Review Article
Food Science and Technology
ISSN 0101-2061 (Print)
ISSN 1678-457X (Online)
DOI: https://doi.org/10.1590/fst.001823

Mechanical damage characteristics and nondestructive testing techniques of fruits: a review

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Abstract

Fruits will be subjected inevitably to various external forces in the process of harvesting, transportation, processing, and storage, which will cause mechanical damage. The research on mechanical properties and damage mechanisms of fruit can effectively control its loss. In this study, fruits are divided into different types according to their morphology and structure. The impact, vibration, static pressure, and other mechanical damage on fruits are studied. It is important to identify the damaged parts of fruit after damage quickly and accurately. Therefore, this study analyzes the application of nondestructive testing technologies such as spectral detection technology, NMR (nuclear magnetic resonance) detection technology, and acoustic and electrical characteristics detection technology in fruit damage detection.

Keywords: fruit; mechanical damage; nondestructive testing; impact characteristic; vibration harvesting.

Practical Application: The review summarized the mechanical damage characteristics and non-destructive testing technology of fruit, which can provide a reference for the design and optimization of damage reduction in the process of fruit harvesting, storage, and transportation, as well as the improvement of related damage detection technology, to effectively improve the harvest efficiency and fruit quality. It is of great significance to the development of food production and perversion. The study can provide an important practical significance for the promotion and application of mechanized and automatic fruit processing equipment.

1 Introduction

With the improvement of human living standards, people have high requirements for quality of life (Kabas et al., 2008). Fruits are rich in amino acids, vitamins, proteins, and minerals necessary nutrients for the human body, which can provide the necessary energy for the human body and trace elements (Li et al., 2019a). In addition, some bioactive substances contain in the composition of fruit also have the effect of disease prevention and health (Zhou et al., 2019), so fruits have become an indispensable important part of a human healthy diet (Ma et al., 2017). At present, China is the first country to produce fruit in the world, then the fruit planting area continued to grow in recent years. The country's fruit production was about 286.92 million tons in 2020 (Zhang, 2022). With the continuous increase in fruit production, its quality has gradually become the focus attention.

In the process of harvesting, transportation, and storage, fruits will inevitably be subjected to different loads such as static pressure, collision, and vibration, which will cause mechanical damage to them. Mechanical damage can directly destroy the cellular structure in the injured part of the fruit, resulting in the rapid softening of the pulp tissue and the browning of the injured part of the tissue (Wang et al., 2008). In the mild case, the appearance grade of the fruit will be reduced, and the senescence will be accelerated. Severe cases can lead to obvious wounds on the surface of the fruit, which will accelerate the rot of the fruit, and seriously affect its quality and economic benefits (Song et al., 2016). The research on mechanical properties and damage law of fruit can effectively control its loss, which can provide the necessary scientific theory for the reduction design, optimization, and improvement of harvesting, grading, packaging, storage, and transportation operation equipment. The study can provide the information for food damage in the process of harvest.

At the same time, it is also important to identify damaged fruits in time. In the field of fruit nondestructive testing, scholars have carried out long-term research and formed a series of testing technologies. Nondestructive testing (NDT) is a technology that uses the sensing characteristics of light, sound, electricity, magnetism, and force to evaluate the external and internal quality information of fruit without damage or affecting the physical and chemical properties of test objects (Liu et al., 2020a). Compared with traditional detection technology, it can ensure the integrity of the test object and avoid the loss of sample components and nutrients in the detection process (Yi et al., 2021). The method has the advantages of fast detection speed, low detection cost, real-time online detection, and so on.

In this study, fruits are divided into berries, drupe, kernel fruit, hesperidium, and nuts according to the morphology, structure, utilization characteristics, and growth habits of fruits. The study on the mechanical damage characteristics of falling impact, vibration, and static pressure are summarized. In addition, the application of nondestructive testing techniques such as spectral detection, NMR detection, and acoustic and electrical characteristics detection in fruit damage detection are analyzed.

Received 09 Jan., 2023
Accepted 03 Feb., 2023
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2 Mechanical damage characteristics of fruits

2.1 Berry

Berry is the fruit formed by the development of a single carpel or multiple carpels synthesized pistil, superior or inferior ovary, thin ectocarp, mesocarp, and endocarp fleshy and containing one or more seeds. Compared with other kinds of fruit, berries contain more species.

Drop impact characteristic

In recent years, given the optimization of berry harvesting parameters, scholars have established the relationship between design parameters, fruit damage, and harvesting efficiency through drop impact test and FEM (finite element method). The characteristics of drop impact were explored.

Bao et al. (2017) took fruit deformation energy as an index to evaluate the degree of fruit damage and studied the internal damage caused by the collision between blueberries and fruit board during the harvesting process. The evaluation criteria for mechanical damage of blueberry fruits are shown in Table 1. Wang et al. (2020) applied the pendulum device to carry out the drop impact test on two kinds of litchi fruits, which studied the characteristics of impact force, surface pressure, and contact surface in the impact process with the change of drop height. The results show that the method could be applied to evaluate the damage to litchi fruit and optimize the design of the litchi vibrating device. The deformation stage of litchi fruit during impact is shown in Figure 1.

Ma et al. (2018) conducted drop impact tests on grapes at different heights combined with simulation, which analyzed the relationship between drop impact velocity and impact damage degree of fruit. Zhao et al. (2019) carried out an explicit finite element dynamic method to evaluate the impact damage of wolfberry. Hussein et al. (2018) explored the bruising sensitivity of pomegranate fruits during long-term storage through drop impact tests at different heights. Du et al. (2019) predicted the damage sensitivity of kiwifruit fruit by FEM and verified it by high-speed camera recording. The simulation of the falling process of kiwifruit fruit in different directions is shown in Figure 2.

The research on the impact characteristics of the fruit falling, impact height, impact angle, and fruit board material have obvious effects on fruit damage. Moreover, scholars have established corresponding damage indexes to evaluate the degree of damage according to different fruits. Table 2 shows the comparison of different fruit damage selections.

Vibration characteristics

Vibration harvesting is the main mechanical harvesting method for berries, such as blueberries, wolfberries, mulberries, and so on. Many scholars have established the relationship among harvesting parameters, such as vibration frequency, and fruit damage, harvesting efficiency through vibration detection devices, and combined with frequency sweep analysis, explore the vibration characteristics of fruits.

Ding et al. (2016) studied the vibration shedding rule of mulberry through a dynamic test system and explored the optimal vibration parameters of mulberry vibration harvesting. The results show that when the amplitude is 18 mm, the rotation speed is 1700r/min, and the main vibration frequency is 28Hz, the fruit picking rate is the best.

He et al. (2017a) established the vibration separation test platform to carry out the fruiting branch and vibration separation test on wolfberry. They used high-speed photography to analyze the dynamic response of its branches, then obtained the optimal parameter combination of the picking effect and the acceleration response relationship between the tertiary branch and the fruiting branch. The results can provide a reference for mechanized harvesting of wolfberry.

The motions of litchi fruit during vibration harvesting can be studied by a high-speed camera. Wang et al. (2019) applied

Table 1. Evaluation criteria for mechanical damage of blueberry fruits.

Softening degree	Deformation energy ($E/\times10^{-3}$ J)	Damage evaluation
No change	(0,0.68)	No damage
mild	(0.68,2.72)	Slightly damaged
moderate	(2072,7.86)	Moderate damage
severe	(7.86,10.4)	Severe damage
rupture	10.4	rupture

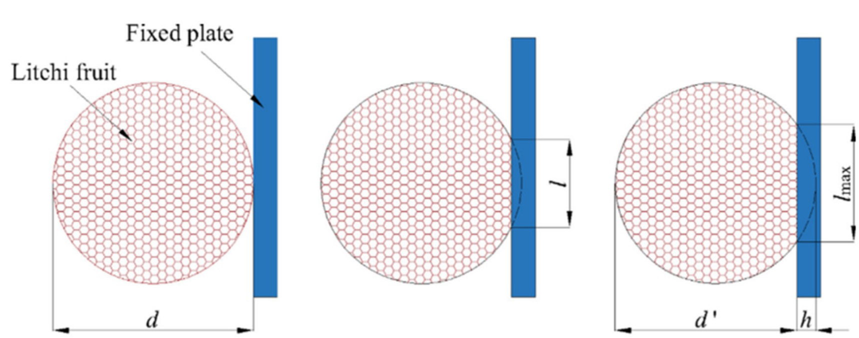


Figure 1. Deformation stage diagram of litchi fruit during impact.

Table 2. Comparison of different fruit damage selections.

Fruit species	Select factors	The damage index	Conclusion
Blueberries	Angle of fruiting plate Drop height The fruit quality	Fruit deformation energy	When the distance between the fruit and the fruiting plate was close to 600 mm and the Angle of the fruiting plate was close to l5°, the damage degree was minimal.
Litchi	Drop height	The compressed volume	The damage sensitivity decreases with the increase in drop height. 'Nuomici' is more resistant to impact damage than 'Guiwei' when the drop height is changed from 600 mm to 800 mm.
Grapes	Impact velocity	Coefficient of collision recovery	When the collision speed was less than 1.5 m/s, the damage inside the grape was small. When the collision velocity was 1.5 m/s, the maximum stress inside the grape was 0.19 MPa, and the grape began to suffer great damage.
Wolfberry	Drop height The impact Angle Material of impact	Fruit bruising rate	When the drop height is 0.2-0.5 m, the impact Angle is 10-30°, and the impact materials are wood, foam board, and nylon board, the fruit will not be damaged.
Pomegranate	Drop height	Sensitivity to damage	The bruised area and volume of pomegranate fruits increased significantly with the increase in drop height and cold storage time.
Kiwi fruit	Drop height	Sensitivity to damage	Damage is more likely to occur in the horizontal direction, and the damage volume and sensitivity errors measured by simulation and experiment are less than 17.1% and 18.3%, respectively.

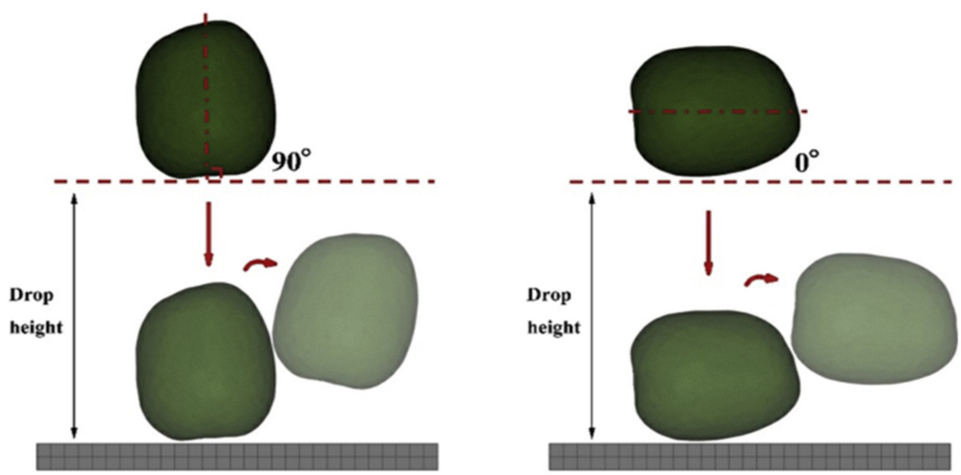


Figure 2. Simulation of falling process of kiwifruit fruit in different directions.

it to study the separation time, impact times, and impact energy absorption of litchi fruits in the vibration process at three frequencies, which are 18 Hz, 25 Hz, and 32 Hz respectively. The results show that when the vibration frequency is 32 Hz, the average estimated damage degree is 5.69%. The schematic diagram of the vibration detection device and the moving image of litchi captured by the high-speed camera is shown in Figure 3. Wang et al. (2022a) performed quasi-static traction and tilt tests on litchi, as well as vibration detachment tests with frequencies of 9, 12, and 15 Hz and amplitudes of 100 and 130 mm. The results show that 12 Hz/130 mm and 15 Hz/100 mm are the optimal parameter. The research can provide a reasonable vibration frequency for high rate and low damage mechanical harvesting of litchi fruit.

Xiao et al. (2019) conducted a vibration test on grapes to explore the impact of packaging methods on their physiological quality. It is found that the mass loss rate of the new packaging is reduced by 27.07% and 21.42%, and the surface damage coefficient is reduced by 20.11% and 17.61% under the two vibration modes. Yan et al. (2021) studied the vibration shedding characteristics and dynamic response of table grapes under the excitation of broken stalk through the picking vibration test and frequency sweep analysis under modal superposition. It is drawn that when the frequency of grapefruit falling off is 4 Hz, and the peak rate of mutation is 0.92 mm/s, the peak acceleration is 39.08 mm/s^2, and the maximum swing amplitude is 49.88 mm. The picking test bed and modal analysis of grape bunches are shown in Figure 4.

Compared with other fruits, the berry is small and more fragile, which is more prone to damage during vibration harvesting. At present, the research on the mechanized harvesting of berries is still in the primary stage. Therefore, a large number of harvest parameters are needed as theoretical guidance to ensure that the fruit can fall off smoothly and reduce its damage as much as possible.

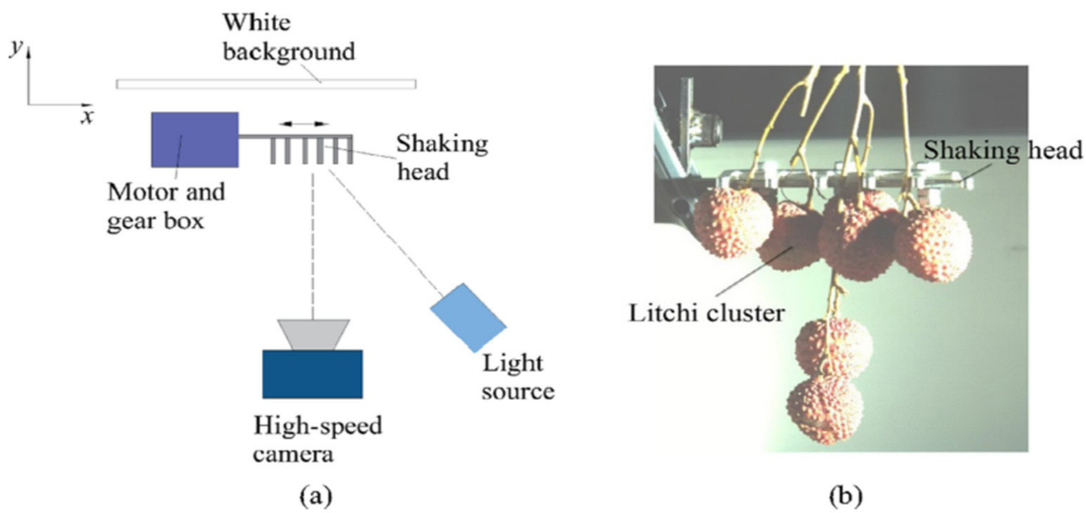


Figure 3. (a) Schematic diagram of vibration detection device; (b) Moving image of litchi captured by high-speed camera.

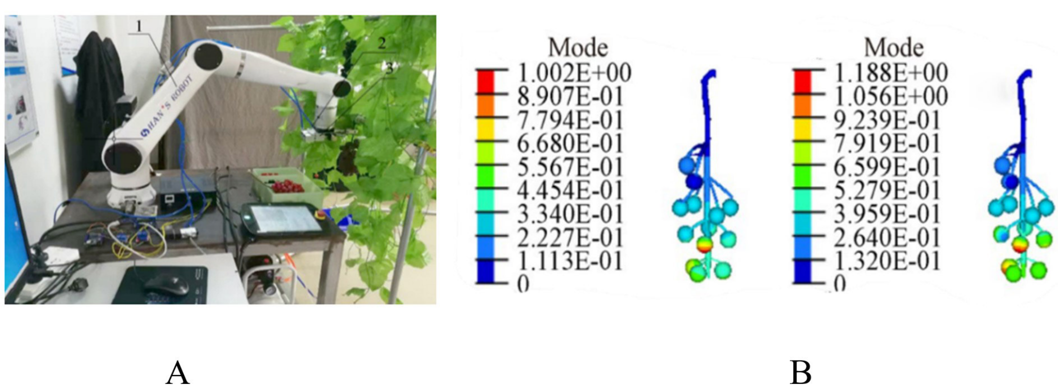


Figure 4. (A) The picking test bed; (B) modal analysis of grape bunches (order 4 ~ 5).

Static pressure characteristics

Given the static pressure characteristics of berries, a large number of scholars have explored the influence of various factors on fruit damage through the combination of experiments and FEM.

Lv & Wang. (2018) explored the effects of fruit diameter, loading speed, and anomalous stage height on the cracking force of blueberries, and obtained the result of blueberry diameter on the damage. Li et al. (2016) applied the FEM to simulate the process of external force squeezing litchi along different directions and obtained the equivalent stress cloud map of the internal organization of litchi. Hou et al. (2021) studied the influence of different parameters on the compression damage of mulberry through a compression test. The results show that the degree of compression damage is mainly affected by the loading displacement during compression. When the loading displacement increased from 3.0 mm to 6.0 mm, the indentation area ratio increased from 0.0725 to 0.2756. This study can provide a reference for reducing the extrusion damage of mulberry in the process of mechanized production and processing.

The static pressure test can be applied to determine the mechanical characteristic parameters of fruit and provide parameters for related harvesting and processing machinery. Meng et al. (2016) conducted compression tests on seedless white grapes under different loading conditions. The results show that the compressive resistance of seedless white grapes is anisotropic, and the longitudinal is greater than the transverse. Tian et al. (2018) used the universal testing machine to determine the mechanical properties of kiwifruit peel and pulp, then conclude that kiwifruit peel has isotropic material, and the pulp has orthogonal anisotropic material.

2.2 Drupe analysis

Drupe is the fruit formed from a single carpel pistil and superior ovary, the pericarp is thin, the mesocarp fleshy and the endocarp hard. It is called a drupe because its endocarp hardens and becomes a nucleus. At present, there are many studies on jujube, cherry, and apricot, and their damage rules of them are explored through mechanical tests related to fruit compression, vibration, and falling.

Drop impact characteristic

Many scholars studied the drop characteristics of drupe fruits. Kabas & Vladut (2015) used the FEM to analyze the drop of peach samples and obtained the stress distribution and deformation morphology under the impact. Zhou et al. (2016a) studied the effects of buffer material, drop height, and fruit receiving surface inclination on cherry fruit bruising damage. In the experiment, a force sensor and high-speed camera are applied to measure impact force and deformation respectively. The results show that the maximum impact force increases linearly with the increase in height. The damage of mechanically harvested fruit is lower when the tilt angle is 60°. The homemade fruit drop research platform is shown in Figure 5. Han et al. (2022) modeled cherry-to-rigid surface and collision systems using dynamic FEM, and developed a horizontal collision test bed of fruit and rigid surface to validate the prediction accuracy of the fruit finite element model.

Through the drop test analysis of peach, cherry, and other fruits, it can be drawn that the high-speed photography system is widely used in the analysis of the drop process. In the process of harvest, selecting the appropriate material and angle of the fruit plate can effectively reduce fruit damage. The height of the fruit drop should be minimized according to the specific harvest environment.

Vibration characteristics

The inertial force of fruit is the key factor to the fruit harvesting effect. According to the research, it is found that the position, frequency, amplitude, and time of vibration have a great influence on the magnitude of inertial force. Therefore, it can get a better harvesting effect by selecting appropriate vibration parameters.

San et al. (2018) established the vibration response model of the almond tree to analyze its vibration response status at different locations after vibration excitation. The result shows that when the almond tree is excited at 11.56Hz, the acceleration value of each detection point is the maximum. Yang et al. (2019) applied the FEM to analyze the influence of different vibration characteristics parameters on the vibration detection points of apricot trees and carried out experimental verification. The optimal vibration harvesting combination is obtained as follows: vibration time is 7.207 s, vibration frequency is 15Hz, and excitation point amplitude is 10 mm. The finite element model of the almond tree and vibration detection platform is shown in Figure 6.

Zhou et al. (2016b) studied the effect of vibration frequency on the motion, separation time, and damage of cherry fruit by capturing fruit trajectories at 10, 14, and 18Hz with the high-speed camera. The results show that the vibration frequency has significant effects on fruit removal time and fruit damage rate.

In addition, a large number of scholars have studied the vibration characteristics of jujube. For example, the vibrating picking head was applied to vibrate the branches of winter jujube and its movement rule and shedding track in the harvesting process are explored (Fu et al., 2018). Fu et al. (2017) took red jujube as the research object and studied its vibration-harvesting effect. Ding et al. (2019) optimized the excitation frequency of the jujube excitation device and conducted field experiments on its working performance and operation effect. The research can provide the basis for the design of the excitation system of the harvester.

The reasonable vibration parameters can not only improve harvesting efficiency but also reduce fruit damage. The vibration frequency has a greater impact on fruit damage. The effects of vibration parameters on partial fruit damage and harvesting efficiency are shown in Table 3.

Static pressure characteristics of experiment

Many scholars studied the static compression mechanics and mechanical damage characteristics of jujube by combining experiments with FEM. The compression experiments and finite element simulation were conducted on jujube and analyzed its elastic modulus and contact stress under different compression directions (Peng et al., 2017). Lu et al. (2017) conducted horizontal and vertical compression tests on two kinds of jujubes at different loading speeds. Zhang et al. (2016) conducted compression

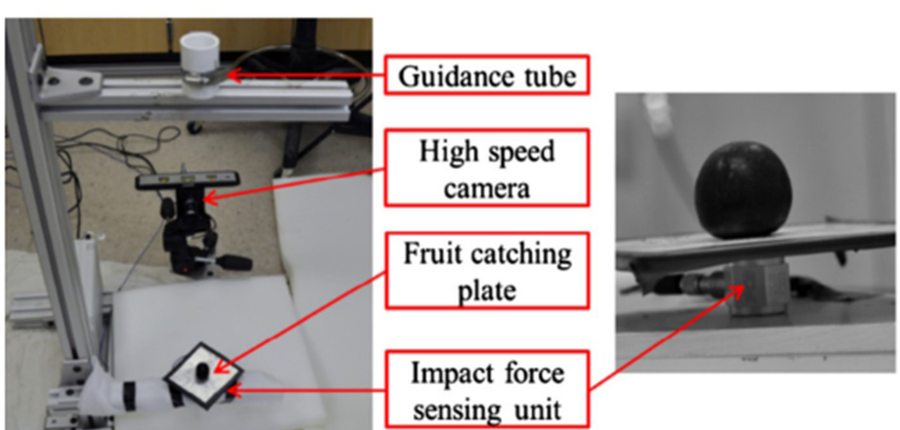


Figure 5. Fruit drop research platform.

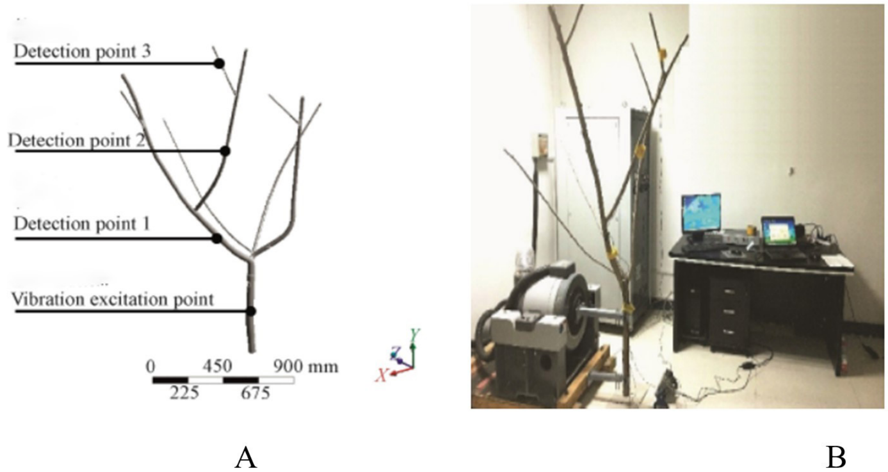


Figure 6. Almond finite element model (A) and vibration detection platform (B).

Table 3. Effects of vibration parameters on fruit damage and harvesting efficiency.

Fruit	Vibration parameters	Conclusion	Reference
Cherry	Frequency	The speed of fruit removal was faster at high frequencies, and the damage rate was the lowest (47.1%) at 14 Hz.	Zhou et al. (2016a)
Apricot	Frequency	When the almond tree was excited at 11.56 Hz, the acceleration value of each detection point reached the maximum.	San et al. (2018)
Red Jujube	Frequency amplitude	When the amplitude was 7 mm and the frequency was 17 Hz, the force transfer effect was better in the process of vibrational harvesting.	Fu et al. (2017)
	Frequency	When the excitation frequency was 16.5-17.4 Hz, the net harvest rate was more than 90% and the damage rate was less than 8%.	Ding et al. (2019)
Winter Jujube	Frequency	At frequencies of 15 Hz, 20 Hz, and 25 Hz, the proportion of the number of fruit dropped in the rotation type was 81%, 66%, and 78%, respectively.	Fu et al. (2018)

experiments on fresh jujube fruit and established the finite element model for fresh jujube by observing the rupture characteristics of fresh jujube. The results showed that the compressive ability of fresh jujube was anisotropic. These studies can provide the theoretical basis for loss reduction design in the process of harvesting, transportation, and storage of fresh jujube.

2.3 Kernel fruit

The center of the kernel fruit has several seed chambers made of thin walls, which contain seed kernels. The apple and pear are the representative types.

Drop impact characteristic

Many scholars explored the drop impact characteristics of apple fruits by establishing corresponding damage indexes and analyzing the effects of various test parameters on fruit damage. Stropek & Gołacki (2016) used high-speed cameras and pressure sensors to conduct impact tests on apples and obtained the relationship between plastic deformation energy and impact velocity. It indicated that the collision recovery coefficient could be used as a parameter to measure fruit damage. Ahmadi et al. (2016) applied FEM to analyze the impact between apples and rigid plates, and then analyzed the impact characteristics of each layer of apple peel, cortex, and core. The results show that at the speed of 1 m/s, the parameters of the collision between apples are smaller than those of the collision between apples and rigid bodies. The stress distribution in the finite element model when apples collide at 1m/s is shown as Figure 7.

Hu et al. (2021) improved the conventional drop test, set apples to collide with materials with the horizontal forward velocity at a certain height, and explored the influence of different impact materials, horizontal velocity, and falling direction on fruit damage. Scheffler et al. (2018) established a coupling model of apple, then studied the bruising formation caused by multiple collisions and the variable duration with the DEM (discrete element method). Stopa et al. (2018) carried out impact tests on apples with different heights, established the relationship between the bruised area and the damaged volume of the fruit, and determined the damage threshold of the apple, which could effectively evaluate the damage of the apple. The image comparison of the fruit surface and bruising depth when the drop height is 40 mm is shown in Figure 8.

Similarly, a large number of studies have been conducted on the impact characteristics of pear fruits. Yousefi et al. (2016) studied the impact of drop height, impact surface material, and drop direction on the fall damage of pear fruits. The results show

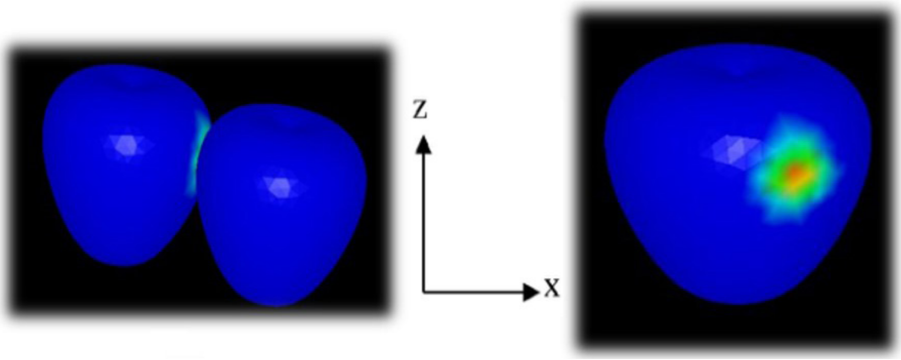


Figure 7. Stress distribution in finite element model of Apple collision at 1 m/s.

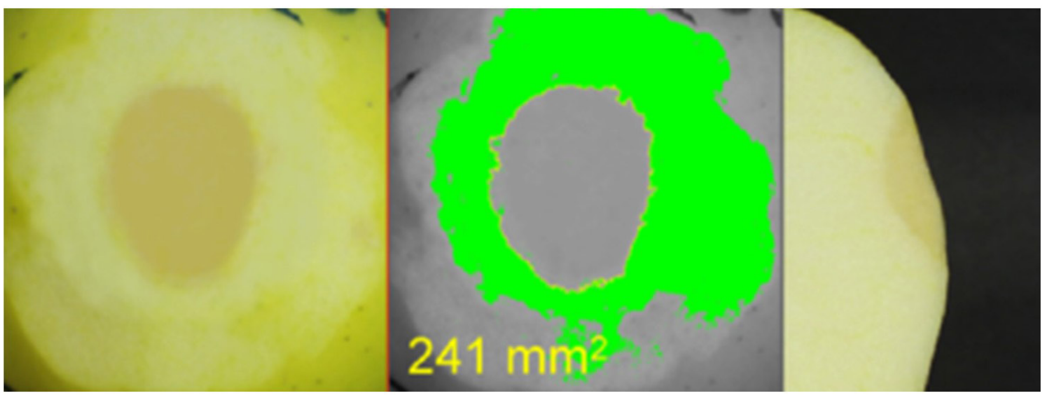


Figure 8. Comparison of fruit surface and bruise depth images.

that the damaged area of unripe pears on the wood surface is the smallest in the vertical direction and the drop height of 200 mm, while the damaged area of unripe pears on the steel surface is the largest in the horizontal direction and the drop height of 1000 mmi. Salarikia et al. (2017) studied the falling process of pear fruit and evaluate the stress and strain distribution patterns resulting from the collision of pear fruit with different materials. Celik (2017a) also determined the damage sensitivity of pears under various impacts conditions by FEM. Stropek & Gołacki (2020) analyzed the impact results recorded by the high-speed camera to explore the relationship between damage sensitivity, internal damage energy, and impact velocity. The results show that both the sensitivity and internal damage energy increase with the increase in impact velocity. The self-made impact test platform is shown in Figure 9.

Figure 9. Impact test bench.

To carry out a drop impact test on fruit, it is necessary to define the damage index and establish the relationship between the damage index and test parameters. Table 4 shows the fruit damage indexes and corresponding conclusions during the experiment.

Vibration characteristics

Vibration frequency and amplitude are important parameters to study the vibration characteristics of fruits. The reasonable vibration parameters can ensure the fruits fall off with as little damage, which is the key factor to realizing vibration harvest.

He et al. (2017b) analyzed the dynamic response of apple fruit to its position under different vibration frequencies. The results show that the position of the fruit has an important effect on the fruit shedding during shaking. When the vibration frequency is 20Hz, about 90% of fruits with a location index greater than 0.06 are detached. The positions of the shaking point and sensors

Table 4. Fruit damage index and corresponding conclusions.

Fruit	Damage index	Conclusion	Reference
Apple	Sensitivity to damage	In the range of impact velocity where damage occurs (0.75-1.5 m /s), the damage sensitivity increases with the increase of impact velocity.	Stropek & Gołacki (2016)
	Damage threshold	The damage threshold and anti-damage properties of apples can quickly and effectively evaluate the degree of fruit damage.	Stopa et al. (2018)
	Damage volume	The impact damage of the apple decreased with the increase of the horizontal velocity of the impact material, and the maximum damage of the apple and rubber plate could be reduced to 51.43% of that of the rubber plate at rest.	Hu et al. (2021)
Pear	Sensitivity to damage	The peak deformation of the two varieties was 42% and 39% of the scratch depth on average. The contact width was 146% and 135% of the scratch width on average.	Stropek & Gołacki. (2020)

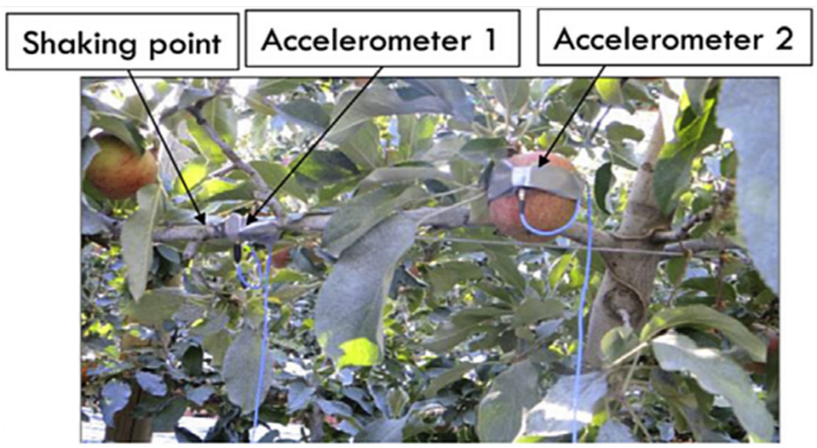


Figure 10. Position of shaking point and installed sensors.

are shown in Figure 10. Fu et al. (2019) studied the influence of vibration amplitude on the mechanical harvesting of apples by using a linear obsessive shaking table with adjustable amplitude and frequency. The results show that the fruit removal efficiency increase significantly with the increase of the amplitude in a certain range.

Pears will inevitably be damaged by vibration in transportation, then the scholars have made a study on this. A shaking table was applied to simulate transportation conditions and the damage caused by vibration and the change in its viscoelasticity during transportation were studied (Liu et al., 2016a). Cao et al. (2017) studied the vibration characteristics of pear under the regular vibration system, then the influence of vibration parameters such as vibration acceleration and vibration frequency on pear damage were drawn. Wang et al. (2022b) studied the mechanical damage of pear under random vibration excitation considering package type, vibration level, and vibration duration. The research provided references for the vibration-resistant packaging design of the pear, thus minimizing its mechanical damage of it in the supply chain.

Static pressure characteristics

The basic mechanical parameters and compressive properties of fruit were analyzed by the compression test, which provides a theoretical reference for the related research. Pham & Liou (2017) studied the elastic modulus, fracture, compressive strength, and other mechanical properties of pear through a static compression test. Li et al. (2018) analyzed the mechanical properties of apple cubes under compression, which established its compression mechanical model, and obtained the compressive elastic modulus of apple and the maximum elastic limit under compression. Li et al. (2019b) explored the influence of compression amount, loading position, loading rate, and other factors on the static pressure characteristics of fragrant pear. Yang et al. (2021) conducted a static pressure damage test on fragrant pear and established a mathematical model of the relationship between the deformation with different maturity and the area of static pressure damage.

The apples and pears are the fruits that are often cut into regular-shaped pieces to represent the whole fruit during compression test analysis. In addition, variety also has a great influence on a fruit's mechanical properties.

2.4 Hesperidium analysis

The citrus fruit is formed by the combination of several ovaries and the pericarp has oil cells. Citrus, as a representative fruit of citrus fruit, has done a lot of research on its mechanical damage characteristics. It provides a reference for the design and damage protection of related harvesting machines. In addition, the vibration harvesting characteristics of oranges were also studied.

Drop impact characteristic

Chen et al. (2018) took the drop height and buffer material as test factors to analyze the drop characteristics of wide-peel citrus. The results show that the fall height of citrus should be controlled within 90cm, and EPS (Expanded Polystyrene) material has the best reduction effect, which has the mechanical damage degree of citrus at 6.46%. Namdari Gharaghani & Maghsoudi (2018) studied the behavior of citrus fruits under impact through a drop test and then evaluated them through a verification test. The drop test device and the determination of the contact area are shown in Figure 11.

Although the oil cells outside citrus fruit can protect the pulp to a certain extent, the oil cells are easy to chafe under the impact, which leads to the invasion of various pathogens and increases the damage. The research can provide a reference for the design and protection of relevant equipment in citrus harvest and postharvest.

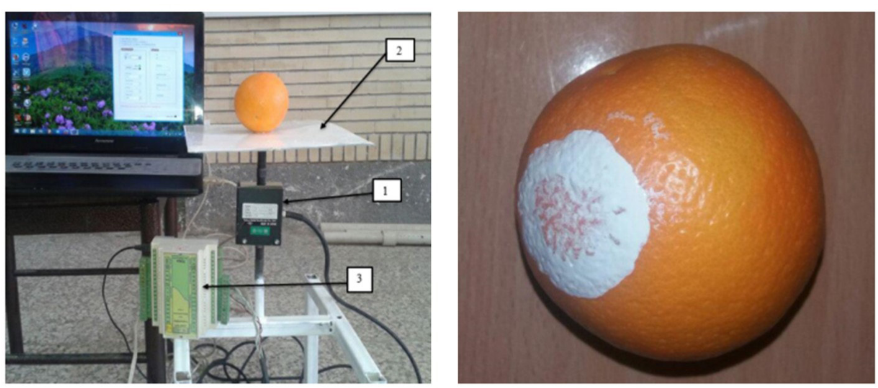
Vibration characteristics

Liu et al. (2018b) studied the effects of vibration tooth frequency and penetration depth on citrus fruit shedding. The results show that the vibration frequency positively impacted the maximum stress at the end of the fruit stem. The vibration frequency of 5 Hz is sufficient to make the fruit fall off. Castro-Garcia et al. (2017, 2020) analyzed the frequency response of ripe and immature orange fruits through a vibration transfer test. They determined three frequency ranges below 10 Hz with the highest vibration transfer value. Subsequently, they analyzed the effect of fruit and leaves on the dynamic response of citrus branches by applying forced vibrations. The response tests of citrus branches are shown in Figure 12.

Vibration frequency is an important parameter that affects citrus fruit shedding. In the process of vibration simulation analysis, the influence of the blade and branch on the overall vibration effect should be considered.

Static pressure characteristics

Liu et al. (2019) analyzed the effect of storage time on the mechanical properties of wide-peel citrus fruits through a



A B

Figure 11. (A) Experimental dropping test setup. (1) Axial load cell, (2) rigid plate connected to the load cell, and (3) and transmitter; (B) Determination of contact area for Stress calculation after impact.

(a) (b) (c)

Figure 12. Citrus branch response to forced vibration, tested in three stages: (a) in-fruit branch; (b) out-of-fruit branch; (c) out-of-leaf branch.

compression test. The results show that storage time is highly positively correlated with mass loss, and negatively correlated with fruit hardness and elastic modulus. Miraei Ashtiani et al. (2019) applied the FEM to predict the mechanical damage of grapefruit under different directions of external compression forces. The results show that its flesh is more prone to damage than the skin, and the internal texture reach the yield point when the longitudinal and lateral displacements are 9.55 mm and 13.7 mm, respectively.

2.5 Nut fruit

Nuts have hard fruit and skin and contain less water, more fat, and protein. Its mechanical properties are different from other fruits, so there are few studies on this kind of fruit. The research on static pressure characteristics of peanuts and walnuts related are the following.

Wang et al. (2017a) analyzed the damaged mechanical properties of peanut pods by taking the damage form, damage force, and deformation of peanut pods as experimental indexes, and peanut variety, force position, moisture content, and loading speed as influencing factors. Guo et al. (2020) studied the effects of pressurizing speed, pressurizing method, pressurizing number of peanut kernels, and peanut varieties on the crushing force of peanut kernels.

Wang et al. (2017b) conducted a static compression test on the walnut and obtained the breaking force and compression displacement of the walnut squeezed in different directions, which provided the necessary basic parameters for the design and optimization of the walnut hierarchical breaking machine. Liu et al. (2020b) explored the influence of water content, loading speed, and loading direction on the compression characteristics of walnut with an experiment, and then established a finite element model to analyze the extrusion cracking of walnut. Celik (2017b) used explicit dynamics to analyze the deformation of thin-shelled hickory nuts under compressive loading. The results show that the loading direction has a great influence on fruit deformation. The process of walnut fruit digitization and finite element modeling are shown in Figure 13.

Most nuts have hard shells. The study of the mechanical properties of shells and kernels can provide necessary theoretical parameters for the development and optimization of related hulling machinery, and effectively reduce the damage during the mechanical hulling process.

2.6 Results and discussion

The mainly summarizes the impact, vibration, and static pressure mechanical damage characteristics of berries such as blueberry, lychee, and wolfberry, drupes such as jujube and apricot, kernel fruit such as apple and pear, hesperidia such as citrus and orange, nuts such as peanut and walnut. The methods and damage evaluation indexes were introduced for different fruits, and the influence of different factors and parameters on fruit damage was analyzed. The results show that the mechanical damage caused by shock and vibration mainly concentrate in the harvesting process, while the damage caused by static pressure mainly occurred in the storage and transportation process. Among the impact characteristics of the fruit, the impact height, impact angle, and the material of the fruit board had a great influence on the damage to the fruit. In the study of vibration characteristics, it was found that vibration frequency was the main factor affecting fruit damage.

3 Non-destructive testing technology for fruit damage

At present, fruit nondestructive testing technology mainly includes spectral analysis technology, machine vision technology, spectral imaging technology, dielectric property analysis and detection technology, acoustic characteristics detection technology, NMR detection technology, electronic nose technology, and so on. According to different test objects and test indicators, nondestructive testing techniques have their advantages. The application of NMR detection technology, spectral detection technology, and acoustic and electrical correlation detection technology in fruit damage detection was analyzed.

3.1 NMR detection technology

Since fruits are rich in water, the water distribution between damaged and healthy areas is different after fruit damage. The distribution of water particles inside the fruit can be visualized with NMR imaging, and then the quality and defects inside the fruit can be tested nondestructively.

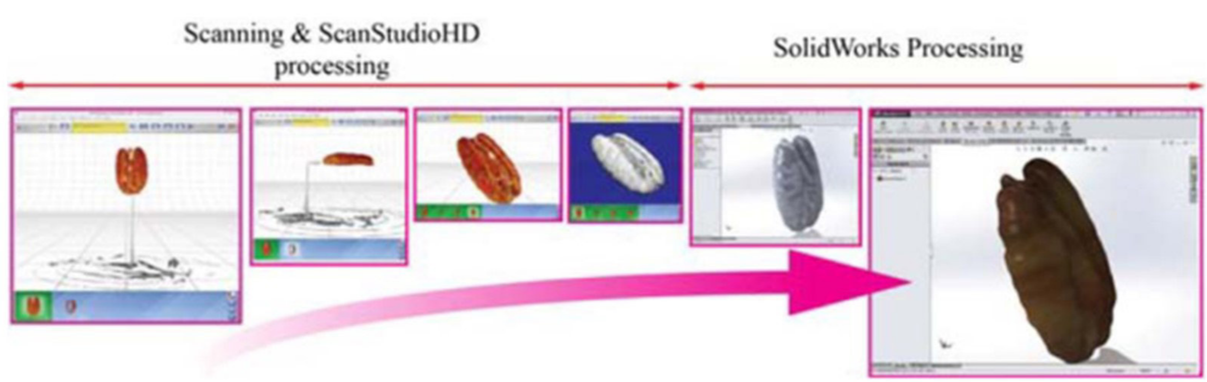


Figure 13. Walnut fruit digitization and finite element modeling process.

Chen et al. (2013) applied low-field NMR technology to study the changes and migration rules of internal water in cherries stored at room temperature. Sun et al. (2016) applied low-field NMR and imaging technology to analyze the changes in internal water distribution, status, and content of fresh jujube during storage at different temperatures. Zhou et al. (2012) applied NMR image processing technology to identify and grade three different defects of a pear fruit, including crush damage, drop damage, and internal browning. They established a correlation model between the firmness of pear fruit and the magnetic resonance texture coefficient.

Razavi et al. (2018) took pear fruit as the research object and conducted non-destructive testing on the damaged volume of fruit at different time intervals after loading by using NMR and image processing technology. Qiao et al. (2019) used low-field NMR and imaging technology to analyze the MRI data of water migration in blueberry fruits during room temperature storage and put the data into BPNN (back propagation neural network) model for verification and recognition. The results showed that LF-NMR and MRI were suitable for the analysis and detection of fruit putrid diseases, which could provide a theoretical basis for nondestructive testing of fruit diseases. The NMR images of blueberries at different storage times are shown in Figure 14.

The detection of fruit damage by NMR imaging technology mainly focuses on water distribution and mobility. The main detection methods used at present include signal amplitude, image, relaxation time, and free diffusion coefficient detection, among which the analysis and detection based on relaxation time are widely used. Due to the high cost of the instrument, it cannot be widely used in practice. Moreover, this technology mainly performs qualitative research on fruit defects, and research is needed in quantitative analysis and differentiation of different damage degrees.

3.2 Spectral detection technology

Hyperspectral imaging detection technology

Hyperspectral imaging detection technology is the most common type of fruit quality detection, which is usually used for the detection of internal quality and external defects. Table 5 describes the application of hyperspectral imaging technology in the detection of damage in some fruits.

Liu et al. (2018a) applied a hyperspectral reflectance imaging system to identify strawberry defects by combining image processing with spectral analysis. They established the relationship between quality parameters and spectral features, and developed linear and nonlinear algorithms to identify defect types (Liu et al., 2018a). Li et al. (2022) proposed a method combining hyperspectral image features and spectral features to predict the mechanical parameters of yellow peach.

Many scholars used hyperspectral imaging technology to detect the internal quality of jujube fruits. Wu et al. (2016) used hyperspectral imaging technology to identify common defects such as bruises, pests, and cracks of jujube fruits and evaluated the hyperspectral images of fruits by principal component. The study demonstrated the feasibility of using hyperspectral

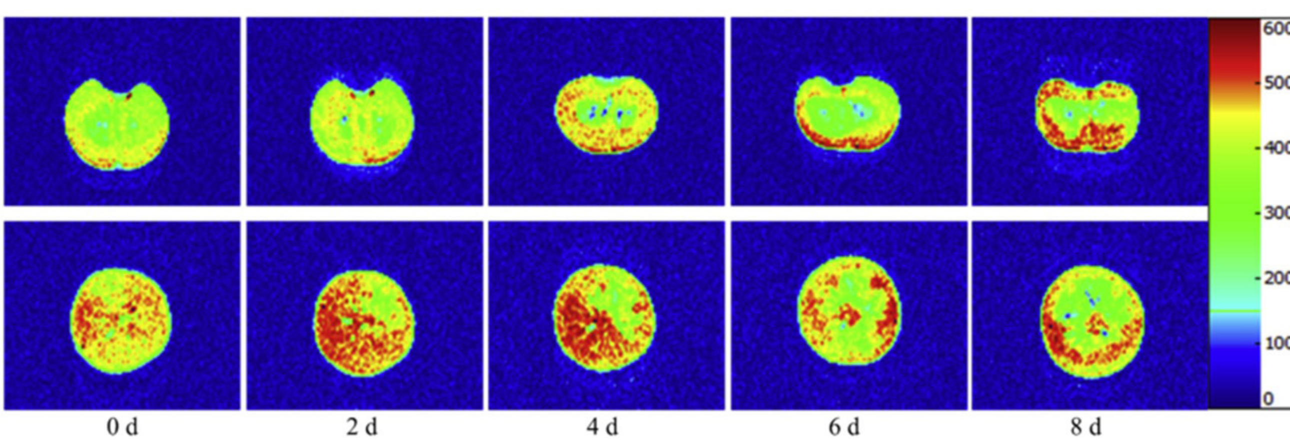


Figure 14. MRI images of blueberries at different storage times.

Table 5. Application of hyperspectral imaging technology in damage detection of some fruits.

Detection object	Spectral range (nm)	Detection method	Evaluation	Reference
Apple	1000-2500	PLS	94.4%	Keresztes et al. (2016)
Blueberry	950-1650	SVM	94%	Jiang et al. (2016)
Pear	400-1000	PCA	87.5%	Fang et al. (2020)
Strawberry	650-720	SVM	96.91%	Liu et al. (2018a)
Jujube	918-1678	PCA	100%	Wu et al. (2015)

Note: PLS = partial least squares; SVM = support vector machine; PCA = Principal component analysis.

image technology to identify common defects in fruit. Xue et al. (2015) used hyperspectral imaging technology to simultaneously detect the external defects and soluble solid content of jujube. Wu et al. (2015) applied characteristic wavelength principal component analysis combined with a band ratio algorithm to identify cracks, insect eyes, and bruises of long jujube.

Keresztes et al. (2017) developed a detection system for apple scratches, which used shortwave infrared hyperspectral imaging to detect scratches on three different apples. They applied an area normalization technique to preprocess the scratch detection. The experimental procedure flow chart of apple abrasion detection is shown in Figure 15.

The studies show that hyperspectral imaging detection technology is mainly applied to fruits such as apples, strawberries, and jujube, but due to the influence of instrument cost, performance, and processing speed, the technology is mainly applied to some basic fields. Therefore, it is necessary to improve the hardware and analysis and reduce the cost of the instrument.

Visible/near-infrared spectroscopy detection technology

The visible/near-infrared spectrum can be subdivided into the visible spectrum (400-780 nm) and near-infrared spectrum (780-2500 nm), which has been widely used to identify and classify defects and lesions in various fruits. The application of visible/near-infrared spectroscopy in the detection of damage for some fruits is shown in Table 6.

To distinguish different grades of blueberry bruises, Zheng et al. (2022) used near-infrared hyperspectral reflectance imaging to get the actual bruising rate of blueberries. The actual damage rate of blueberries was 1.1% with the optimized parameters. Liu et al. (2016b) collected the near-infrared diffuse transmission spectra of yellow peach surface defects and normal fruits and analyzed the spectral damage characteristics of yellow peach samples. Huang et al. (2017) applied near-infrared spectroscopy and electronic nose technology to predict the eating time of peach fruits before rotting. Zhao et al. (2016) used near-infrared spectroscopy to non-destructively identify the browning of plum fruits. Moscetti et al. (2016) applied near-infrared spectroscopy to sort olive fruits damaged and undamaged by hail. Wang et al. (2020d) applied visible-NIR interaction spectroscopy to nondestructively assess cold damage in kiwifruit.

Zhang et al. (2018) used a feature band selection method based on an ant colony optimization algorithm and variable selection principle to measure the six citrus blemishes. The six common damage conditions of citrus fruits are shown in Figure 16.

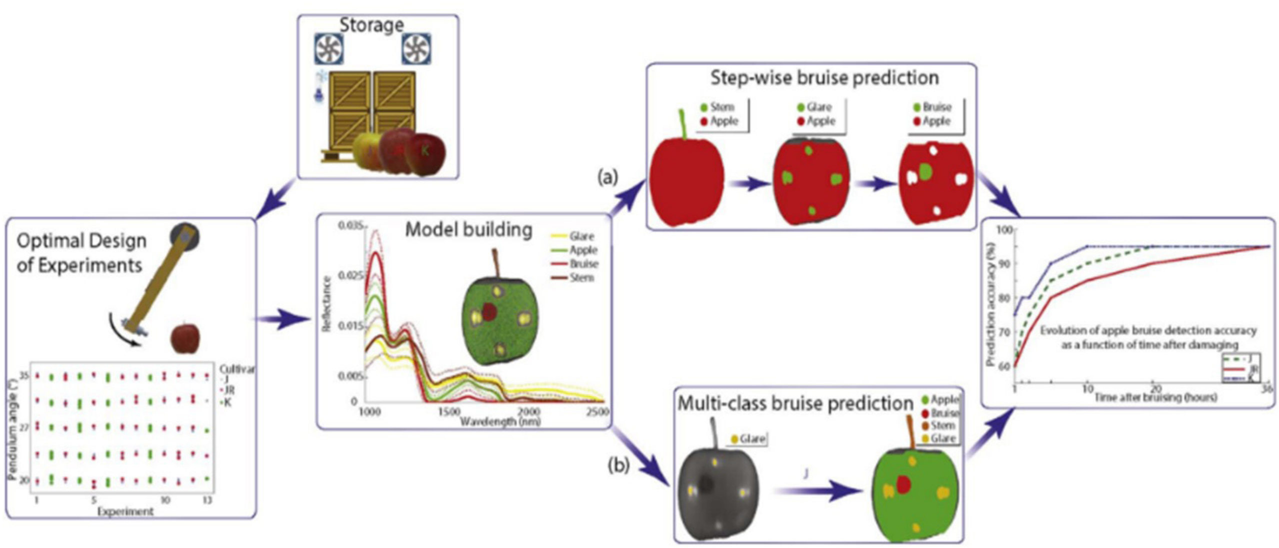


Figure 15. Flow chart of the experimental procedure for Apple abrasion detection. (a) Step-wise bruise prediction; (b) Multi-class bruise prediction.

Table 6. Application of visible/near-infrared spectroscopy in the detection of partial fruit damage.

Detection object	Spectral range (nm)	Detection method	Evaluation	Reference
Peach	350-1150	LS-SVM	100%	Liu et al. (2016b)
	900-2500	PLS	82.26%	Huang et al. (2017)
Plum	4000-12500	PCA	100%,98.75%	Zhao et al. (2016)
Citrus	200-900	SVM	>90.8%	Zhang et al. (2018)
Kiwifruit	400-1000	PCA	qualitative	Wang et al. (2020d)
Apple	350-1100	PLS	qualitative	Grandón et al. (2019)

Note: LS-SVM = Least squares-support vector machine; PCA = Principal component analysis; SVM = support vector machine; PLS = partial least squares.

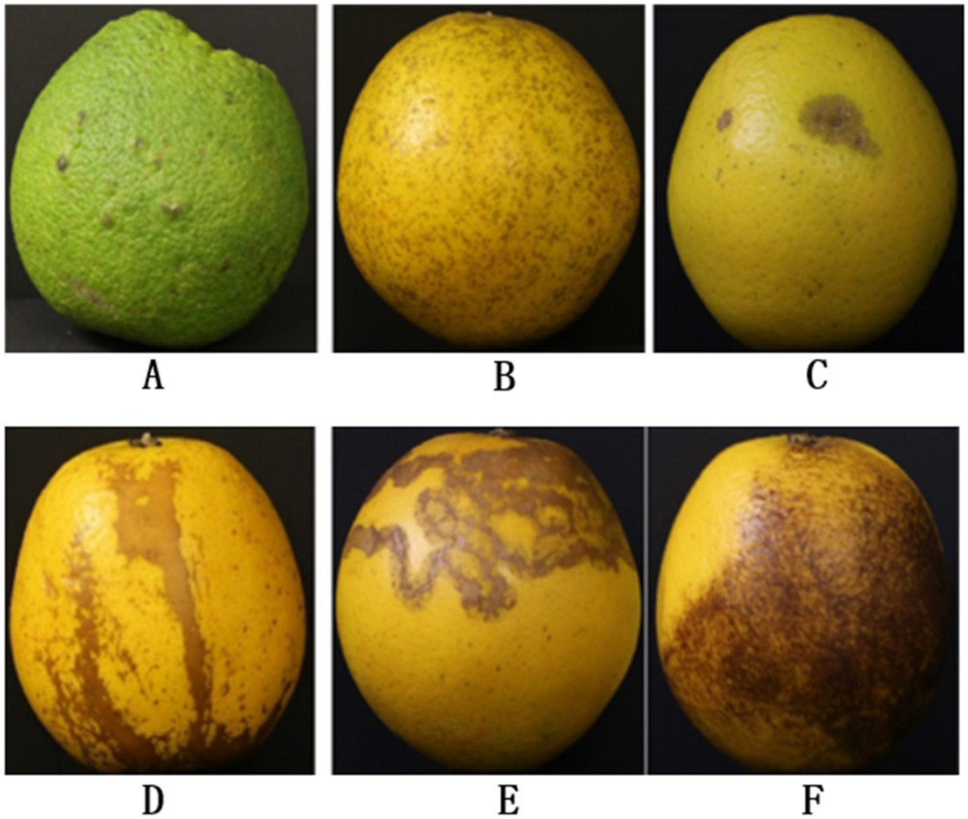


Figure 16. Six common types of damage to citrus fruits. (A) Huanglongbing (HLB); (B) melanose; (C) oleocellosis (oilspot); (D) wind scar; (E) leafminer; (F) rust mites.

Near-infrared (NIR) camera has a strong ability to show bruises as bruised tissue is more sensitive to NIR light. Yuan et al. (2022) used near-infrared camera imaging technology combined with deep learning methods to detect early bruises in apples. Jian et al. (2017) applied visible light and shortwave near-infrared technology, combined with ensemble learning, to perform nondestructive testing of apple bruise sensitivity. According to different collision energy levels and aggregated data, three prediction models were developed. Grandón et al. (2019) used visible/near-infrared spectroscopy technology to establish prediction models for apple fruit with no sun damage and mild sun damage, respectively. The method improved the ability to prevent and control apple sunburn.

Visible/near-infrared spectroscopy can be divided into qualitative and quantitative detection. Qualitative detection is mainly applied to distinguish the spectral characteristics of damaged and healthy fruits. Quantitative detection establishes the relationship between spectral features and damage-related features. Its accuracy is greatly affected by related algorithms and established models, so effective prepossessing and modeling methods should be adopted.

3.3 Acoustic and electrical characteristics detection technology

The samples have different absorption and scattering of sound waves due to the different acoustic characteristics, which resulted in different degrees of sound attenuation. This method can be applied to realize nondestructive testing of fruit damage. The defects in fruit are determined by analyzing the vibration response of fruit samples under certain excitation in the application of the acoustic method.

Zhang & Wu (2020) evaluated the sensitivity of each characteristic parameter to the internal browning of pear by using a self-made acoustic vibration nondestructive testing device system, which is shown in Figure 17. The internal early browning model and light browning model of the pear was constructed, with an accuracy of 91.84% and 81.82%, respectively. The results can provide a reference for the development of real-time online detection and automatic grading technology of internal browning of pear by acoustic vibration method.

Nakano et al. (2018) applied the acoustic vibration method and a unique method based on the ratio of the third and second resonance frequencies to identify the kernel splitting of peach fruits without loss. The results showed that 95% of the fruit samples were detected as pitted fruit, whereas only 1.5% of the normal fruits were not classified as pitted fruit.

The acoustic detection method has the advantages of simple instruments and convenient operation, but it is only suitable for fruits with certain hardness. Furthermore, it can not guarantee the process of generating the sound signal, which will not cause damage to the fruits.

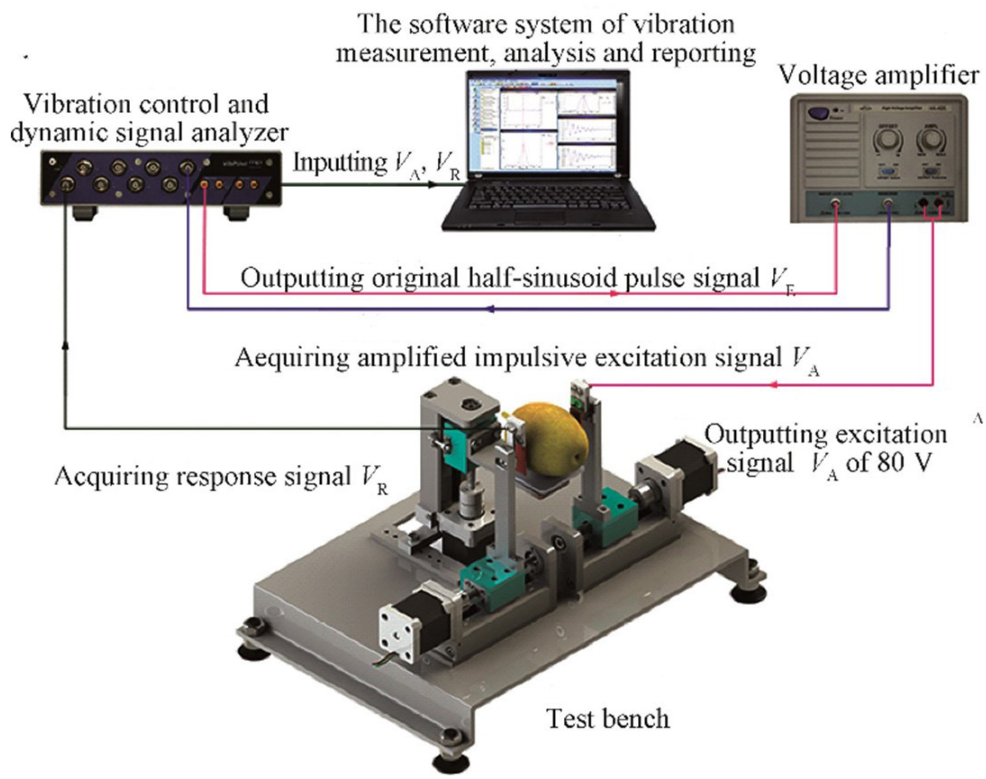


Figure 17. Pear acoustic vibration non-destructive testing system.

Nondestructive testing based on electrical properties can be used to determine the quality of fruits, such as damage and disease. The testing technology has the advantages of simple operation steps and sensitive instrument response. Fan et al. (2021) constructed a mathematical model of electrical parameter values, which can determine the damaged area of Korla fragrant pear. The study proposed a quantitative evaluation method of damage degree based on electrical characteristics. Wang et al. (2018) used principal component analysis (PCA) combined with different classification models to distinguish good and diseased apples by the eigenvalues of electrical indicators at each frequency point, and the recognition accuracy reached 100%. Bian & Tu (2019) used the parallel plate electrode method to synchronously monitor the electrical parameters of apples under static pressure. The results show that with the increase of static pressure and the prolongation of static pressure time, the relative dielectric constant and loss factor of fruit increases, and the electrical parameter could predict the degree of apple damage.

Although the detection method based on electrical characteristics is feasible in principle and technology, there are few studies on the application of this method to evaluate fruit damage, and it has not reached the practical stage.

4 Conclusion

In recent years, scholars have carried out a lot of research on the mechanical damage characteristics of different fruits and made certain achievements in the mechanical damage test, damage influencing factors analysis, damage evaluation index establishment, and finite element simulation analysis. It has a high reference value for the development and optimization of related machinery and equipment in harvesting, as well as the improvement of damage reduction methods in storage and transportation, but the research still needs to be further strengthened. Firstly, more effective and unified damage evaluation criteria and prediction models should be established by fully considering the differences in the biomechanical properties of fruits. In addition, make full use of nonlinear FEM to establish a multi-level model of the fruit, realize the fruit from the microscopic damage to the macroscopic damage simulation and calculation, to further analyze the law of mechanical damage under different types of forces or dynamic loads.

For nondestructive testing of fruit damage, this study summarized the application of various testing techniques in fruit damage detection in recent years. It can be seen that the above detection technologies have their advantages, but most of the other technologies are in the experimental stage, except for the near-infrared spectroscopy detection technology, which is widely applied at present. Therefore, a large number of theories are still needed to apply to the application development of these technologies. In the subsequent research, attention should be paid to data processing and algorithm research to ensure the accuracy of detection. In addition, appropriate detection techniques should be selected according to the characteristics and damage types of target fruits, and the detection conditions and environment should be fully considered to minimize the interference of external factors. Finally, the development of detection equipment should be strengthened to reduce the detection cost.

Nondestructive testing technology can quickly and effectively identify fruit damage, which is an important means to study the mechanical damage characteristics of fruits. At the same time, the research on the mechanical damage mechanism of fruits can also guide the innovation and improvement of nondestructive testing technology.

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