Recent progress and future prospects for mechanized harvesting of fruit crops with shaking systems

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Abstract: Mechanized harvesting technologies with shaking systems for fruit industry have been widely investigated and significantly developed over the past several decades which were presented by a large amount of literature. This paper reviews the research and development progress of mechanized harvesting of fruits systematically with a focus on the theoretical study, fruit crop variety, shaking system categories, abscission chemical agents, and their actual applications. Based on the comprehensive review, mechanized harvesting systems for different fruit crops appear multifarious shaking modes with various vibratory mechanisms and structural dimensions. Major advantages in the development of fruit mechanical harvesting with effective vibratory patterns and catching frames provide a series of economic and agronomic benefits, such as reducing labor costs, promoting standardized planting, and increasing productivity. However, fruit injury and tree damage are the main reasons why mechanical shaking systems are rarely used for fresh fruit harvesting because of tenderness and frangibility of the fruit crops. Therefore, more efforts should be concentrated on the innovative shake-and-catch system with suitable frequency and amplitude to achieve low fruit damage or even nondestructive harvesting for fresh fruit market. This overview summarized the advantages and bottlenecks of these shaking systems for fruit harvesting and proposed the challenges and some constructive prospective viewpoints aimed at the major issues of mechanical harvesting techniques. In addition, employing sorting technologies to classify the postharvest fruits provide a new direction for the further development of mechanized harvesting in high-value fruit crops, as well as bring more benefits to growers and increase their interest in equipment investment on the mechanical shaking harvester for the fruit industry.

Keywords: fruit crop, mechanized harvesting, shaking system, fruit injury, postharvest classification
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1 Introduction

Fruit harvesting as the ultimate goal of orchard production is a seasonal and time-consuming job. Manual picking as a conventional fruit harvesting method is highly labor intensive and inefficient in terms of both economy and time[1]. It is still the main way for fresh fruit harvesting even with the help of some semi-mechanical or semi-automatic harvest-assist platforms[2-4]. The ratio of labor cost for fruit harvesting occupying the producer's total production investments is about 35% to 45%[5]. As we all know, more and more labors are gradually transferring a large proportion of workers from agricultural activities to other industries[6,7]. Thus, this situation leads to labor shortage in agricultural production. In addition, there has been a very short period of maturity stage available for fruit harvesting. Therefore, improving the efficiency of fruit harvesting is becoming more and more urgent and important. With the development of fruit harvesting technologies, it is encouraging that mechanical harvesting systems replacing human labor have been widely investigated and significantly enhanced to a great extent in many kinds of fruit production, such as grape, olive, blueberry, orange, and other processing fruits. It is suitable for harvesting mature fruits efficiently with standardized management and large-scale fruit production. Therefore, mechanical harvesting systems for fruit production play a critical role in the fruit industry gradually.

In recent several decades, more and more new technologies and methods for fruit harvesting with good adaptability and practicability have been developed. In particular, automated picking robot for fruit harvesting has made great progress in the laboratory stage, but there is still a long way to satisfy the need for

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actual production, especially its lower efficiency compared to the manual harvesting method and mechanized harvesting technology[8]. So far, the shaking system as the main fruit removal pattern for fruit mechanical harvesting has been studied for many years since the early 1960s. Coppock[9] proposed and investigated the concept of the shake-and-catch harvesting system. From then on, more and more kinds of shaking systems were developed and applied to harvest different fruits. The details of these harvesting technologies relating to different fruit varieties and shaking system categories are summarized in Section 3 and Section 4 respectively.

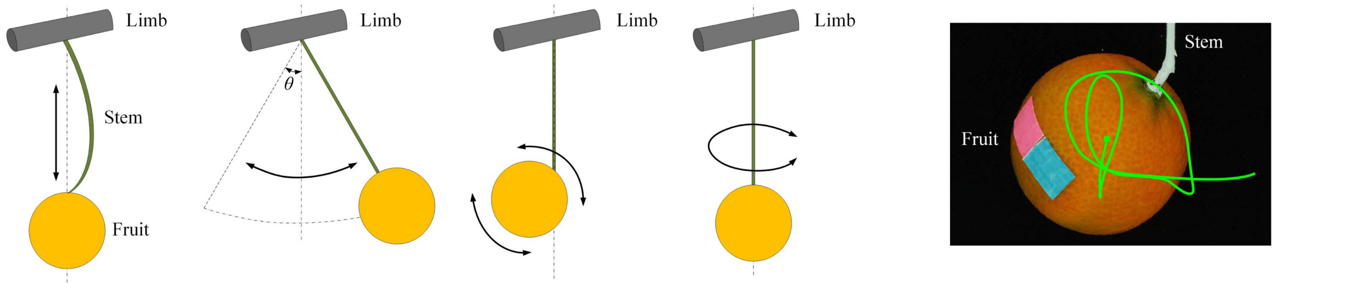
As the studies on the fruit mechanical harvesting technology continue, some review literatures about mechanical harvesting for fruit industry have been illustrated. Li et al.[1] overviewed several kinds of shakers of the mechanical harvesting methods very briefly for potential use of automatic fruit harvesting system. Sanders[5] compared mechanical harvesting techniques of four kinds of shaking methods in brief for orange harvesting systems. Chen et al.[10] introduced existing shaking technologies and analyzed its vibratory mechanism for fruit mechanical harvesting. As all these review literatures summarized above, mechanical shaking system is the main harvesting method to detach fruits from trees for realizing the mechanization of fruit harvesting. However, there has been no review systematically discussing the vibratory mechanism and recent progress of the mechanical shaking systems for fruit harvesting that have been developed. To review the mechanized harvesting of fruit crops with shaking systems comprehensively, this paper concisely sums up the main features and achievements of the different mechanical shaking systems that have been investigated for different fruits. Meanwhile, it also attempts to summarize the advantages and disadvantages of these mechanical shaking systems for fruit harvesting and highlights the potential agronomic requirements, innovative mechanical structure design, and future prospects to enhance the mechanized harvesting technologies. In addition, the feasibility of the universal shaking system with variable frequency and amplitude to improve the utilization is also discussed to reduce the costs of harvesting different fruit crops using the same harvester.

The content of this review was organized with following several sections. Firstly, the basic principle of fruit detachment by shaking system for fruit mechanical harvesting was introduced in Section 2. And then, an overview of the fruit varieties harvested by mechanical shaking system was summarized in Section 3. Furthermore, the categories of the different mechanical shaking systems and their structural patterns as the main components used to successfully detach fruits for fruit harvesting were analyzed in Section 4. In addition, the assist and challenge of the abscission chemical agents for fruit detachment were also represented in Section 5. And the major issues and comparisons of the mechanized harvesting of fruit crops were discussed in Section 6. Finally, some constructive viewpoints and prospective trends aimed at the major issues for mechanical fruit harvesting were proposed in Section 7. The last section demonstrated the summary of this review paper with recommended aspects for the further development of mechanized fruit harvesting.

2 Basic principles of vibratory fruit harvesting

In general, mechanical shaking system is a kind of device that can produce a reciprocating motion using some kinds of vibratory mechanism. The essential principle of the shaking system for fruit detachment is based on the transmission of vibratory force to the limb with ripe fruits. Specifically, mechanical vibratory device transmits the vibration energy to the different zone of fruit trees[11,12]. And then, the forced vibration with a certain frequency and amplitude oscillates the branches with some form of shaking and inertial force. When the adhesion strength of the inertial force is greater than the detachment force in the weakest point of fruit stem, this forced vibration can complete the detachment processing for fruit harvesting[10]. In addition, the fruits fall off the tree branches randomly when the centrifugal force of the fruit reaches the tipping point during the vibration. Furthermore, mechanical shaking harvester making the ripe fruit vibrate and detach from its stem is affected by several factors, such as the fruit features (mass, volume, maturity, peduncle length, peel firmness), the mechanical and geometrical characteristics of the trees and the parameters of the forcing vibration (frequency, amplitude, duration, location).

Besides, the analysis of fruit vibration motion is complex during mechanical shaking harvesting, which is important to investigate optimal operating parameters and contribute to innovative machinery development. In most cases, four elemental patterns of fruit motion include flapping up and down, pendulum, rotating, and twisting as shown in Figures 1a-1d, which have been widely used to simplify the kinematic analysis of fruit vibration[13]. Actually, the fruit motion trajectory as shown in Figure 1e under external vibrational excitation is composited with the above elemental patterns confirmed by high-speed artificial vision[14]. These motion patterns result in different fruit detaching forces that are related to different fruit varieties and vibration modes. With the development of fruit harvesting technologies, many kinds of mechanical shaking systems have been developed for different fruit crops during the last several decades. The different fruit varieties and mechanical shaking systems will be elaborated in Section 3 and Section 4, respectively.



a. Flapping up and down b. Pendulum c. Rotating d. Twisting e. Irregular swing trajectory investigated by artificial vision[14]

Figure 1 Fruit motion patterns under vibrational excitation

3 Fruit varieties of mechanized vibratory harvesting

Mechanical shaking systems are effective to achieve mass removal of mature fruits during harvesting season. Based on a large number of previous studies, a brief classification of main fruit crop varieties for mechanized vibratory harvesting application was summarized in Table 1, including orange, apple, peach, apricot, olive, jujube, cherry, grape, blueberry, walnut, chestnut, almond, hazelnut, coffee, pistachio, ginkgo and pinecone. Obviously, these fruit crops with different physical and mechanical properties harvested by mechanical shaking systems were studied and investigated over the last almost 60 years.

Table 1 Brief classification of fruit crop varieties with effective mechanical vibratory harvesting

Varieties	Features		Purpose	References
	Profile view	Description		
Orange		Spheroidal shape with thick elastic pericarp ranging from 0.77 to 4.0 mm	Juice industry	[5,15-21]
Apple		Nearly spherical shape with thin peel ranging from 0.183 to 0.215 mm	Fresh market	[4,22-26]
			Juice/Sauce	[27-31]
Peach		Nearly spherical shape with core and thin peel	Juice/Sauce	[32]
Apricot		Spherical shape with core and thin peel	Dried slices	[33-35]
Olive		Spindly shape with core and thin peel	Oil	[36-43]
Jujube		Elliptic shape with core and thin peel	Dried date	[44]
Cherry		Nearly spherical shape core and with thin peel	Fresh market	[45,46]
			Sauce	[47,48]
Grape		Elliptic shape with thin peel ranging from 0.238 to 0.334 mm	Wine	[49-53]
Blueberry		Oblate shape with thin peel	Fresh market	[54]
			Sauce	[55-57]
Oil-tea camellia		Small spheroidal shape with kernel and soft pericarp	Oil	[58]
Walnut		Spheroidal shape with thick pericarp and kernel wrapped by hard shell	Nut	[59]
Chestnut		Hemispherical shape with kernel and tough shuck wrapped by shell with burrs	Nut	[60]
Almond		Oblate shape with kernel and hard shell	Nut	[61,62]
Hazelnut		Nearly spherical shape with kernel and hard shell	Nut	[63]
Coffee		Oval shape with kernel and thin pericarp	Coffee bean	[64-67]
Pistachio		Elliptic shape with kernel and shell	Nut	[68]
Ginkgo		Nearly spherical shape with kernel and thin peel	Nut	[69]
Pinecone		Spindly shape with kernel and multilayer hard shell	Nut	[70-72]

Note: The pictures in Table 1 were cited from https://image.baidu.com/.

According to the references listed in Table 1, it is clear that more previous studies focused on mechanized vibratory harvesting for orange, apple, olive, grape, or coffee on account of its huge industrial demand to some extent. Initially, Jutras and Coppock as the first researchers presented a promising method of vibration for citrus fruit harvesting around the 1960s[9,73]. During the next several decades, some kinds of shaking devices have been developed and investigated for harvesting citrus fruit, such as limb shaker[21,74,75], conical scan air shaker[76], trunk shaker[19,20] and canopy shaker[77,78]. On the other hand, more investigations have been carried out for harvesting apples using mechanical shaking systems compared with the mechanized harvesting of peach[79], apricot[33,34], jujube[44], cherry[46], and blueberry[57]. In 1969, the shake-and-catch frame method was proposed to harvest apples investigated by Marshall et al.[80] And then, straddle-frame trunk shaker and mobile limb shaker were designed for harvesting apples respectively[27,81,82]. Later, a kind of canopy apple harvester using a continuous horizontal shaking method was also developed[83]. With the progress of fruit harvesting technologies, a series of shake-and-catch mechanical vibratory devices were developed and studied for fresh market apples in recent years[4,23,30].

As we all know, the peel of some fruits is very thin less than 1 mm, such as apples, peaches, apricots, olives, jujubes, cherries, grapes, and blueberries. It's easier to be damaged when they are dropped from a relatively high place or stricken by the mechanical shaking system. On the other hand, the epicarp of orange with a thicker elastic pericarp also easy to be bruised during mechanical harvesting, which leads to post-harvest decay seriously[84]. In view of this vulnerable situation, these fruits are harvested by mechanical shaking systems for the processing industry without regard to fruit injury. Furthermore, the small serried fruits such as olive, cherry, grape, and blueberry are more time-consuming and labor-intensive by manual harvesting. Compared to the above-mentioned fruits, some nuts such as walnut, chestnut, almond, hazelnut, pistachio, and pinecone are wrapped with the hard shuck. It is difficult to be damaged when it is stroke and dropped from the high trees. Besides, oil-tea camellia, coffee, and ginkgo fruit usually only need its kernel or seed enfolded with exocarp so that the damage to the pericarp is not considered.

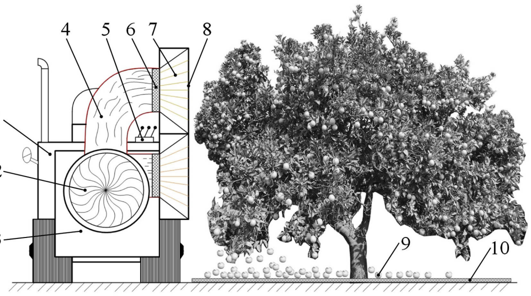
Therefore, the nuts are more effective to harvest using mechanical vibratory methods. Meanwhile, agricultural engineers are trying to develop various mechanical shaking systems to improve harvesting efficiency based on the special features of different fruit crops.

4 Mechanical shaking systems for fruit harvesting

To solve the labor intensity and low efficiency of fruit harvesting through manual picking, the past six decades have witnessed many innovative developments of mechanical shaking systems which have been investigated for the fruit processing industry, or even for the fresh market. So far, various shaking systems for fruit harvesting have been explored by many agricultural engineers. The mechanical shaking systems are summarized in this section including air shaking system (ASS), limb shaking system (LSS), trunk shaking system (TSS), and canopy shaking system (CSS). The details of these mechanical shaking systems are illustrated as follows.

4.1 Air shaking system (ASS)

Air blowing as a kind of vibrating method to oscillate the tree canopy to detach fruits has been investigated around the last 1970s. The air shaking system (ASS) for fruit harvesting consists of air blower, vortex chamber, air deflector, air regulating valve, and other accessories as shown in Figure 2, which can be traced back to the 1960s. Jutras et al.[85] as a pioneer developed an air shaking harvester using a high-volume and high-velocity oscillating air blast for harvesting citrus fruit. The oscillating air blast machine was constructed to study the feasibility of this principle for harvesting citrus fruit mechanically. The results indicated that the oscillating air blast system could obtain the fruit removal percentage ranging from 40.0% to 95.6% at a travelling speed of about 0.4 km/h with air velocities ranging from 44 to 51 m/s. This investigation verified the feasibility of the oscillating air blast for fruit detachment. However, some small green fruits falling off were observed during the harvest of Valencia oranges. And fruit damage was also generated so this air blowing method was unsuitable for fresh fruit harvesting.



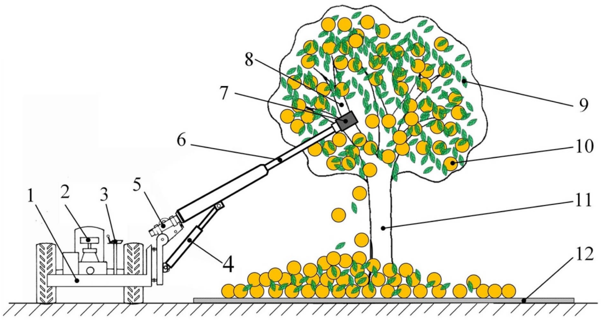
1. Tractor 2. Air blower 3. Air plenum 4. Vortex chamber 5. Control panel 6. Air regulating valve 7. Air deflector 8. Air outlet 9. Fruit 10. Canvas

Figure 2 Schematic diagram of air shaking system

And then, Whitney[86] designed a kind of shaking system with air harvester concept for removing citrus fruits between 1963 and 1967. Over the next decade, a citrus removal device was developed using oscillating forced air vibrating the tree canopy for citrus fruit detachment[87-89]. After that, improved air shakers were developed and constructed, such as Three Air Shaker patterns[90], Conical Scan Air Shaker[76], and Self-Propelled Air Shaker[91]. However, the air shaker concept for fruit removal has not been continued because of its ineluctable disadvantages. For one thing, the efficiency of the fruit detachment using air shaking system is relatively low if it is not using abscission chemicals for fruit loosening. For another thing, the air shaker requires much more power to produce the oscillating air blast that needs higher capital investment.

4.2 Limb shaking system (LSS)

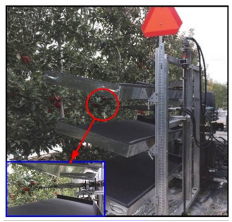
The original simple limb shaking for detaching fruits is hand-held shaker gripping and vibrating the individual branches of the fruit trees which is too labor-intensive for fruit harvesting. In the early exploration, Lenker and Hedden[92] investigated the limb properties of citrus to obtain necessary information as criteria for designing new inertia-type limb shaker to harvest citrus fruit effectively. And then, Coppock[74] developed a self-propelled limb shaker as a component of a shaker-pickup harvesting system which obtained a fruit removal efficiency of about 90% with the harvest rate averaged from 6.1 to 9.3 trees per hour for citrus harvesting. Besides, Sumner[21] designed and constructed a full-powered positioning limb shaker and tractor-mounted limb shaker for harvesting oranges. The field test results showed that the fruit removal percentage of the full-powered positioning limb shaker was 96.1% for trees sprayed with abscission chemical and 90.0% for unsprayed trees. In addition, a tractor-mounted limb shaker was developed and obtained a harvesting rate of 40 trees per hour at a fruit removal efficiency of 95% during chemically loosened orange harvesting[75]. Overall, the tractor-mounted limb shaking system was proposed and composed of operating lever, holding device, vibrator and other accessories as shown in Figure 3a.



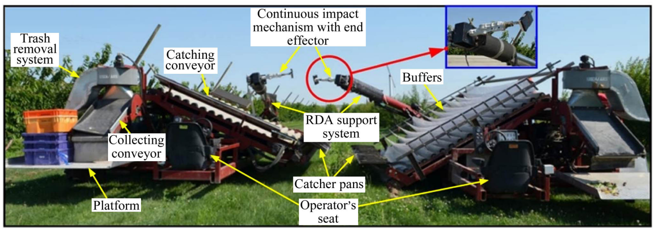
1. Tractor 2. Driving seat 3. Operating lever 4. Hydraulic cylinder 5. Vibrator 6. Expansion rod 7. Holding device 8. Branch 9. Leaf 10. Fruit 11. Trunk 12. Canvas

a. Schematic diagram of the limb shaking system

b. Semi-automated eccentric limb shaker[93]



c. Multi-layer shake-and-catch apple harvesting system with limb shaker[25]



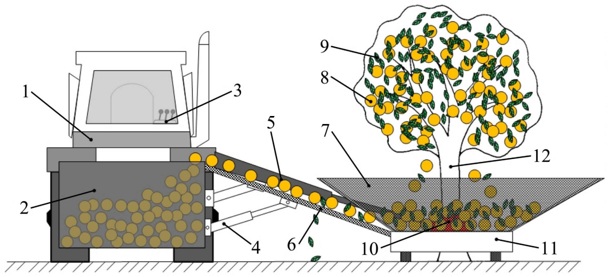
d. Mechanical shake-and-catch prototype of sweet cherry harvesting system[48]

Figure 3 Tractor-mounted limb shaking systems

Moreover, the limb shaking system (LSS) was also studied and applied to the mechanical harvesting of the other fruits. For instance, a limb shaker mounted on the rear of a tractor was designed and described as a mobile shaker moving from orchard to orchard for apple harvesting which obtained a harvest rate of 20-53 apple trees/h with a fruit removal efficiency of 90%[81]. A semi-automated mechanical fruit harvesting system was developed based on eccentric limb shaker with two limb graspers as shown in Figure 3b, which acquired fruit removal efficiency of 88% within the actuation zone of the fruit section[93]. Furthermore, Zhang et al.[25] evaluated a shake-and-catch harvesting system consisting of a mechanical limb shaker and a multi-layer apple collection mechanism at Washington State University (Figure 3c), which achieved relatively high fruit removal efficiencies around 85% and fresh marketable fruit about 88% to 92%. Besides, Larbi et al.[48] introduced a prototype of mechanical shak-and-catch harvesting system for sweet cherry with limb shaker as shown in Figure 3d, which was operated on opposite side of the tree row to harvest fruits at the same time. And then, a limb-shaking harvester for fresh market sweet cherry was designed and studied to investigate the effect of shaking frequency, duration and excitation position on fruit detachment and damage[46,47,94]. There is no doubt that the limb shaking system is feasible to harvest fresh fruit selectively but with a relative low harvesting efficiency because of the limb vibrational excitation one by one.

4.3 Trunk shaking system (TSS)

Compared with the partial vibration using air shaking system (ASS) or limb shaking system (LSS), trunk shaking system (TSS) can make the whole tree vibrating simultaneously actuated by vibrator as shown in Figure 4a. Hence, it has a relatively higher efficiency for fruit harvesting. Initially, a straddle-frame trunk shaker with shake-and-catch system for harvesting fresh market apples was designed and investigated by Berlage and Langmo[27]. However, trunk shaker with different vibratory patterns for mechanized apple harvesting would produce inevitable fruit damage to some extent. For example, a pendulum type of impulse trunk shaker compared with inertial trunk shaker on open-center and central-leader trees for apple harvesting, the impulse trunk shaker caused more apple damage than the inertial trunk shaker[95,96]. Besides, a spring activated trunk shaker with either double-impact or recoil-impact mode was studied to harvest semi-vigorous open-center apple trees. The results showed that the trunk shaker with double-impact or recoil-impact mode caused less apple damage than inertial trunk shaker[82]. Trunk shaker technique was also used to be applied to the mechanical harvesting of citrus fruit. Two types of trunk shakers were employed in two shaking modes to harvest 'Hamlin' and 'Valencia' oranges over three harvest seasons[20]. And then, Hedden et al.[97] carried out two experiments to collect performance data on trunk shakers for harvesting 'Hamlin' and ‘Valencia’ oranges for five seasons to evaluate the effectiveness of four trunk shaking patterns. Besides, The motions of two trunk shakers were investigated during the harvesting of 'Hamlin' and 'Valencia' oranges on linear and multidirectional shaking patterns[98]. Furthermore, three field experiments using trunk shaker for harvesting mature 'Hamlin' oranges to measure the fruit removal performance of the above two shaking patterns were conducted[19]. It indicated that the orange removal percentage of the linear shaking pattern was superior to the multidirectional shaking pattern by 1% to 6% with shaker head displacement of 6-7 cm and frequency of 7 Hz. In addition, Moreno et al.[99] evaluated an orbital trunk shaker equipped with a three-point grip system and clamps (Figure 4c) by means of abscission chemical agent for citrus fruit harvesting with the percentage of detached fruits up to 85% and demonstrated that it may be a feasible solution for fresh fruit detachment.



1. Tractor 2. Fruit box 3. Control panel 4. Hydraulic cylinder 5. Expansion device 6. Conveyer 7. Catching device 8. Fruit 9. Leaf 10. Vibrator 11. Gathering unit 12. Trunk

a. Schematic diagram of trunk shaking system with catch frame

b. Trunk shaker with reverse umbrella for olive harvesting[100]

c. Trunk shaker with clamps for citrus harvesting[99]

d. Tractor-drawn trunk shaker for olive harvesting[101]

Figure 4 Mechanical trunk shaking systems

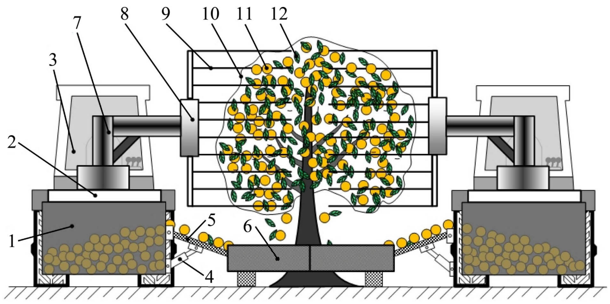
In recent years, lots of studies on trunk shaking technique have also been conducted for the mechanical harvesting of olive fruits. Initially, the effects of trunk shaking duration and repetition on the removal efficiency for olives harvesting were studied to analyze the detachment process of the olive fruits[102]. Later, a tractor-drawn trunk shaker with catch frame as shown in Figure 4d for harvesting a traditional oil olive tree was evaluated and obtained a mean harvest efficiency of 90.5%[101]. Besides, a commercial tractor-drawn trunk shaker maximizing the fruit quantity while maintaining its quality was developed for the mechanical harvesting of Spanish 'Manzanilla' table olive with the harvesting efficiency about 74%[103]. In addition, an orbital trunk shaker with reverse umbrella (Figure 4b) for harvesting different olive cultivars was employed to measure the optimal vibration frequency, acceleration and shaking duration to maximize the fruit removal percentage[100]. Furthermore, an automatic trunk-detection system of trunk shaker was developed to improve the harvesting efficiency and reduce operator’s influence on the inaccurate clamping process[104]. However, it needs to be pointed out that the trunk shaking system should avoid badly damaged bark which may cause the death of fruit trees.

4.4 Canopy shaking system (CSS)

In general, a canopy shaking system (CSS) is using a vibratory device with reciprocating shaking rods to strike the branches of the tree producing vibration to detach fruits. There are lots of investigations concentrating on canopy shaking system for fruit mechanical harvesting by former researchers. For instance, a vertical canopy shaker as early research work has been investigated and designed for 'Valencia' orange harvesting[77]. And a continuous horizontal canopy shaking harvester was developed for removing apples using two positive-displacement type shaker heads to drive six discs with rubber teeth to shake the canopy at a frequency of 10 Hz and a peak to peak amplitude of 26 mm[83]. Later, Peterson and Takeda[105] developed an over-the-row canopy shaking system to evaluate the feasibility of mechanical harvesting for fresh market quality of Eastern thornless blackberry, which utilized a direct-drive spiked-drum shaker for selective fruit removal and an energy-absorbing catching conveyor to collect the berries. Besides, a kind of picking-head canopy shaker for table olive harvesting was designed by AgRight (Madera, CA)/Korvan (Lynden, WA) and modified by Dave Smith Engineer(DSE, Exeter, CA) removing accessible fruits with efficiency of 90%[106]. And then, a mechanical beater mounted on a tractor plus hand-held pneumatic combs was developed to shake the canopy of the large olive trees with a canopy volume of 140-360 m^3 for mechanized olives harvesting[40]. In addition, an experimental canopy rotary drum shaker consisting of a series of fingers composed of fiberglass rods with rubber padding and end caps was developed to selectively harvest Jatropha curcas fruits with minimum plant damage[107]. Moreover, a type of tractor-powered continuous travel canopy shaking harvester without catch frame (Figure 5g) at an operator-determined frequency for sweet orange removal was introduced[108,109]. Furthermore, a two-section canopy shaker composing of top and bottom shaking rods mounted on two rotating drums as shown in Figure 5f was proposed and developed to minimize tree damage and maximize fruit removal for canopy shaking harvesting[110]. Thus, we can see that different patterns of the canopy shakers are related to the fruit features and tree canopy parameters.

Compared with the air shaker, limb shaker, trunk shaker and canopy shaker as mentioned above, continuous canopy shaking systems with catch frame and cushioning materials are relatively more efficient for fruit harvesting, which simultaneously vibrate both sides of the tree canopy as shown in Figure 5a. In fact, the continuous canopy shaker has a catch frame connected with a conveyer system to transfer the fruits to the following truck or box. Based on this concept, a self-propelled continuous canopy shaker (Figure 5b) manufactured by Oxbo International Corporation (Byron, N.Y.) has a set of tines which can insert the tree canopy and shake the branches to detach fruits from both sides of the tree for citrus harvesting[78]. In addition, "ShaMolive" harvester with four independent canopy shaker heads (Figure 5c) fitting for irregular crowns could circuitously reach the whole canopy volume of big trees, which had a catch frame with several conveyors supported on two axles and four wheels[111]. Furthermore, self-propelled over-the-row canopy shaker integrated with catch frame was applied commercially to harvest intensive fruits with medium or small fruit trees as shown in Figures 5d and 5e.

So far, this kind of straddle-type continuous canopy shaking system with catch frame and buffer device has been widely used for the mechanical harvesting of fruit crops without regard to fruit damage, such as olive[112], grape[49], blueberry[55] and jujube[44]. The continuous canopy shaker has obtained popularity and acceptance compared with the trunk shaking system because it does not stop at each tree with higher efficiency for fruit harvesting. Basically, the canopy shake-and-catch harvesting system has the same procedure for most varieties of fruit crops but with a great variation of different vibratory harvesting patterns depending on the tree structures, fruit features, or even the agronomic requirements. As a whole, it should be concerned that continuous canopy shaking system can achieve a high efficiency for fruit harvesting but also make a lot of leaf shedding or even fruit damage.



1. Fruit box 2. Tractor 3. Driving cab 4. Hydraulic cylinder 5. Conveyor 6. Catch frame 7. Stand column 8. Vibration device 9. Shaking rod 10. Canopy 11. Fruit 12. Leaf

a. Schematic diagram of canopy shaking system

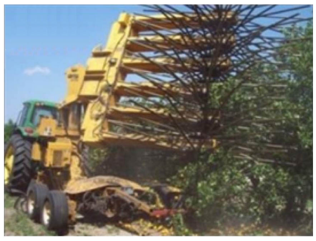
b. Self-propelled continuous shake and catch system[78]

c. Olive mechanical harvesting with four canopy shaker heads[111]

d. Over-the-row canopy shaker for olive harvesting[112]

e. Self-propelled shake-and-catch grape harvester[49]

f. Prototype of two-section canopy shaker[110]



g. Tractor-drawn canopy shaker[113]

Figure 5 Mechanical canopy shaking systems

5 Assist of abscission chemical agents for fruit harvesting

To increase the fruit removal effectiveness and facilitate the mechanical harvesting of fruits, investigations of abscission chemical agents have been also conducted toward reducing the fruit-stem detachment force. With the development of fruit harvesting technologies, using abscission chemical agents was confirmed as a feasible method to loosen the mature fruits and increase the fruit detachment efficiency during harvesting season.

Previous studies on utilizing abscission chemical agents to reduce the binding force for detaching mature fruits have indicated that the abscission chemicals can greatly improve the vibratory harvesting performance. Early field trials as pre-harvest processes with potential abscission chemical agents were carried out for mechanical harvesting of citrus, such as Hamlin, Jaffa, and Valencia oranges in Florida[114]. And then, Wilson et al.[115] conducted a series of harvesting experiments using air carrier sprayers with abscission chemical agent which achieved a harvesting efficiency of 1.5 acres per hour by an experimental air shaker. In addition, four abscission chemical agents were applied to the same orange trees for 3 consecutive years to harvest fruits with a shake-and-catch frame system, which indicated that these abscission chemical treatments could be useful as a supplementary method for fruit harvesting without significant effect on subsequent orange yields[116]. Furthermore, two experiments were conducted in a commercial 'Valencia' orange grove to investigate the effects of sprayer type, airflow rate, and nozzles output on deposition of abscission chemical agents, and the fruit removal conditions using a trunk shaker[117,118].

In specific applications, Sessiz and Ozcan[119] designed a branch shaker with a constant amplitude of 60 mm and frequency of 24 Hz spraying with abscission chemical agents using an air compressor for olives harvesting. Field trials indicated that it could obtain the lowest fruit detachment force and the highest fruit removal rate of about 96% when employing the abscission chemical concentration of 12.5 mL/L. Besides, an abscission chemical agent [5-chloro-3-methyl-4-nitro-1*H*-pyrazole (CMNP)] was applied to 'Hamlin' and 'Valencia' orange trees at concentration ranging from 0 to 500 ppm in a volume of 300 gallons per acre combined with mechanical harvesting by a trunk shaker and a continuous canopy shaker. It demonstrated that the CMNP application increased the harvesting capacity of shakers, reduced the harvesting time on each tree and obtained high percentage of mature fruits removal[120-122]. In addition, different orchards of mandarin and orange trees were sprayed with different doses of ethephon before mechanical harvesting from 2008 to 2011. Particularly, ethephon and monopotassium phosphate (PO_4H_2K) were applied to reduce the lemon fruit detachment force, which gained an overall detachment rate of up to 77% with the trunk shaker and 66% with the hand-held shaker[123]. It indicated that the abscission chemical agents increased the detachment rate of fruits significantly but without affecting their quality[99].

To sum up, all these applications of abscission chemical agents are beneficial to facilitate the fruit detachment efficiently and reduce the fruit or tree damage partially during mechanical harvesting. However, there are several factors affecting the use motivation of the chemical agents, such as human health, tree defoliation, fruit variety, spraying location, fruit without calyx, tree age, canopy volume, leaf area index, planting density, and so on[5,99,124]. Especially, abscission chemical agents for fruit detachment are likely to pollute the injured fruits, soil, or water, which probably exists hidden trouble in food safety for our health. And the food safety concerns cause considerable postharvest and economic losses. Therefore, it is a big challenge for application of the abscission chemical agents and not persistent in practical use for fruit mechanical harvesting so far.

6 Discussions

The information provided in this review shows that several kinds of mechanical shaking systems have been developed with higher efficiency and lower labor cost for fruit harvesting. In particular, trunk shaker and canopy shaking system can potentially increase the labor productivity by 5 to 15 times that of hand-picking and decrease the unit harvesting cost by 50% or more for the fruit juice industry[125]. What's more, mass fruit harvesting based on a continuous canopy shaking system can obtain a harvesting rate up to 3 times higher than that of trunk shaker because of its continuous harvesting process[78,101]. However, there are also some disadvantages that we must figure out properly even though mechanical shaking system has many obvious advantages for fruit harvesting under the situation of labor shortage and seasonality.

6.1 Distinction of the mechanical shaking systems for different fruit harvesting

As we all know, different varieties of fruits have various tree shapes and mechanical properties which determine the different structures and shaking patterns of vibratory harvesting machinery, such as structural dimension, shaking frequency, amplitude, duration, fruit removal percentage, fruit damage rate, and so on. Recently, continuous canopy shaker and trunk shaker are the main types of harvesting systems commercially used in orchards, while limb shaking system has also some special advantages for selective harvesting of fruit crops. The categories of the existing mechanical shaking systems with different performance parameters for various fruit harvesting are listed in Table 2. It can be seen that diverse fruit varieties utilize different types of shaker with various shaking parameters for fruit mechanical harvesting. Obviously, almost all of the mechanical shaking systems are employed to harvest fruits for processing industry on account of the fruit damage. While a few researchers investigated that the limb shaking system could also be used for the fresh apple harvesting effectively[23-25,29,126]. It indicated that limb shaker with catching device would be a promising pattern to harvest fruits selectively with relative high fruit removal percentage and low fruit injury for fresh fruit market.

As listed in Table 2, the performance parameters of the listed shaking systems are obviously different even though the similar types of shakers were used for harvesting the same variety of fruits. This difference is probably caused by multiple factors such as the characteristic of the shaking systems, mechanical properties of fruits and morphological structure of fruit trees. Therefore, it is a great challenge and future development trend to explore a multifunctional shaking system with regulable parameters for improving the versatility of the fruit mechanical harvester.

6.2 Fruit injury during mechanical harvesting

It is obvious that the mechanical shaking system can increase the fruit harvesting efficiency significantly, but the fruits are usually used for industrial processing instead of fresh market because of its fruit injury. To be more specific, the detached fruits have random collisions with branch, catch frame, vibratory device or even other fruits inevitably during the fruit vibration and dropping from the tree. The collision causes a certain degree of fruit mechanical injury which is susceptible to infection by microorganisms resulting in postharvest rot diseases[84]. Therefore, the mechanized harvesting of fruits by shaking system would probably reduce the fruit quality. In view of this disadvantage, how to reduce the damage to fruits caused by vibration harvesting is a prominent problem to be solved urgently in mechanized fruit harvesting.

In recent years, some researchers investigated the fruit damage level and injury mechanism during the fruit harvesting by mechanical shaking system. Particularly, mechanical damage caused by fruit-to-fruit impact is a main challenge for mechanical harvesting of bunchy fruits such as litchi, sweet cherry, grape, and so forth. Wang et al.[136] indicated that the damage degree of litchi fruits increased with the longer peduncle at all impact conditions and had the lowest average damage level with a vibration frequency of 32 Hz. Besides, a series of studies on sweet cherry injury during mechanical harvesting was carried out to analyze the fruit damage percentage related to the vibratory parameters such as shaking frequency, duration and excitation position. The experimental results of sweet cherry harvested by mechanical shaker showed that lower shaking frequency caused more slight damage with longer detaching time, and higher frequency caused more serious damage with shorter duration[13]. While it could lead to a higher fruit removal efficiency without more fruit damage when the limbs of sweet cherry were excited at both the lowest and highest excitation positions[137]. In addition, the effects of different nominal speeds and striking frequencies on the potential for fruit damage were also investigated. It demonstrated that the operating parameters of the canopy shaker are crucial to minimize the fruit damage evaluated by an over-the-row harvester in individual olive groves[112].

Table 2 Categories of the mechanical shaking systems with different parameters for fruit harvesting

Variety	Shaker Type	Frequency/Hz	Amplitude/mm	Shaking duration/s	Forward speed /km·h^{-1}	FRP/%	FDR/%	Postharvest treatment	References
Orange	LSS	4.5-5	6	4	N/A	53.4	N/A	Processing	[17]
	TSS	10-21	38	3	N/A	81	N/A		[127]
		15	12	4-5	N/A	72	N/A		[18]
		7	60-70	5-10	N/A	94.9	N/A		[19]
	CSS	4.5	212	N/A	1-1.5	84.7	N/A		[128]
		4.7	457	N/A	3	82.6	N/A		[110]
		4.1-4.9	212-313	N/A	1-1.5	78.7-89.0	N/A		[15,16]
Apple	LSS	20	14.3	2-5	N/A	91.43	N/A	Processing	[129]
		7	150	61	N/A	90	N/A		[81]
		15-25	36	2-5	N/A	84-90	≤15	Fresh market	[23-25,29]
		20	28.6	2	N/A	91.43	≤5		[126]
	TSS	7	21	2	N/A	89-95	20	Processing	[82,95]
Peach	LSS	22.5	60	73-140	N/A	93	13	Processing	[32]
Grape	CSS	5-9	30-90	N/A	3.5	95	N/A	Brewing	[50,51]
Olive	LSS	35	25	10	N/A	90.6	N/A	Oil expelling	[130]
	TSS	20-25	N/A	13.3	N/A	90	N/A		[102]
	TSS	28.1	N/A	15	N/A	85	N/A		[131]
	TSS	23-27	N/A	6-8	N/A	85-93	N/A		[100]
	CSS	5.26	200	N/A	0.4	90	≥35		[106]
	CSS	4-5	120-170	N/A	0.5-1	77.3	N/A		[132]
Jujube	TSS	9.0-16.7	N/A	47	N/A	91.4	N/A	Drying	[133]
	CSS	15	9	N/A	1.08	96.2	≤2.8		[134]
	CSS	6.7	N/A	5	N/A	95.8	10.7		[135]
	CSS	10-15	6-9	N/A	1-3	93.2	0.9		[44]

Abbreviation note: LSS-limb shaking system, TSS-trunk shaking system, CSS-canopy shaking system, FRP-fruit removal percentage, FDR-fruit damage rate, N/A-not applicable.

Fruit injury caused by mechanical shaking system is the biggest obstacle to the popularization and application of the mechanized fruit harvesting. Gallardo et al.[54] pointed out that blueberry growers would likely migrate toward the mechanization of fruit harvesting if the mechanical shaking harvester could be economically viable and achieve the point of reducing fruit damage. For the past few years, there are some studies focusing on the vibratory parameters, fruit catching devices and buffer material of the mechanical harvesting system to reduce fruit damage. Chen et al.[46] evaluated a self-propelled impact harvester with much higher acceleration and a hand-held vibratory harvester with catching surface comprised of cotton cloth to collect detached fruits during cherry harvesting. It showed that the vibratory shaker with buffer device achieved a higher detachment rate and less fruit damage compared with the impact harvester. Zhou et al.[138] investigated the effect of cushion material, fruit drop height and tilt angle of catching surface on fruit bruise damage during the vibratory harvesting of sweet cherry. The results indicated that the cushion materials with sufficient thickness could substantially reduce the maximum impact force with fruit tissues, and the tilt angle of catching surface affected the fruit damage level significantly. Furthermore, mechanical shaking system for fresh apple harvesting was also investigated preliminarily[25,139]. A multilayered shake-and-catch system composed of a limb shaker and three catching surfaces was developed and evaluated for fresh apple harvesting on a trained vertical fruiting wall. The results showed that the developed shake-and-catch harvesting system could achieve a fairly high percentage of marketable fresh apples about 85%[24].

To sum up, fruit injury is an inevitable challenge for mechanized fruit harvesting, especially for the perishable fruit with thin peal. Meanwhile, agronomic requirements suitable for mechanized vibratory harvesting are also important factors affecting the mechanical damage of fruits, such as tree shapes and planting patterns. Fortunately, the developed targeted shake-and-catch system with cushion materials and multilayered catching surfaces is a promising mechanical solution for mass harvesting of fresh market fruits.

6.3 Tree damage caused by mechanical vibrator

A challenge of major concern in fruit harvesting by mechanical vibrator is not only sufficient removal of the fruits with low bruise damage but also avoiding excessive breakage of tree limbs, badly damaged trunks or overmuch removal of leaves. Torregrosa and Orti[18] demonstrated that the hand-held limb shaker produced plenty of defoliation of the trees with longer vibration duration of about 4-6 s and the frequency of more than 15 Hz. Recently, Sola-Guirado et al.[15] investigated the tree damage using a lateral canopy shaker and described the damage level by means of the visual classification and identification of the broken branches, dropped shoots and trunk bark in three categories (Figure 6a). Besides, Jimenez-Jimenez et al.[131] pointed out that the occurrence and intensity of trunk damage depended on the clamping system configuration including geometry, material feature and grabbing pressure. The strong vibration by trunk shaker could cause completely ruptured bark as shown in Figure 6b. The consequence is that some of the fruit growers are reluctant to use these mechanical harvesting machines because of their concern about significant tree damage which can potentially affect the subsequent growth of the trees and reduce the next year's fruit yield even though it has high efficiency for fruit harvesting[108].

a. Different tree damage levels caused by canopy shaker[15]

b. Badly bark damage by trunk shaker[131]

Figure 6 The visual classification of the tree damage

To reduce the tree damage and increase the application of mechanical shaking system for fruit harvesting, some researchers proposed several effective methods. Gupta et al.[140] verified that the optimized tine configuration of the top, middle and bottom section of the canopy shaker could provide a 24% to 45% reduction in the damage to the tree canopy when vibrating at different frequency and amplitude. Based on this viewpoint, a kind of two-section of top and bottom canopy shaking system with variable frequency was developed for citrus mechanical harvesting, which could generate less tree damage while maintaining a relative high fruit removal percentage under optimized frequency combination[110]. In addition, the materials or shapes of the shaking rod of the canopy shaker could significantly influence the tree damage level investigated by Pu et al.[141] Therefore, aiming at solving these bottlenecks of fruit mechanical harvesting, the prospects for future challenges are outlooked in the next section.

7 Future prospects

7.1 Innovative design of the vibratory harvesting system

In general, there is a significant advantage to fruit harvesting by mechanical shaking system with high efficiency, but it still needs to pay more attention to reduce the fruit injury and tree damage. To put the mechanical harvesting technology into practical application, it should satisfy the requirements of high efficiency, low damage, attractive price and good quality for fruit harvesting. In most cases, the machine design of the mechanical shaking harvester will determine the shaking frequency, amplitude, duration and other key parameters which affect the performance of the harvesting and catching system directly. Some of the existing mechanical shaking systems as mentioned in Section 3 were studied and evaluated to get the optimal frequency and structural parameters to reduce the tree damage or fruit injury through longstanding experimental investigations. Therefore, it is essential to develop the innovative or optimizing design of the fruit harvesting systems with particular vibratory patterns.

The following aspects for innovative design of mechanical shaking harvester can be improved: 1) Based on the physical characteristics and mechanical properties of the tree and fruit, it is necessary to utilize the computer aided design technique and digital design simulation method to shorten the design period and experiment duration because of the seasonality of the fruit production. It is effective to develop and evaluate a simulation framework for the optimum design parameters of the canopy shaking machine to investigate the interaction mechanism between the tree and canopy shaker using finite element methods[113,140]. 2) Developing a self-adaptive adjustable shaking system with variable frequency and amplitude to adapt the canopy structure, branch density and fruit spatial distribution might be a promoting pattern for fruit harvesting with low fruit injury and tree damage. Liu et al.[142] verified that the variable frequency shaking modes with suitable catching systems are potential methods for fresh apple mechanical harvesting. And a two-section canopy shaker composed of top and bottom shaking systems with variable frequency producing less tree damage was developed and evaluated by Pu et al.[110] 3) Novel shake-and-catch harvesting technology equipped with an innovative catching device and cushioning material is desirable to reduce fruit bruise damage significantly. Fu et al.[22] indicated that the targeted shake-and-catch harvesting method was feasible and prospective for mechanical mass harvesting of fresh market apples. Besides, an innovative air suspension-based catching mechanism combined with a tree limb shaker was fabricated and evaluated to collect fruits, which was able to reduce the risk of apple injury and improve the fruit quality[30]. 4) Developing some universal mechanical shaking systems for harvesting different fruit crops can tremendously improve the utilization of harvesters, which is a big trend to reduce the cost of fruit production. Meanwhile, module design of the key components using computer aid technology can provide a useful method to shorten the machine manufacturing period.

7.2 Integration of fruit mechanical harvester and tree agronomy

With the continuous improvement of agricultural mechanization and automation technology, integration of agricultural machinery and agronomy is the basic requirement for the development of various agricultural equipment in practical application. It is clear that diverse fruit trees have different physical characteristics, mechanical properties and fruit distribution. Besides, mechanical shaking systems combined with suitable agronomic specifications for fruit harvesting enable to reduce the mechanical damage to fruits effectively. Furthermore, shake-and-catch harvesting technology is a typical application to adapt tree architecture for fruit detachment and bruise reduction. And fruit trees planted with a precision pruning strategy and standardized agronomy can improve the efficiency of the vibratory mechanical harvesting of apples[143,144]. However, there is still no satisfactory shaking harvester to meet the requirement of commercial use for the fresh apple harvesting, which would be an important research field in the future.

7.3 Postharvest classification of the mechanized harvesting fruits

At present, the fresh fruit harvesting is always heavily dependent on manual picking which is labor intensive and time-consuming. The practicability of fruit mechanical harvesting is a critical requirement because of rising labor costs and uncertain labor availability. In order to solve the practical problems for fruit production, previous researchers have investigated various mechanical shaking harvesters for fruit harvesting in the past several decades. So far, the mechanical mass harvesting and robotic selective harvesting technology are considered as the main fruit removal methods. However, the mechanical mass harvesting is easy to produce unacceptable damage rate of fruits or trees, while robotic system for fruit picking is limited by insufficient target recognition, operating speed and controlling robustness. Therefore, it is essential to develop a new-type mechanical shaking harvester equipped with optimal vibration parameters, multilayered fruit catching device and cushion materials for mass harvesting with high efficiency and low damage to fruits or trees. Meanwhile, there is a promising strategy that classification system can be used to sort the postharvest fruits into two categories, namely the fruit without injury for fresh market and other fruits with little damage for industrial processing as shown in Figure 7, which can make great progress for the further application of the mechanical shaking systems for fruit harvesting. In particular, evaluating the fruit surface defect or even internal bruising level is the key to the fruit classification system. Recently, optical sensing technologies have been studied as potential effective tools for non-destructive evaluation and inspection of fruit quality, such as hyperspectral imaging[145-148], contactless NIR spectrometer[149,150] and visible spectroscopy[151], which have been widely investigated to develop accurate classification systems in fruit industry.

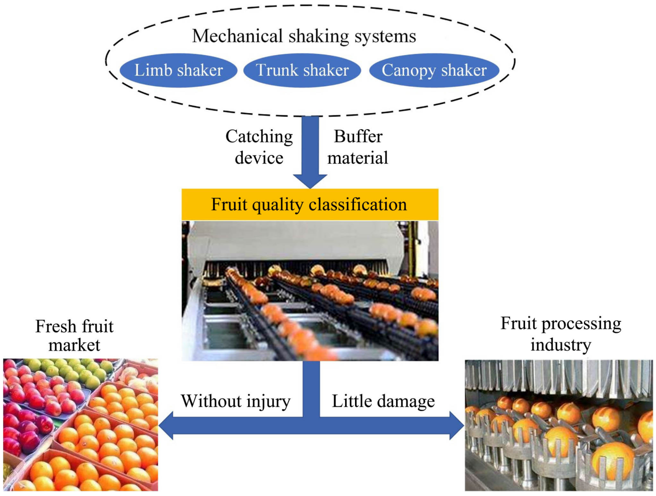


Figure 7 Strategy diagram of postharvest classification for the mechanized harvesting fruits

8 Conclusions

This paper generalized the principle of the vibratory fruit harvesting and reviewed recent applications of several kinds of mechanical shaking systems investigated by lots of previous researchers for different fruit harvesting. As mentioned in this review, mechanized harvesting is one of the most important steps in the long and complicated growth cycle of large-scale fruit production from grower to consumer, which appears multifarious shaking modes for diverse fruit varieties with different physical and mechanical properties. Furthermore, the development of mechanical shaking systems with effective vibratory patterns can obtain a series of economic and agronomic benefits, such as reducing labor costs, promoting standardized planting and increasing productivity. In addition, this overview also summarized the advantages and disadvantages of these shaking systems for fruit harvesting, and proposed the challenges and prospective trends of mechanical harvesting techniques with low fruit damage or even nondestructive harvesting for fresh fruits in the future.

In conclusion, the following recommended aspects for the further development of the mechanized fruit harvesting can be improved that: 1) designing self-adaptive adjustable shaking system with variable frequency and amplitude should be suitable for some fruit crops, which might be of great importance to improve the universality of the mechanical shaking system for fruit harvesting; 2) developing innovative multilayer catching device with cushioning material would be a promising pattern to lower the drop height and avoid fruit-to-fruit collisions for bruise reduction, which is likely to meet the requirement of commercial use for the fresh fruit harvesting; 3) collaborating with agricultural engineers and horticultural scientists might be a potential solution to promote the integration of mechanical shaking systems and tree canopy structure, or even avoid the occurrence of grown clustered fruits by appropriate thinning technology; 4) employing sorting technology to classify the postharvest fruits into two categories that one is damaged fruit processed for industrial products, and another is nondestructive fruit without injury for fresh market, which would bring more benefits to growers and increase their interest in equipment investment on the mechanical shaking systems for fruit harvesting.

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