability and can be imitated to design packaging for protecting fruit against mechanical damage.

The unique spongy mesocarp layer of pomelo exhibits a special damping system property that makes it of particular interest to researchers and engineers when developing impact resistant structures. Due to the complex, layered structure of its mesocarp, which consists of an interconnected porous coating with a branching network of fibers, pomelo is capable of dissipating more than 90 % of the impact energy, thus preventing damage to the flesh (Bührig-Polaczek et al., 2016). The principle of this natural product has been widely used to develop new materials for enhanced impact absorbers based on metal foams (Fischer et al., 2010; Seidel et al., 2013; Mazzolai et al., 2014; Bührig-Polaczek et al., 2016). Inspired by the unique structure of pomelo peel, Zhang et al. (2019) constructed a novel hierarchical honeycomb and investigated its compression resistance and energy absorption capacity (Fig. 6A). The results showed that the specific energy absorption and equivalent plateau stress of the hierarchical honeycomb could be 1.5 and 2.5 times higher than the corresponding values of a conventional honeycomb in the case of out-of-plane and in-plane compression, respectively (Zhang et al., 2019). Li et al. (2019b) combined the pomelo pericarp-like layer, fiber bundles, and gradient foam to form a micro-gradient structure for effective energy absorption (Fig. 6B). The resultant bio-inspired composites were expected to be used as protective packaging materials for commercial applications in future (Li et al., 2019b).

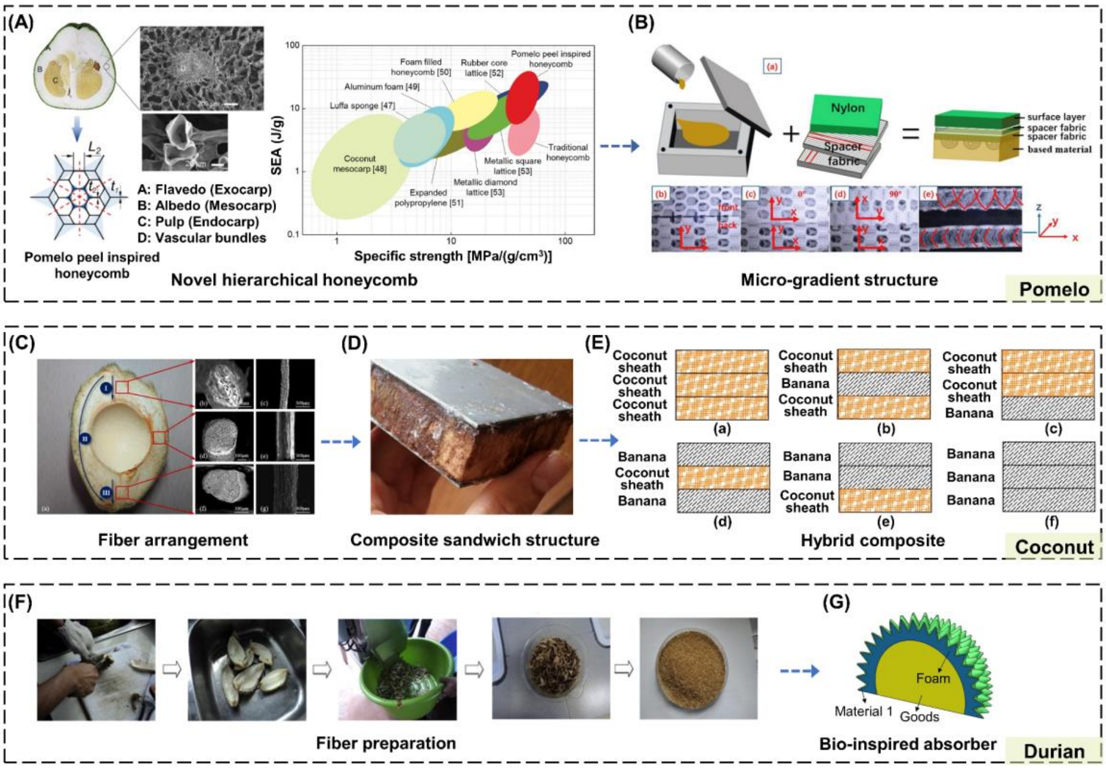

Figure 6. Protective packaging designs inspired by the structures of pericarps. (A) a novel hierarchical honeycomb inspired by pomelo pericarp (Zhang et al., 2019); (B) a

micro-gradient structure consisting of a combination of pomelo pericarp-like layer, fiber bundles, and gradient foam (Li et al., 2019b); (C) fiber arrangement of coconut pericarp (Lu et al., 2020); (D) application of coconut mesocarp as the core of a composite sandwich structure (Liu et al., 2017); (E) a hybrid composite using a combination of coconut sheath and banana fibers in a polyester matrix (Senthil Kumar et al., 2016); (F) durian peel waste produced from durian fruit showed potential as a new natural fiber-based reinforcement material (Manshor et al., 2014); (G) the spherical shape related to the thorns and mesocarp material of durian can be used as an alternative sustainable material and be imitated to design an effective bio-inspired absorber for packaging applications (Ha et al., 2020).

Coconut has outstanding crashworthiness, which is attributed to its multilayered and multiscale structure, including macroscopically ordered pericarp and microscopically disordered mesocarp (Lu et al., 2020). According to Lu et al. (2020), the fiber arrangement in the coconut increases its energy absorption capacity and affects the propagation of stress waves, thus protecting the coconut endocarp (Fig. 6C). The study provides a bio-inspired template for the design of functional gradient composites (Lu et al., 2020). In addition to their fiber orientation, coconut mesocarp materials also exhibits significant energy absorption properties of the porous materials in the grain direction (Nguyen et al., 2016). Composite reinforcement with natural coconut fibers is gaining increasing interest attributed to its low cost and easy availability (Mulinari et al., 2011; Kandare et al., 2014; Verma & Gope, 2015). For example, Liu et al. (2017)

used coconut mesocarp as the core of a composite sandwich structure with glass fiber reinforced plastic sheets (Fig. 6D), and Senthil Kumar et al. (2016) developed a hybrid composite using a combination of coconut sheath and banana fibers in a polyester matrix (Fig. 6E), both of which have shown good impact resistance.

Durian peels have a complex fibrous structure composed of cellulose (60.7 %), hemicelluloses (22.1 %), and lignin (17.2 %) (Manshor et al., 2014). The high cellulose and hemicellulose content reduces the brittleness of the lignocellulosic material in durian peels, resulting in more flexible, ductile thorns and mesocarp that can absorb more energy when loaded by mechanical forces (Manshor et al., 2014). Like other lignocellulosic fiber, durian peel fibers can reinforce polylactic acid through extrusion and injection molding processes for a variety of applications. After cleaning, chopping, grinding, drying, sieving and pretreatment with 4 % sodium hydroxide (Fig. 6F), the treated durian fibers showed potential as a novel natural fiber reinforcement by improving the properties and thermal stability of polylactic acid biocomposites (Manshor et al., 2014). The mesocarp and thorns of durian play an important role in protecting the flesh of the durian fruit when it falls to the ground (Reddy, 2012). Ha et al. (2020) showed that the spherical shape related to the thorns and mesocarp material of durian resulted in an excellent energy absorption efficiency, which can be imitated to design an effective bio-inspired absorber for packaging applications (Fig. 6G). Therefore, the structure of durian fruit peel offers alternative new insights on the design of future packaging for handling fresh fruit.

5 Future research directions

Future research areas include:

Innovative packaging designs that are reusable and biodegradable are the future trends for fruit packaging. For specific fruit with irregular shape or soft texture, such as ripe bananas, grapes, and strawberries, new packaging designs need to be studied and developed to provide better protective performance. In future research, the packaging should be customized according to the characteristics of the fruit to effectively reduce mechanical damage at a reasonable cost. On the other hand, it should be noted that the presence of vents reduces the mechanical strength of the carton and increases the likelihood of package failure (Fadiji et al., 2019). Therefore, model-based engineering design approaches should be further explored to find a balance between conflicting specifications such as mechanical strength versus sufficient airflow characteristics (Berry et al., 2017). In this regard, the virtual prototyping design approach that has recently been successfully applied to develop novel multi-layer ventilated packaging for handling pomegranate fruit holds considerable promise for wider applications in the horticultural industry (Mukama et al., 2020b; Ambaw et al., 2022). In addition, to further avoid mechanical damage to fruit during postharvest handling and logistics, research on hybrid strategies combining packaging with other protection methods is needed.

Attention must be paid to fruit diversity and maturity. Damage susceptibility is different during different stages of fruit ripening (Bugaud et al., 2014; Cañete et al., 2015). To reduce economic losses caused by mechanical damage, the fruit industry often harvests fruit that is not yet mature and has a relatively hard texture. However, this type of fruit has sub-optimal taste properties. Research and development of particular packaging designs for fully ripened fruit is necessary, as it is commercially more valuable and can establish new markets; however, at present, there have only been a few works related to protecting ripe fruit. On the other hand, little information is available on fruit with a relatively hard texture, large sizes, or thick rinds, such as watermelons, pineapples, and pomegranates. Although such fruit are relatively less prone to impact and compression damage compared with those with thin rind, the skin damage may occur when fruit are exposed to high forces, and mechanical vibration can still cause internal damage to these fruits (Zhou et al., 2015). Therefore, suitable packaging methods are still needed for such fruit.

A more thorough study of the environmental factors affecting the development of mechanical damage in the fruit supply chain is necessary. Previous simulated vibration tests in a laboratory environment were typically conducted at room temperature, with less consideration of other temperature and humidity levels (Zheng et al., 2022). Recently, several studies have noted the significance of environmental factors and conducted tests in environments similar to real supply chains, such as bananas (Fernando et al., 2019a), peaches (Lin et al., 2020), and oranges (Zheng et al., 2022). However, there is still a lack of research in this area. As fruit transportation is usually carried out in refrigerated conditions, it is important to study the effects of temperature and humidity on the protective ability of packaging methods against mechanical damage. This would allow to optimize the supply chain and protect fruit against mechanical damage.

Universally applicable test methods are needed to measure fruit susceptibility to vibration damage. The vibrations that occur during transportation are inevitable and are a major hazard in maintaining fruit quality throughout the postharvest supply chain (Fernando et al., 2021). International standards (e.g., ASTM) based on simplified Power-Spectral-Density (PSD) profiles of averaged intensity have been commonly used to simulate vibration tests in many previous studies (Fadiji et al., 2016a; Lin et al., 2020; Zheng et al., 2022). However, during road transportation, the vibration excitation of fruit in packages and corresponding in transit vibration profiles may differ due to many factors, such as road condition (Lu et al., 2008), vehicle speed (Lu et al., 2010), suspension type (Van Zeebroeck et al., 2008), stacking (Fernando et al., 2021), and package position (Zheng et al., 2022). Therefore, to obtain a more realistic and applicable vibration simulation, vibration profiles along the transit passage should be used to simulate the vibration tests. Fernando et al. (2019a) measured the vibration profile of a multi-trailer road train stacked with bananas over 3000 km and successfully loaded the profile into a vibration table for simulation vibration test. In general, there are two ways to achieve simulated vibration test: one is to record the field vibration profiles during transportation and then select similar vibration profile in ASTM standards for simulated tests, while the other is to directly upload the obtained profile data for use in the simulated vibration test. However, this requires consideration of the limitations of equipment in taking whole profile data.

Most important mechanical forces that cause fruit damage must be identified. In different phases along the supply chain, such as harvesting, handling, packaging, transportation, and retail, the main mechanical forces applied to the fruit and the corresponding damage degrees can differ (Fernando et al., 2019b). Therefore, it is better to compare the damage degree of multiple mechanical forces on fruit to determine the main forces in one experiment. Insight into which forces are prevalent and when, where, and how these forces occur and are collectively applied to the fruit is important to minimize mechanical damage. However, only a few studies have compared the effects of different mechanical forces on fruit in one experiment, let alone investigated how multiple mechanical forces are applied collectively on fruit. Such comparative and systematic studies of different forces will help to choose appropriate packaging and optimize pallet stacking, which can reduce or even avoid the most important causes of mechanical damage.

Correlation between the internal structure of fruit and its susceptibility to damage requires further investigation. The internal structure of fruit plays an important role in resisting the damage caused by mechanical forces. For example, when an external force was applied, the locular gel tissue of tomato was first injured by mechanical damage, followed by the mesocarp and exocarp tissues (Li et al., 2013). More insight into the effect of the anatomy of fruit with respect to damage susceptibility is necessary. Advanced techniques such as MRI, OCT, and X-ray CT to observe the internal structure differences of intact and damaged fruit may be useful for this purpose (Zhou et al., 2015; Diels et al., 2017; Li et al., 2019a).

Mechanisms underlying the fruit response to mechanical damage need to be clarified. Although there is considerable research on mechanical damage to fruit, it has been basically investigated in terms of damage phenotypes (e.g., damage degree and physiological indexes) (Li & Thomas, 2014; Opara & Pathare, 2014). The experimental evidence thus far has not been sufficient to explain the mechanisms of damage caused by mechanical forces at the cellular and molecular levels. In-depth and systematic investigations at the cellular and molecular level of the physiological processes that lead to mechanical damage are necessary and mathematical models based on the FEM and DEM methods. It is important to include also the natural variability in shapes and sizes of the fruit (Rogge et al., 2015). Multiscale models should be developed to study the effect of macroscopic forces on microscopic stresses and strains. These models should also be able to describe the actual failure mechanism of cells. This may lead to a better understanding of the damage mechanisms in fruit and provide the basis for theories and practices to improve fruit packaging design and protective measures to avoid mechanical damage.

6 Conclusion

Fresh fruit are susceptible to mechanical damage along the postharvest supply chain, resulting in poor consumer acceptance and loss of sensorial quality attributes. To understand how fruit responds to external stresses, the mechanisms of damage development have been studied, including those on mechanical and physiological responses. Mathematical modeling such as FEM and DEM provide advanced ways to describe and predict fruit deformation, which is important to understand the mechanical responses of fruit to external forces. Recent studies on the physiological response of fruit to mechanical damage have focused on the analysis of mechanisms at cellular and molecular levels. In particular, microcompression-holding test was used to investigate the microscale viscoelastic-plastic behavior of isolated cells, while several pathways were found involved in the fruit response to damage, including lignin and ethylene biosynthesis and lipoxygenase metabolism.

Measurement of mechanical damage to fruit allows grading of damaged fruit and calculating postharvest loss. Besides direct manual and optical measurement, some studies used physiochemical indexes for indirect measurements, such as firmness, respiration rate, and ethylene production. Also, studies have focused on measuring fruit susceptibility to mechanical damage based on bruise thresholds and the amount of damage per unit of E_i and found that fruit susceptibility was influenced by several factors, such as cultivar, ripeness, temperature, and packaging design.

Packaging methods can effectively mitigate mechanical damage to fruit and are, therefore, a hot topic of research in the fruit industry. For external packaging, improvements in the protective properties of cartons generally focused on strength, structure, and the configuration of ventilation holes. Plastic containers have been increasingly applied for product distribution due to their reusability and environmentally friendliness. Paper- and foam-based materials are commonly used in interior packaging, but their suitability differs with the fruit. Recently, the pericarps of pomelo, coconut, and durian were found to have excellent protective structures and were imitated for bionic-based packaging designs.

In addition, future research directions are provided, including in-depth and systematic studies of damage mechanisms, optimization and customization of packaging designs, and development of multiscale models to study the effects of macroscopic forces on microscopic stresses.

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Declaration of Interest

None.

Ethical statement

This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent

Not applicable.

CRediT authorship contribution statement

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Figure caption

Figure 1 Diagrammatic illustration of the structure of present review.

Figure 2 Mechanisms of damage development include the mechanical responses and the physiological responses of fruit to external forces. Vibration, impact, compression, and puncture damage are mainly consequential of mechanical force stresses. The mechanical damage of fruit can be described and predicted by mathematical models. Fruit subjected to mechanical damage exhibit a variety of physiological responses at the cellular and molecular levels. FEM: finite element method. DEM: discrete element method.

Figure 3 Compressed volume for assessing litchi damage (Wang et al., 2020). (A) relationship between compressed depth and impact energy of 'Guiwei'; (B) relationship between compressed depth and impact energy of 'Nuomici'; (C) relationship between damage degree and compressed volume for the two cultivars; and (D) damage susceptibility of the two cultivars at four different drop heights.

Figure 4 Studies on the occurrence and quantification of mechanical damage to fruit help to optimize packaging solutions. (A) different types of mechanical forces; (B) quantification of mechanical damage; (C) external and interior packaging applications (Acıcan et al., 2007; Jarimopas et al., 2008; Lin et al., 2020).

Figure 5 A potential trade-off packaging solution for fruit transportation. CFBs: Corrugated fiberboard boxes. RPCs: reusable plastic containers.

Figure 6 Protective packaging designs inspired by the structures of pericarps. (A) a novel hierarchical honeycomb inspired by pomelo pericarp (Zhang et al., 2019); (B) a micro-gradient structure consisting of a combination of pomelo pericarp-like layer, fiber bundles, and gradient foam (Li et al., 2019b); (C) fiber arrangement of coconut pericarp (Lu et al., 2020); (D) application of coconut mesocarp as the core of a composite sandwich structure (Liu et al., 2017); (E) a hybrid composite using a combination of coconut sheath and banana fibers in a polyester matrix (Senthil Kumar et al., 2016); (F) durian peel waste produced from durian fruit showed potential as a new natural fiber-based reinforcement material (Manshor et al., 2014); (G) the spherical shape related to the thorns and mesocarp material of durian can be used as an alternative sustainable material and be imitated to design an effective bio-inspired absorber for packaging applications (Ha et al., 2020).

No color is required for any figures in the print version.

Table 1. Fruit susceptibility to mechanical force and its measurement.

Mechanical force	Experiment approach	Fruit	Influence factor	Indicator to measure susceptibility	Main results about susceptibility	Reference
Impact	Pendulum impactor test	Tomato	Cultivar, location of impact	A logistic regression function based on accurate impact data, fruit parameters, and a sensory-based score	Tomato bruise susceptibility was dependent on cultivar and location of impact	Van Linden et al. (2006)
		Apple	E_i	BV/E_i (mm^3 J^{-1})	E_i threshold: 353–881 mm^3 J^{-1} for test apples	Zhu et al. (2016)
		Pear	Impact velocity	BV/E_i (cm^3 J^{-1})	E_i threshold: 2.8–3.3 cm^3 J^{-1} for 'Lukasówka' and 2.9–3.4 cm^3 J^{-1} for 'Xenia'	Stropek and Gołacki (2020)
		Litchi	Cultivar, drop height	Damage degree per unit compressed volume (mm^{-3})	Damage susceptibility decreased with the increase of drop height	Wang et al. (2020)
	Spherical impactor test	Apple	Management practice, harvest date, and fruit	BV/E_i (mm^3 J^{-1}) $BV/(E_i \times m_F)$ (mm^3 J^{-1}g^{-1})	The management practices and harvest date could affect the fruit susceptibility to impact force	Opara (2007)

		size			
	Coconut	Maturity, impact energy level	BV (mm^3), E_i (J)	BV threshold (immature: 422.8 ± 47.9, mature: 345.5 ± 47.1, overmature: 307.9 ± 48.0) E_i threshold (immature: 0.264, mature: 0.245, overmature: 0.207)	Kitthawee et al. (2011)
	Banana	Cultivar, maturity, and fruit temperature	Lowest impact energy producing a visible bruise (J)	Positively correlated with peel electrolyte leakage (R = 0.78), negatively correlated with hardness (R = -0.45), not correlated with polyphenolic content	Bugaud et al. (2014)
	Loquat	Maturity	BA, BV, bruise color	Susceptibility increased as the fruit softened during ripening	Cañete et al. (2015)
Drop test	Apple	Package design, layer, and drop height	BV/E_i (mm^3 J^{-1})	Fruit in the bulk package had 66 % higher bruise susceptibility than fruit on trays	Fadiji et al. (2016b)
	Apple	Cultivar, drop height	Velocity (m s^{-1})	Maximum safe velocity was 0.25 m s^{-1}	Stropek and Gołacki (2013)

		Olive	Cultivar, Ei	BV/E_i (mm^3 J^{-1})	Higher in the ‘Manzanilla’ cultivar, followed by ‘Hojiblanca’ and ‘Gordal Sevillana’ cultivars	Jiménez-Jiménez et al. (2013)
		Pomegranate	Cultivar, drop height, and fruit temperature	BV/E_i (mm^3 J^{-1}) $BV/(E_i \times m_F)$ (mm^3 J^{-1}g^{-1})	Susceptibility: ‘Wonderful’ > ‘Herskawitz’ > ‘Acco’ cultivars	Hussein et al. (2019a)
Vibration	Simulation	Pear and avocado	Maturity	Damaged fruit (% of total)	Susceptibility increased as the fruit softened during ripening	Thompson et al. (2008)
		Apple	Package design and frequency	BA, BV, bruise percentage	Susceptibility: MK6 > MK4 package; top layer > bottom layer	Fadiji et al. (2016a)
	Transit-simulation	Fig	Cultivar, road condition	Total damage score	‘Sarilop’ cultivar was more susceptible under off-road conditions, while ‘Bursa Black’ cultivar was more sensitive under long highway road conditions	Çakmak et al. (2010)
		Watermelon	Vibration frequency, acceleration, and	Percentage of the decay on the modulus of elasticity	Watermelon was susceptible to vibration at 7.5 Hz frequency, 0.7 g acceleration, and 60 minutes duration	Shahbazi et al. (2010)

			duration			
		Banana	Package layer	Mechanical damage index	Greater susceptibility in the top two layers	Fernando et al. (2020)
Compression	Compression tester	Apple	Packaging design	*BA*, *BV*, non-bruise percentage	Susceptibility: MK6 > MK4 package	Opara and Fadiji (2018)
	Universal Testing Machine	Coconut	Maturity, compression energy level	BV (mm^3), E_i (J)	BV threshold (immature: 2073.8 ± 382.2, mature: 1435.9 ± 329.4, overmature: 1090.5 ± 414.4) E_i threshold (immature: 2.17 ± 0.28, mature: 1.13 ± 0.19, overmature: 0.76 ± 0.19)	Kitthawee et al. (2011)
Friction	Rubbing against fiber tray cup surface	Pear	Cultivar (genotype)	Friction discoloration score	Substantial variation of susceptibility between genotypes	Saeed et al. (2014)

BA: bruise area; BV: bruise area; E_i: impact energy; m_F: specimen mass (g).