RESEARCH ON COMB BRUSH HARVESTER AND DAMAGE MECHANISM TO MATERIAL. A REVIEW
/
梳刷式收获装置的研究现状及对物料的损伤机理综述

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ABSTRACT

Mechanized harvesting of crops is very important in the field of agricultural engineering, then the brush harvesting is a common way. The comb brush device is divided into four types: comb tooth type, roller spring finger type, belt comb finger type, and rod comb finger type. The picking rate and breakage rate are the indexes to evaluate the effect of comb brush harvesting devices. How to improve the picking rate and reduce damage rate is of great significance to the popularization of the devices. To improve the picking rate, the design of comb teeth should conform to the growth characteristics of crops. In this study, the application of four comb brush devices in harvesting crops was introduced, then the working principles and results were summarized. Meanwhile, the research status of a variable finger spacing device was summarized. In addition, to study fruit damage caused by brush devices during harvesting, three common analysis methods were summarized. The application situations and key steps were listed, and the modeling methods of material fruit in simulation analysis were analyzed. The study is intended to provide a reference for improving the harvesting effect of comb brush device. In the future, with the deepening combination of agronomy and agricultural machinery technology, comb brush harvesters will be more widely applied.

摘要

农作物的机械化收获是农业工程领域的一个重要环节，梳刷收获是一种常见的收获方式。目前梳刷装置分为梳齿型、滚筒弹齿型、带状梳指型以及杆条梳指型四种。采摘率和破损率作为评价梳刷装置优劣的指标，如何提高采摘率并降低破损率对梳刷装置的推广具有重要意义。提高采摘率，梳齿的设计要符合作物的生长特点，本文介绍了四种梳刷收获装置在收获不同作物时的应用情况，并归纳出其工作原理和优缺点，同时对变间距梳齿装置的研究现状进行了总结。此外，为了研究梳刷装置收获时对果实的损伤情况，总结了三种常用的分析方法，对其应用场景和关键步骤进行了总结，同时对仿真分析时物料果实建模的方法进行了归纳。本文旨在为提高梳刷装置的收获效果提供参考，未来随着农艺和农机技术不断深入结合，梳刷式收获装置将会得到更广泛的应用。

INTRODUCTION

With the improvement of living standards, people pay more and more attention to the quality of agricultural products, which has high requirements for the cultivation, management, harvest, transportation, and other links of crops, especially the harvest. It is easy to miss the best harvest period of crops, which affects the quality of agricultural products and causes economic losses. Therefore, the way to solve this problem is to apply machine harvesting.

Comb harvesting is a common harvest way at present, which is widely used in agricultural production. As one of the major food crops in the world, rice feeds more than half of the global population (*Li et al., 2020*). China is the world's largest producer of rice, with a planting area of 3×10^7 hm^2, accounting for about 23% of the world's total planting area (*Shen et al., 2016*). The common rice harvesting method is brush threshing (*Teng and Liu, 2020*). By the end of 2019, the comprehensive mechanization of rice production in China was 81% (*Feng and Liu, 2020*). Even so, problems such as unclean threshing and incomplete separation still exist in the process of rice harvest (*Hou, 2020*). Chili is a spicy crop with the widest planting area in the world. Since 1994, the planting area and total output of pepper in the world have been steadily increasing (*Hespeler et al., 2021; Jiang et al., 2018*). As a popular cash crop, chili harvester has been developed since the 1960s, and comb brush type device is a common type of harvest (*Funk and Walker, 2010*).

Up to now, chili harvester has developed relatively mature, to solve the problem of large breakage rate is still difficult. Lycium chinensis is mainly distributed in East Asia (*Potterat, 2010*). In China, the planting area of Lycium chinensis is about 1.333×10^5 hm^2, and the planting area is increasing year by year (*Hai et al., 2019*). Currently, the common mechanical picking is achieved by combing brush (*Wang et al., 2018*). However, due to the late start of the development of the harvesting device for Lycium chinensis, the mechanization degree of harvesting is still very low, which seriously restricts the development of the Lycium chinensis industry (*Teng, 2021*). Castor is one of the top ten oil crops, mainly grown in India, China, Brazil and other places. Its processed products are widely used in national defense, aviation, chemical industry and other fields *(Costa et al., 2018; Severino et al., 2013; Sun et al., 2012)*. At present, a common way to harvest castor beans is to brush it *(Kong et al., 2019)*. Cerasus Humilis *(Liu et al., 2021)*, Camellia Oleifera fruit *(Wu et al., 2022)* and other crops are also commonly harvested in this way, as shown in Fig.1. For the same crop, different types of comb and brush devices have different picking rates and damage rates. Therefore, it is of great significance to study the devices to improve harvesting efficiency and reduce damage rate.

The damage rate is one of the important indexes for harvest device. Research on the damage mechanism of materials during harvesting is the premise to obtain a low breakage rate. The damage in the process of comb brush harvesting is caused by the collision between the material fruit and the harvesting device. Its essence is that the material produced plastic deformation after beyond the yield point (*Celik, 2017*). With the development of computer technology, the simulation method has been widely applied to agricultural engineering (*Du et al., 2019*). It can analyze the process of material damage, which has become the main way to study material damage.

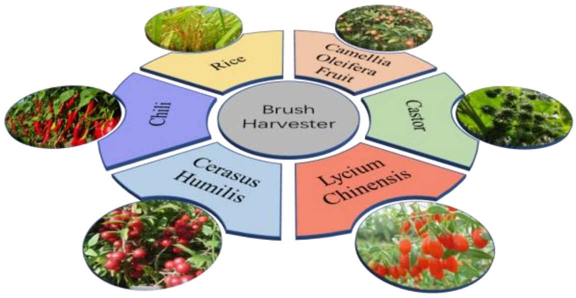


Fig. 1 - Application of brush harvesting

This study first summarizes the working principle and development status of brush harvesting and introduces four types of comb brush harvester. Then, the damage mechanism of the material fruit during the brush harvest was analyzed, the common methods and material modeling methods were summarized. Finally, the development of brush harvesting has been prospected.

COMB BRUSH TYPE OF HARVEST

The principle of comb brush harvesting is that the finger of comb moves periodically with the picking device. When the branch with fruit enters the finger of the comb, the fruit is forced to be separated from the stem by the impact force between the finger and the fruit. There are four types of brush which are comb tooth type, roller spring finger type, belt comb finger type, and rod comb finger type (*Hu et al., 2011*).

Comb tooth type brush harvesting device

The main working parts of the comb tooth type harvesting device are comb teeth, frame, and transmission device. The comb teeth moves according to a certain trajectory, and the plants are forced to be picked after entering the comb finger. These harvesting devices generally do not have collecting devices, so it is still necessary to collect the fallen fruit manually or by machine.

The structure design of the brush harvesting device needs to adapt to the growth characteristics of target crops. *Zhang et al.* (*2018*) designed a kind of Cerasus humilis brushing picking device, as shown in Fig. 2. When it works, the two brush parts open, then the finger of the comb enters the plant and gathers. The whole frame moves upward to complete the picking. It can harvest the fallen plants, and the harvesting efficiency is more than 80%. *Luo et al.* (*2017*) designed a tooth comb dial knife type picking device for Camellia oleifera fruit, as shown in Fig. 3. The device is carried out by hand, and its main parts are picking head, dial knife, pull wire, and long rod. It can effectively reduce the damage to Camellia oleifera fruit when picking. However, due to its lack of collection devices, the picked fruits directly fall to the ground and still need to be picked up manually. The fruit is finally picked by manual pulling the ring, which has a large workload and intensity. To further reduce the working intensity, *Du et al.* (*2021*) designed a hand-held Camellia oleifera fruit brush picking machine with variable spacing. It is powered by a generator and enables variable-spacing combs. Field tests show that when the recovery rate is 480 r/min, the damage to the buds is reduced. Table 1 shows the comparison of the characteristics of the two crop picking devices.

Fig. 2 - Cerasus humilis brush picking device

Fig. 3 - Tooth comb dial knife type Camellia oleifera fruit picking device

Table 1

Comparison of different crop picking devices

Crops	Advantages	Disadvantages
Cerasus Humilis	High mechanization and high efficiency	Large damage, there is a phenomenon of omission of picking, the crop damage
Camellia Oleifera fruit	Small damage, high net recovery rate	Labor intensity, need to pick up manually

Roller spring finger type brush harvest device

Roller spring finger type brush harvest device mainly include picking roller, spring finger, conveyor belt, frame, transmission system, and other components. Its working principle is that the picking roller is powered by the machine itself while working, the spring fingers on the roller rotate with the roller and advance with the machine. Since the size of the fruit is larger than the distance of two springing teethes, the fruit after being picked continues to rotate with the springing teeth until it is thrown onto a conveyor belt behind.

Wang et al. (*2017*) optimized the threshing device because of the problem of poor threshing and separation capacity of the current longitudinal axial flow rice combine harvester. The threshing device is changed into the same diameter differential cylinder threshing device of the longitudinal axis. Through the test, it was found that the loss rate is reduced by 0.09%, and the breakage rate is reduced by 0.017%. *Dow* (*2003*) invented a tractor-type pepper picking device powered by a tractor. *Liu et al.* (*2020*) designed a comb-type cerasus humilis harvesting device, as shown in Fig. 4. To prevent the branches from being twined during work, the length of the comb was designed to be greater than 1/2 of the length of the cerasus humilis branches. The front section of the comb was set at 120°, which can not only prevent the fruits under the comb brush from falling to the ground but also facilitate the feeding of the branches. The test showed that the picking rate of the device can reach more than 95% when the roller speed is 25 r/min. *Ehlert et al.* (*2014*) designed a picking roller chamomile harvester, which adopted a double-blade picking comb. Field tests shows that the double-blade picking comb could play a certain role in preventing winding. *Li et al.* (*2016*) designed a comb-type castor harvest machine based on the bionics principle. The comb finger was designed into a finger-like structure, which could simulate manual picking to ensure the integrity of castor fruit. The results show that when the roller speed was 45 r/min and the unit forward speed was 2.5 m/s, most fruits can be harvested. *Hu et al.* (*2020*) designed a flexible comb brush device for apples planted with vertical fruiting wall architecture. The roller of the device is designed in the vertical direction, the comb finger and the harvesting platform can move up and down at the same time, which can reduce the falling height of apples and reduce the harvest damage of apples. Field experiments shows that the picking effect is better when the advance speed of the unit is 0.084 m/s and the rotation speed of the roller is 36 r/min.

Zhang et al. (*2018*) designed a hand-held variable spacing comb brush device of Lycium chinensis based on the principle of roller spring finger type device, as shown in Fig. 5. As the grooved cam rotates, the pressing plate rotates with it. When the pressing plate is at the end of the great arc of the cam, the comb finger is in a normal working state. When the platen is at the end of the small arc, the platen forces the comb to open laterally.

The picking device can effectively solve the problem of Lycium chinensis fruit stuck between two adjacent comb teeth when the comb brush is harvested. Field experiments show that when the tooth spacing is 8 mm and the finger length is 45 mm, the net recovery rate can reach 90% and the damage can be kept within 9%. This variable spacing comb brush device retains the characteristics of the roller spring-tooth type harvesting device but also can achieve a high net rate and low damage rate. Its processing accuracy requirements are high, which is not conducive to the research and development of large-scale harvesting devices.

Fig. 4 - Comb type Cerasus humilis harvesting device

Fig. 5 - Variable spacing Lycium chinensis brushing device

Belt comb finger type brush harvesting device

The main working parts of the picking device include grain distributor, picking belt, fan, drive system, frame, etc. The picking section consists of two picking strips, which are covered with snap fingers. The picking belt moves from bottom to top while moving along with the machine, as shown in Fig. 6. When the plant enters between the picking belt, the fruit is forced down by the comb fingers and continues to move with the picking belt.

This type of harvester was originally used to harvest tomatoes, then it was adapted in the late 20th century to harvest chilies. *Hu et al.* (*2012*) designed a belt comb finger type chili harvesting device and conducted prototype tests, as shown in Fig. 7. The picking device designs the comb finger on the picking belt with different lengths, the length of the front comb teeth is shorter than that of the back so that the front is easy to enter the chili plants, which is easy to pick the fruit of chili. Through the orthogonal test, it is found that the picking speed has the greatest influence on the picking performance, and the picking speed is the best as 2.17 m/s. This type of harvesting device has higher requirements on the material of the belt, and the processing is complex, which is not conducive to promotion.

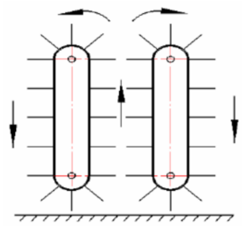


Fig. 6 - The movement direction of picking belt

Fig. 7 - Belt comb finger type chili harvesting device

Rod comb finger type brush harvesting device

Rod comb finger type picking device mainly includes grain distributor, picking roller, conveyor belt, rack, and so on. The working principle is that a pair of picking rollers rotate in reverse, and the comb finger moves with the picking rollers. When the plant enters the two picking rollers, the finger of the comb forces the fruit to be pulled down. The plucked fruit continues to rotate with the picking rollers until it is thrown to the two conveyor belts arranged parallel to the two picking rollers.

Fig. 8 - Roller brush type castor harvester

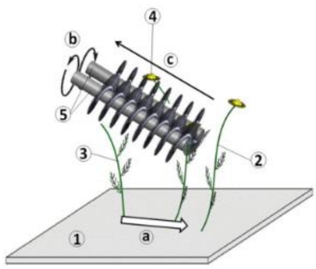


Fig. 9 - Rotary comb brush chamomile harvesting device

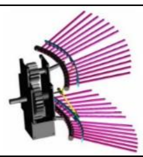
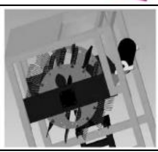
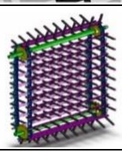
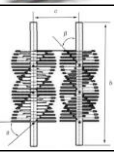
Zhang et al. (*2019*) developed a rolling brush-type castor picking device. This device changed the comb fingers used in the past and replaces them with power scrapers and auxiliary brushes. The power scraper used a longer power board to comb the castor fruit, and the auxiliary brush solved the loss caused by the fruit belt after picking and reduced the operating loss rate. *Liu et al.* (*2021*) improved the device in combination with the planting pattern and growth characteristics of castor beans, as shown in Fig. 8. The main working part of the device consists of a brush roller shaft and its surrounding flexible brush wire. The castor beans are picked by the impact generated by the rotation of the flexible brush wire. Results show that the picking rate of the device is more than 90%, and the breakage rate of the grain is only about 0.1%. *Liu et al.* (*2020*) designed an inclined double-helix finger comb chili harvesting device. The picking roller of the harvesting device is tilted and the comb fingers on it are arranged in a way of four spiral lines. *Brabandt et al.* (*2011*) designed a spiral chamomile harvesting device, as shown in Fig. 9, which chamomile is forced down by a pair of counter-rotating combs. *Di et al.* (*2020*) designed a brush-type Camptotheca Acuminata leaf-picking machine. The picking device arranged two picking axes horizontally, and the comb finger on the device was installed on the spring. When the comb finger touched the branch, the comb finger could automatically give way to avoid causing damage to the branch. To change the size of the picking roller can achieve the harvest of different height plants.

Table 2 is the comparison of the four brush harvesting methods. The comb tooth type brush device cannot achieve continuous operation, which is now mostly designed as a small machine to cooperate with manual use. The roller spring finger type device is used to harvest the fruits of dwarf plants and crops. It can also harvest crops with moderate plant height, but the roller size is larger.

Belt comb finger type or rod comb finger type device is generally used for crops with relatively tall plants. Due to the complex structure of the belt comb finger type device, low intensity of picking belt, it is mostly replaced by a rod comb finger type device. At present, the most commonly used picking methods are roller spring finger type and rod comb finger type.

Table 2

Comparison of four brush methods

Comb brush type	Structural diagram	Advantages	Disadvantages
Comb tooth type		Good picking effect, low damage, simple structure, convenient manufacture	Cannot operate continuously, operation efficiency is low
Roller spring finger type		Large operation width, simple structure, a wide range of application	It is easy to pull the stem into the roller when working
Belt comb finger type		Large area for simultaneous operation, high operating efficiency	Complex structure, difficult to manufacture, at the same time assembly fan, power consumption is large
Rod comb finger type		Can be picked on both sides of the plant at the same time, good picking effect	The distance between the two rollers is not easy to determine

SIMULATION OF MECHANICAL DAMAGE MECHANISM

In the process of brush picking, when the fruit collides with the machine, it is easy to produce damage. At the moment of contact between the material and the comb tooth, the contact position will be subjected to a large impact force which experiences elastic and plastic deformation processes. The elastic deformation will not cause material damage, while the plastic deformation will rupture, deformation, dislocation, or soft flesh inside the material cells, leading to collision damage (*Sang et al., 2008*). Therefore, it is extremely important to analyze the crop damage mechanism for picking. At present, there are three methods to analyze the mechanism of crop damage, which are finite element method, discrete element method, and test analysis method.

Finite Element Method

The finite element method (FEM), as a commonly used numerical method, is widely used to solve complex agricultural problems (*Du et al., 2019*). Through the simulation analysis and calculation of the material structure and characteristics, the influence of parameter changes on the material damage can be obtained.

Kang et al. (2017) used the finite element method to analyze the damage of calcium fruit when the comb teeth of different section shapes were harvested, and judged the damage degree by comparing the stress on the fruit. The results show that when the width between alveoli is 12 mm, the triangular comb tooth section shape has the least damage to fruit, which provides reference for the design of calcium fruit harvesting device. *Ji et al.* (*2017*) applied ANSYS software to study the damage of robot picking apple. They simulated the contact process between apple and plane and curved finger, which concludes that curved finger has less damage to apple. *Ahmadi et al.* (*2016*) studied the collision damage of apples in the transportation process, then analyzed the collision damage between apples and rigid bodies as well as between apples. It is concluded that the collision between apples and rigid bodies is the main cause of the damage, so it is very important to choose the appropriate material during transportation. *Li et al.* (*2021*) established an extended finite element model (XFEM) for tomato fruit to study the fracture mechanical response under mechanical compression. The model was applied to analyze the pre-crack propagation of tomato fruit under compression. The results shows that the pre-crack propagation would be rapid when the deformation percentage is more than 20%. *Celik et al.* (*2019*) used the FEM to simulate the collision between a single potato and a potato pile. The simulation results show that the stress values of impact and impact potatoes were 3.13 MPa and 1.40 MPa respectively, which provides a deeper understanding of dynamic bruise caused by potato transportation. *Zhao et al.* (*2019*) used finite element explicit dynamic simulation to evaluate impact scratch of fresh Lycium barbarum fruit. The results show that the fruit would not be damaged when the drop height is 0.2-0.5 m, the impact angle is 10-30°, and the impact materials are wood, foam, and nylon panels. *Zhu et al.* (*2016*) used FEM to study the fruit picking process of peanut harvesters. The impact response characteristics of the joint between peanut pod and roller blade after frontal impact were obtained. *Celik* (*2017*) used the FEM to study the impact deformation characteristics of pears. The bruise susceptibility of pear was analyzed by studying the impact height, impact surface, and impact direction, then the damage prediction model was established by using the response surface analysis method. After testing the prediction model, the maximum error between the simulation results and the empirical model results was about 7%. *Du et al.* (*2019*) analyzed the damage of kiwifruit at different ripening stages falling from different heights in horizontal and vertical directions by FEM. The severity of damage was determined by comparing the area of units exceeding the kiwi yield stress in the model. The maximum error between the simulation result and the experimental data is 17%.

FEM can be used to analyze the damage of materials to obtain the force size, stress-strain, and absorbed energy of the material at each time. By analyzing these parameters, the time, position, and final volume of material damage can be accurately obtained. However, there is a certain error between the data obtained by the finite element method and the experiment. Controlling mesh type and mesh size is a common method to improve simulation accuracy. Table 3 shows mesh types and mesh sizes used for some material fruits.

Table 3

Mesh division and simulation results of different fruit

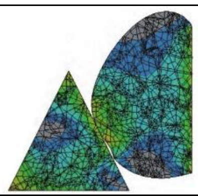
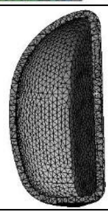
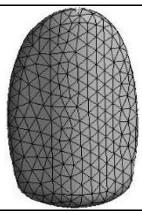
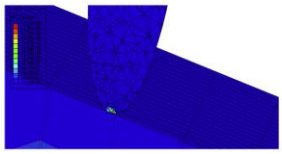
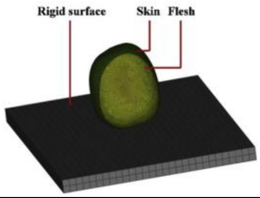
Material fruit	Divide area	Mesh type	Meshing result	Conclusion
Cerasus Humilis	Whole	Tetrahedron		When the load is 5N, the compressive contact stress of the comb teeth with triangular section is the least *(Kang et al.,2017).*
Castor	Castor shell	Tetrahedron		Dynamic analysis of different impact velocity, castor by the stress nomogram, when the impact velocity reaches 6 m/s, castor shell reached the yield limit of the material, the three chambers gradually separated *(Yang, 2019)*.

Table 3
(continuation)

Material fruit	Divide area	Mesh type	Meshing result	Conclusion
Castor	Castor bean seed	Tetrahedron		
Lycium chinensis	Whole	Tetrahedron		When the fall height is 0.2-0.5 m, the impact Angle is 10-30°, and the impact material is wood, foam board and nylon board, the fruit will not be damaged, and the impact damage is predicted successfully *(Celik, 2017)*.
Kiwifruit	Flesh	Tetrahedron		The higher the maturity is, the more likely it is to cause damage. Horizontal falls are more likely to cause damage than vertical falls. *(Du et al., 2019)*.
	Skin	Triangle		

Discrete Element Method

The discrete element method (DEM) can be used to analyze the force relationship between agricultural material particles (*Zeng et al., 2021*). It achieves the stimulation effect with the actual material damage by selecting the appropriate collision model and calibrating parameters. At the same time, the mechanical state and material to minimize the impact of the material are obtained by changing the mechanical parameters, so as to guide the practice according to the simulation results.

Hou et al. (2022) established a discrete element model of rice in order to analyze the grain breakage in the mechanical process of rice harvesting, and used discrete element method to simulate the process of harvesting and threshing. The simulation results showed that the normal force and tangential force were 28.4 N and 22.3 N, respectively, and 14.43 N and 8.74 N, respectively. The results indicate that the threshing roller with rigid and flexible coupling rod teeth could reduce the damage rate of rice.

Bao et al. (*2020*) used the DEM to analyze the collision damage of blueberries during mechanical picking and judged the damage degree of blueberries by analyzing the change of deformation energy value of blueberries. The results show that mechanical harvesting would only cause mechanical damage to a small part of fruits, and the probability of damage is about 20%. Blueberry fruits will be damaged not only in the picking stage but also in the conveying stage. Similarly, *Dariusz et al.* (*2020*) studied the damage of blueberry fruits when they are transported by reciprocating conveyor and vibrating conveyor. The simulation results show that the normal force and tangential force of conveying blueberries with a reciprocating conveyor belt are less than those with a vibrating conveyor.

Van Zeebroeck et al. (*2006*) studied the impact of vibration frequency, stacking height, and apple size on collision damage during apple transportation by applying DEM. The results show that vibration frequency is the main influencing factor of damage. *Scheffler et al.* (*2018*) used the DEM to predict the damage of fresh apples during handling and controlled the prediction accuracy of impact force of apples in drop test within 11%.

Pinto et al. (*2018*) used the DEM to study the deformation of peaches under cyclic load. At the same time, they used the same excitation conditions in the laboratory. Finally, it is concluded that the DEM could fully estimate the final deformation of peaches.

Wang et al. (*2019*) analyzed the impact force condition of a single corn kernel during threshing by using EDEM software and obtained that the maximum force received by the kernel in X, Y, and Z directions are 18.7 N, 92.5 N, and 22.0 N, respectively.

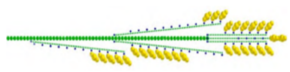
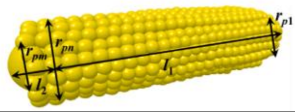
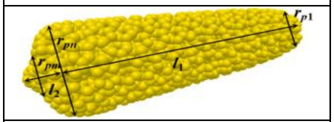
In order to study the damage of corn grains in the process of harvesting and transportation, *Li et al. (2022)* conducted simulation experiments in EDEM to verify the constitutive model and discrete element model of corn ear. The results show that the grain filling model could explain the mechanism of grain threshing and the stress of each grain in the process of grain threshing.

Liu et al. (*2018*) selected the Hertz-Mindlin contact mechanics model to calibrate parameters of virus-free micro potato, established the micro potato model as sphere and ellipsoid in EDEM. The impact recovery coefficients between the micro tubers, the steel plate and the micro tubers were measured. Compared with the real test, the simulation errors are 0.57% and 4.17% respectively.

Wei et al. (*2020*) used the DEM to analyze potato damage during operation on the undulating screen surface. Through simulation, they found that for the undulating screen surface with two peaks and two valleys, a small running speed is suitable when the inclination of the undulating screen surface is large. A large running speed is suitable when the inclination of the screen surface is small, and the rate of potato damage and the rate of broken skin are both less than 2%.

Table 4

Some collision models used in material simulation

Material	Discrete element model	Contact model	Conclusion
Rice		Hertz–Mindlin with Bonding V2, Hertz-Mindlin(no slip)	The mean normal force and tangential force of the rigid-flexible coupling rod teeth were smaller than those of the rigid rod teeth when they contacted the branches and ears, and the reduction rates were 21.48% and 39.43%, respectively *(Hou et al. 2020)*.
Corn	 Splicing model  Filling model	Hertz Mindlin with bonding, Hertz-Mindlin(no slip)	The average normal force on the filling model is 201.7 N, the maximum value is 342.0 N, and the minimum value is 104.3 N. The average normal force on the splicing model is 492.6 N, the maximum value is 823.7 N, and the minimum value is 362.6 N *(Li et al. 2022)*.
Potato	 	Hertz Mindlin with bonding, Hertz-Mindlin(no slip)	When the Angle of the undulating screen surface was 35° and the running speed of the separating screen was 1.0 m/s, the rate of potato damage and the rate of broken skin were 1.31% and 1.44%, respectively. When the Angle of the wavy screen surface was 15° and the running speed of the separating screen was 2.0 m/s, the potato injury rate and the skin breaking rate were 1.46% and 1.67%, respectively *(Wei et al. 2020)*.

In discrete element simulation, the similarity between the shape of the discrete element model and the actual shape and the selection of the collision model are particularly important. Table 4 shows the collision models and conclusions used in the simulation of some materials. Secondly, the parameters of the simulation model need to be calibrated. The physical parameters of the material are consistent with the real value, but because of the difference between the simulation model and the real particle in geometry, they are different from the real value. Therefore, the application of retrograde engineering to particle modeling is becoming more and more popular.

Test Analysis Method

The test analysis method is to carry out the mechanical test on the material through the test equipment, to obtain the physical parameters of the material itself. At the same time, a standard is used to judge the degree of damage. This method provides important data parameters for analyzing the mechanism of material damage and can analyze the cause and process of damage from inside the material, which is widely used at present.

Duan (*2014*) analyzed the collision damage mechanism by using Hertz rigid-flexible collision theory and von Mises criterion of plastic materials under the condition of plastic deformation of pepper fruit.

By observing the movement law of pepper fruit during picking with high-speed photography technology, it is concluded that the damage was mainly caused by the impact of the top and side of elastic teeth on pepper fruit. In order to study the impact damage of castor beans, *Hou et al. (2020)* conducted impact tests on two different varieties of castor beans respectively by means of high-speed photography equipment, and judged the degree of damage by comparing the maximum impact force and normal deformation. The results show that impact height has a significant effect on the maximum impact force, and impact height and impact angle have a significant effect on the normal deformation.

Sheng et al. (2022) studied the mechanical properties between tea shell and tea seed of camellia fruit through compression puncture test. The results showed that the higher the water content of camellia fruit, the lower the puncture power of tea shell and tea seed. When the water content was constant, the puncture force of tea shell and tea seed on the outside was greater than that on the inside. The relationship between water content and puncture force was found to provide theoretical basis for mechanized cleaning of camellia fruit. *Du et al.* (*2019*) studied the damage of kiwifruit through physical compression test and drop test. The results show that the bruise susceptibility of kiwifruit is correlated with the maturity of the fruit. The higher the maturity, the easier it is to scratch, while the fall height had little effect on the bruise susceptibility of the fruit. *An et al.* (*2020*) carried out a compression test on strawberries to study the damage mechanism of strawberry fruits and their internal tissues. By observing the area of fruit browning to judge the degree of damage, it was concluded that the percentage of fruit damage mass is only related to the direction of loading. *Yu* (*2020*) took three kinds of red jujube at a brittle maturity stage as research objects and carried out drop impact tests to explore the effects of varieties, impact materials and drop height on the damage. The regression model of collision damage was obtained by response surface analysis, which provides a reference for a mechanical damage theory of jujube. In the process of material harvesting, the collision between materials is inevitable. For this reason, *Wang et al.* (*2018*) used a pendulum impact device to study the collision damage between fruits in litchi harvest. The results show that fruit would be damaged significantly when impact speed was 2.8 m/s and impact times were 15. Therefore, mechanical damage during mechanical harvesting can be reduced by changing the parameters. Based on the Hertz contact theory, *Horabik et al.* (*2017*) used a high-speed camera to measure the rebound height of pea, soybean, and rapeseed seeds dropped and conducted an impact test. It is concluded that the recovery coefficient of seeds decreased with the increase of impact velocity, and the moisture content of different varieties seeds also had an impact on the recovery coefficient. *Hussein et al.* (*2019*) conducted a drop impact damage test on three kinds of pomegranates. It is found that the degree of damage of fruit is linearly related to impact energy. The damage volume and area of fruit increase with increasing temperature. *Fu et al.* (*2017*) used a pendulum impact device to study the impact of different buffer materials on apple damage and judged the damage condition by comparing the damaged area. The results show that the top area of the apple is most sensitive to bruising.

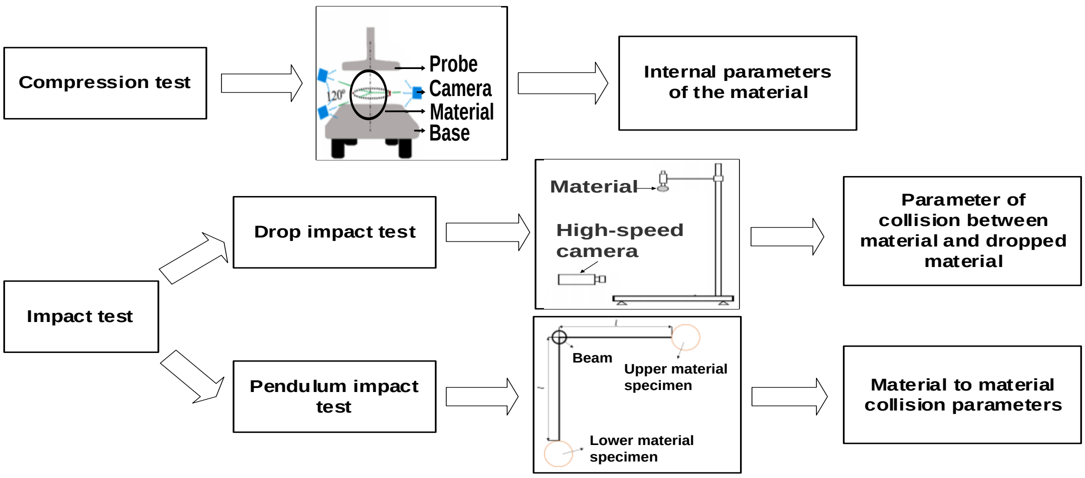


Fig. 10 - Two commonly used tests

The physical parameters of the material fruit can be obtained by using the method of experimental analysis. Common tests include compression test and impact test, as shown in Fig. 10. In addition, high-speed photography is used to observe the state of the harvest. The difficulty is how to determine the degree of damage, and cannot provide complete information to guide the design of machine.

Table 5

Comparison of different analysis methods

Analytical method	Advantage	Disadvantage
Finite element method	The stress and deformation of a single material are obtained	Material properties are difficult to set
Discrete element method	The collision parameters of mass materials are obtained	The setting of boundary conditions is complicated
Test analysis	The test data is true and reliable	Failure to provide complete information to adequately guide process and equipment design

It can be drawn that the impact damage mechanism of materials is mostly analyzed and processed by means of FEM, DEM, and experimental analysis. The comparison of the three methods is shown in Table 4. For simulation analysis, different methods are selected according to a different emphasis. For the impact damage of a single material fruit, the FEM is generally used to analyze, while for the impact damage of a material group, the DEM should be used. In addition, although the FEM and DEM can simulate the impact damage of materials, they are still different from the actual situation. Therefore, to judge the authenticity of the simulation, many researchers apply the experimental analysis. The relationship between the three methods of studying the mechanism of material damage is shown in Fig. 11.

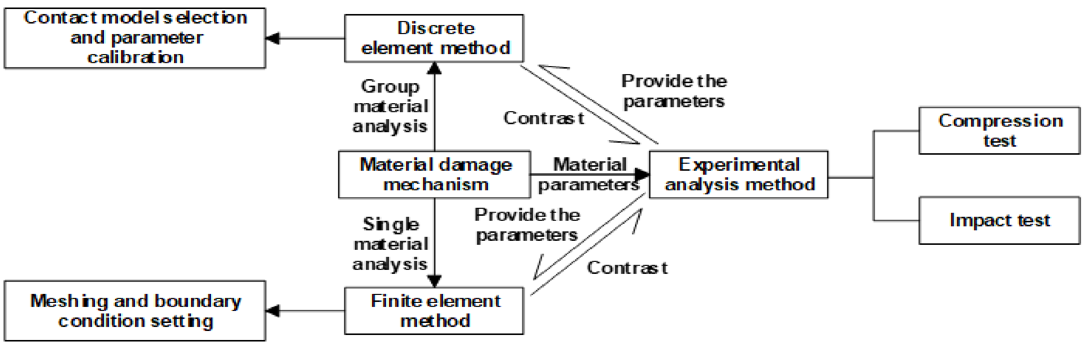


Fig. 11 – Relationships between the three methods

When using the method of simulation for damage analysis, it is necessary to model the fruit of the material. Since the shape of material fruit is not regular, the two commonly used modeling methods at present are to approximate the shape of the fruit to regular shape and modeling the fruit through reverse engineering. *Nikara et al.* (*2020*) approximated the potato to ellipsoid shape and carried out an impact test by using FEM. *Gharaghani et al.* (*2018*) established a citrus model as a sphere and conducted a drop finite element test. *Wang et al.* (*2018*) established a discrete element model of a single soybean by approximating the soybean seed as an ellipsoid and filling it with spheres. *Salarikia et al.* (*2017*) used a non-contact 3D scanner to generate the surface model of pear and used CATIA V5 software to process it into a 3D solid model. *Ji et al.* (*2019*) took the section of an apple with a camera and imported the image into AutoCAD to extract the contour curve of the apple with a spline curve. The real shape of the material can be restored by using the reverse engineering method, and the authenticity of the simulation can be improved.

CONCLUSIONS

Brush harvesting has been studied for more than 60 years since the 1960s. It has been widely used in harvesting different crops. At present, due to the continuous adaptation of agronomy to the development of agricultural mechanization, brush harvesting devices can harvest fruit crops, but has higher requirements for the damage rate. The focus of research on brush harvesters is to realize loss reduction while keeping the high harvest rate. We should further study the shape, structure, and material of the comb finger so that the comb brush harvester can get further development. The main conclusions of this paper are as follows:

(1) The comb brush device is divided into four types: comb tooth type, roller spring finger type, belt comb finger type, and rod comb finger type. Among them, roller spring finger type and rod comb finger type have become the two main types of research at present because of their strong applicability and wide range of crops. In addition, the technology of variable comb finger spacing can effectively improve the picking rate

of the brush device, while the existing variable finger spacing device can only realize the simultaneous change of finger spacing. In the future, it is possible to change the spacing of any part of the finger by developing the structure of the finger and adding sensors.

(2) Damage caused by harvesting with a brush device is collision damage. Three common analysis methods are FEM, DEM, and experiment analysis method. The FEM analysis the main collision between single part damage, while research on group collision damage produced is by DEM. Then the test analysis can obtain the physical parameters by material mechanics experiments. At the same time, it can also provide material parameters for the finite element method and discrete element.

(3) The application scope of comb brush harvesting has been expanded. Comb brush devices are often applied to harvest crops with small fruit mass but large stalk connections. For crops with large fruit mass, vibration is usually used. Compared with vibration harvester, brush harvester has the advantage of less damage to crop root. At present, some crops collected by vibration devices have been harvested by brush. The integration between agronomy and agricultural machinery technology, comb brush harvesting devices will be more widely used in the future.

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