



Mechanization in Fruit Harvesting and Potential of Tree Shakers

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Abstract: Fruit picking is the most labour-intensive and time-consuming step of the fruit production pipeline. Conventional methods rely on manual labour for selective picking of fruits ready for commercialization and post-harvest processing. Mechanization of fruit harvesting can promote the competence of fruit growers by reducing overall costs, dependence on manual labour, and ensuring timely harvests. This study compiles technological advancements in fruit harvesting mechanization, describing the basic working principles of mechanical harvesting devices and their operational parameters. The main challenges of mechanization include asynchronous fruit maturation, high fruit and tree damage, and diversity in orchard structures. Numerous attempts have been made to address these issues using vibratory harvesters or tree shakers, broadly categorized as air shakers, trunk shakers, limb shakers, and canopy shakers. The specific applications and limitations of these harvesters have been discussed. Additionally, studies exploring abscission chemicals for selective harvesting and customized catching units to minimize fruit damage have been reviewed. This study highlights the potential of mechanical harvesters in reducing labour dependence and costs while emphasizing the need for innovating indigenous harvesting systems.

Keywords: Fruit harvester, Vibratory harvesting, Tree shakers, Canopy shaker, Robotic harvester

In the current period of intensification of highly viable agriculture in India, horticultural crops act as incentives for small and marginal farmers. In India, horticulture accounts for 8.5% of the cropped area and holds 30% of agricultural GDP (Gross Domestic Product). This sector has enough potential to improve the socio-economic status of Indian farmers (Anonymous 2007). Presently, India is one of the largest contributors of fruits and vegetables in the world succeeding China as the largest producers of fruits, India shares a large amount of world's total fruit production of 870 million tonnes (MT) by contributing about 97.35 million tonnes yearly (Anonymous 2018). In India, presently (2018-19), total area under fruit crop cultivation is 86673 ha and the total production is 1850259 MT (Anonymous 2020). A variety of fruits and vegetables are grown in different states of India and are marketed with an advantage in the rest of the country.

The conventional way of harvesting of fruit crops requires high labour input and displays low efficiency in terms of time and overall operational cost. In India, the mechanization of fruit harvesting has been carried out, albeit on a very small scale. The availability of labour in abundance and lack of large-scale fruit farming are the main reasons for the inadequate efforts towards mechanization of fruit harvesting (Hegazy 2013, Kumar and Kalita 2017). However, nowadays, the inclination towards the organized fruit farming is underway. Presently, the fruit cultivation depends on manual labour (Prakash et al., 2023). The labour employed in fruit cultivation is predominantly dedicated to harvesting,

which is the most labour-intensive and time-consuming step of the entire production process (Paltrinieri 2015). The natural qualities of fruit products, including shelf-life and perishability, pose a severe time-constraint on the harvesting strategy (Prasad et al., 2018). Harvesting fruits at the optimal stage of maturity is crucial for upholding the postharvest quality as per the satisfaction of the consumer. Hence, attaining optimum quantity of best quality produce in a short time frame is a highly labour-intensive task, which warrants mechanization.

Mechanization plays a vital role in securing the future of fruit growers in developed countries. The use of machinery encourages judicious execution of field operations by reducing the requirement of seasonal labour for small periods of time (Khandetod 2019). Although application of manual harvesting aids/tools reduce overall harvesting costs, their success is surprisingly limited. Further, the conventional system of fruit harvesting from tall tree fruits such as palm, coconut, and mango are prone to serious accidents (Prasad et al., 2018). Hence, development of simple mechanical harvesting devices is necessary since they would allow significant reduction in harvesting labour and help in preventing accidents.

Mechanical harvesting systems are usually designed with the objective of mass extraction of fruits during the season. Such methods involve shaking of limbs, trunks, or canopies of trees. Selection of suitable mechanical harvesters is essential for minimizing the harvest-induced

damage. In most fruit crops, mechanical harvesters are unable to attain the extent of size selection and quality achieved by manual harvesting, and harvesting needs to be followed by a selection procedure for maintaining the quality (Li et al., 2011, Erkan and Dogan 2019). The principal benefit of mechanical harvesting is that the produce may be obtained in short periods of time. However, currently available mechanical systems are unable to replace the fruit selection capability and flexibility of manual pickers. Hence, the sustainability of fruit industries may only be ensured with an optimal adaptation of technological advancements and innovation in mechanical harvesting. Presently, mechanical harvesting technologies mostly utilize canopy shakers (Peterson 1998) and trunk shakers (Torregrosa et al., 2014), and their application is limited to fruits destined for processing. These technologies provide a forced vibration, which is transferred to the fruit resulting in detachment (Castro-Garcia et al., 2019).

In recent years, the horticultural industry has globally supported the innovation of novel fruit harvesting systems. The research in this area is mainly motivated by the need for cost-reduction and enhancement of quality for the consumer. Machine-based harvesting systems provide partial solution for such issues by offering an efficient removal of fruits from the trees and consequently reducing the harvesting cost to about 35-45% of the total production cost (Sanders 2005). Numerous efforts have been made towards mechanized fruit and vegetable harvesting, in various countries (Fig. 1), with significant popularity and remarkable success in diverse crops. Successful mechanization of these operations requires a systems-specific approach, which entails a combined effort of engineers, plant physiologists, food scientists and others.

With this background, this review has been undertaken to describe existing techniques and ongoing researches for harvesting fruits. Various scientific and technical journals

have been referred for data collection, with the aim of collating the latest information on the subject to aid the researchers in further innovation.

Principle and Methods for Fruit Harvesting

Among various available methods of fruit harvesting, three are particularly common: manual harvesting of individual fruits by tugging or twisting the fruit pedicel, use of clippers, secateurs, or scissors to detach individual fruits or fruit bunch/vegetables, and use of customized mechanical harvesters (Crivelli 12).

Manual harvesting devices: Two types of manual fruit harvesting devices are available. The first device involves cutting of each fruit independently using sickle or blade, followed by collection. This device consists of a telescopic boom with an adjustable height, and a cutting unit with fixed and movable blades. A wire string is used to shift the movable blade, and fruit is cut and collected in the attached bag (Rajendra 2023). This mechanism is highly suitable in case of delicate fruits, where a risk of damage due to falling is involved, such as in coconut, orange, mango, and papaya. The second device employment positioners for the harvesting of fruits. In this method, ladders are replaced with platforms or moveable worker positioners for harvesting fruit crops such as apples, pears, citrus, dates, papayas, and bananas (Jacob 2008). This device includes a self-propelled machine which enables the positioning of the worker's platform in all the three dimensions. This device permits the use of multilevel picking platforms to enable a continuous movement of the worker while plucking the fruits, which are thereafter placed in a bin or on conveyors. Manual fruit harvesting is highly labour intensive, time consuming, and tedious, and such picking platforms and different man positioners allow a substantial reduction in harvesting cost (Zhang et al., 2022). Overall, these harvesting aids increase the efficiency of labour and help in reducing the harvesting time.

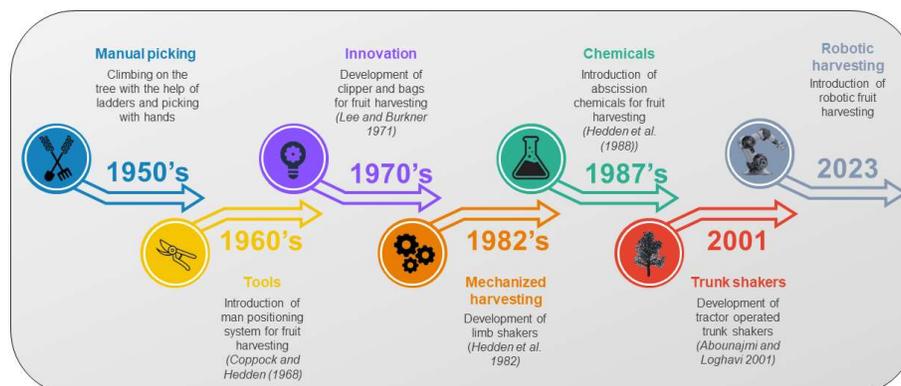


Fig. 1. Timeline of mechanized fruit harvesting

Mechanical harvesting: In general, mechanical harvesting involves application of vibratory or shaking motion on the tree branches (Table 1). Vibrations of suitable frequency and amplitude provide sufficient kinetic energy to the fruits, which are consequently detached from the branches. The vibrations generated from the shaking tool impart a certain force to the branches, leading to the acceleration or deceleration of the branches (Sarkar 2021), which consequently exert a detachment force on the fruits. When the value of the detachment force exceeds that of the attaching force, the fruit is detached from the branch (Liu et al., 2018).

The energy for fruit detachment is provided by the attached trunk or branch shakers. Vibrational motion and the associated forces may be imparted on the tree branch in an efficient and simple manner using inertial vibrators (Chen et al., 2011). The transmission of this vibrational energy to the plant later translates into fruit detachment. To achieve efficient harvesting of fruits with minimal damage, the shaker assembly needs an articulate design and proper operation. The design of a mechanical harvester should not only consider the mechanics of the vibrator and fruit detachment but also aim to minimize damage to the harvested product and the remaining plant structure (Navas et al., 2021). Furthermore, any shear stress on the bark due to slipping of the device should be prevented, since such damage may accumulate over time and lead to the weakening or killing of the tree. Most inertial tree shaker designs employ eccentric rotating masses, and the resulting amplitude depends on the relative mass of the rotating inertial shaker and the mass of the vibrating tree or branch.

The predominant factors influencing the fruit removal efficiency are the biophysical properties of the tree-fruit system and the input vibration parameters. The independent biophysical characteristics of a tree, including the tree architecture (Zhou et al., 2016), branch dimension, and location of fruit, (He et al., 2017) can be experimentally determined; however, accurate characterization of these

properties during vibratory harvesting is challenging.

The application of mechanical harvesters for fruit trees is impeded with various problems, such as selection of fruits based on quality and size, possible damage to fruits and trees, and varying orchard designs (Li et al., 2011). To ensure adequate fruit quality and superior aesthetic value for the consumers, harvesting maybe followed by a post-selection process. In general, fruit crops are harvested when maturity is attained. However, several species undergo non-uniform fruit maturation, and therefore require multiple rounds of harvesting with vigilant selection to maximize the yield. Furthermore, fruits are categorized into tree fruits, which include mangoes, apples, and papayas; vine fruits, which include watermelon and muskmelons; and bush fruits, which include raspberries, blueberries, and cranberries. Such diversity in fruits species warrants customization of mechanical harvesters for specific applications, considering the differences in tree habit and orchard structure. Orchard characteristics, such as variety, location, tree age, tree shape, size and spacing, canopy volume, leaf area index, planting density, pruning level, and cultural practices need to be considered for determining the suitability of mechanical harvesters, whereas the type of harvester and catching units needs to be customized optimally to reduce tree and fruit damage. Till date, mechanical vibratory harvesting systems have been successfully employed for olives, oranges (Torregrosa et al., 2009), sweet cherries (Chen et al., 2011, Du et al., 2019) and harvesting apples (Kleine and Karkee 2015).

Based on past studies, four mechanical harvesting approaches have been employed for fruit-picking, viz. air shaking, trunk shaking, limb shaking, and canopy shaking (Table 2). The air shaking technique involves the use of high-speed air blast through large fans to achieve vigorous movement of the canopy. Alternatively, in the trunk shaking approach, the trunk of the tree is grasped shortly above the ground, and the entire tree is vibrated to detach the fruits. Similarly, individual branches are held and shaken in the limb

Table 1. Investigation of factors affecting fruit harvesting efficiency

Fruit	Factor	Findings	References
Apple	Fruit removal efficiency	The optimum frequency was in the range of 8-12 Hz.	Liu et al., 2018
Citrus	The amplitude and Vibration timing	All the fruits were shed at an amplitude of 15Hz when vibrated for 5 seconds	Torregrosa et al., 2009
Mango	Frequency and Vibration timing	Maximum fruit removal was at vibration frequency of 13 to 11 r/s for 4 s.	Parameswarakumar and Gupta 1991
Aonla	Frequency, Amplitude	The limb shaker operated in the range of 50 mm amplitude and 220 cpm frequency for best results.	Kadam 2010
Cherry	Excitation position	As the distance from the excitation location increases, the fruit removal rate in each region increases.	He et al., 2020, Zhou et al., 2014,
	Frequency	The fruit removal rate was higher at 18 Hz frequency.	Du et al., 2010, Junming et al., 2021

shaking approach. Lastly, the canopy shaking approach involves insertion of several flexible horizontal rods into the tree canopy, which are thereafter vibrated to shake the tree canopy through the leaves and branches in contact with the inserted rods. All these approaches achieve fruit removal by vibration of the tree limbs. However, various issues are associated with the idea of fruit harvesting through vibration, such as low productivity, high rate of damage, and low efficiency. Several studies in the recent years have focused on increasing the productivity by enhancing the level of automation of such fruit harvesting systems (Amatya et al., 2016, Colmenero-Martinez et al., 2018).

The quality and applicability of these shaking mechanisms are usually assessed in terms of efficiency of fruit removal and percentage of damaged products. Removal efficiency is calculated as the percentage of fruits that were removed with the harvester. Since the fruits are subjected to various kinds of pressures, such as twisting, bending, and shear forces, the overall removal force and quality are determined in terms of frequency, amplitude, and duration of the vibrations imparted (Loghavi et al., 2010, Zhou et al., 2014). Furthermore, the height at which the fruits are captured affects the fruit quality after impact on the capturing surface (He et al., 24). In addition, the position of attachment of the shaking tool on the tree trunk or branch is crucial for preventing severe damage to the plant.

Mechanical harvesting techniques air shaking: Fruit detachment may be achieved through turbulent air flow

applied at a significantly high speed (Homayouni 2021). The fruit harvesting systems based on air shaking employ oscillating air blast machines to maximize the fruit detachment rate by controlling the oscillation rate. Air blast machines based on oscillating air pattern were first introduced in 1961. Thereafter, high-efficiency air blast system capable of generating airflows up to 100 mph (160 km h⁻¹) was developed (Whitney and Patterson 1972). The fruit removal efficiency of these machines were further enhanced with the application of abscission chemicals (Whitney and Wheaton 1987) esp. in crops like olive and citrus (Ferguson 2006). The main limitation of these preliminary machines was the high energy requirement, which required large-sized and heavy engines and fans, rendering the design impractical. Further, air blast harvesters were associated with high fruit damage in apple, thus hampering their popularity (Berlage, 6). Overall, various factors need to be considered to optimize the performance of air blast harvesters, including the tree structure, the fruit size and weight, and the overall fruit load. Based on multiple studies, it may be concluded that air shakers significantly reduce the fruit harvesting time as compared to manual harvesting methods, though with compromised yield. In addition, this method poses a higher risk of damage to the fruits and leaves.

Limb shaking: This method has been predominantly applied for the harvesting of citrus fruits, apricots, prunes, peaches, and sour cherries. Such machines are capable of obtaining large fractions of fruit load owing to the less frequent, but

Table 2. Working principle of different type of fruit harvester

Type of fruit harvester	Working principle	Parameters	Limitation	Fruit type	References
Trunk Shaker	The shaking unit clamps the tree trunk above the bud union and below the first scaffold limbs followed by shaking the tree in straight-line linear direction.	Frequency 18 Hz Acceleration 77 ms ⁻²	<ul style="list-style-type: none"> High-shaking frequency Certain problems damaging trees resulting in fungal attacks 	Olives, nuts, citrus, apple, mangoes and pears	Affeldt et al., 1989, Futch and Roka 2005; Sola-Guirado et al., 2014
Limb shaking	By imparting long strokes to limbs at a low frequency or transmission of vibratory forces to the limb.	Amplitude 50 mm Frequency 15 or 20 Hz	<ul style="list-style-type: none"> Bark and limb may damage Even immature fruits can be removed 	Citrus fruits, apricots, prunes, peaches and sour cherries	Erkan and Dogan 2019, Refik et al., 2007
Canopy shaker	Fruits are harvested by the vibrating mechanism causing the tines to impact fruit directly or by impacting fruit-bearing branches	Frequency 1.8 or 8.8 Hz, Acceleration 31.4 ms ⁻²	<ul style="list-style-type: none"> Less harvesting efficiency Mechanical damage of fruits (40%) 	Citrus, olives	Whitney 1977
Air shaker	High-speed, turbulent airflow for detaching fruits through an oscillating air pattern generated by heavy engines and fans.	airflows up to 160 km/h, energy of 186 to 260 kW	<ul style="list-style-type: none"> High fruit damage Heavy due to the size of the engines and fans 	Apple, olive and citrus	Whitney and Patterson 1972; Whitney 1977, Ferguson 2006

longer strokes applied on the branches. However, a significant risk of bark and branch damage is associated with this approach, and removal of unripe fruits is possible. The efficiency may be further enhanced by the application of abscission chemicals (Erkan and Dogan 2019). Limb shakers are equipped with a handle to enable remote control, which aids in fruit picking by allowing the workers to access the highest sections of the canopy (Ferguson 2006). A self-propelled version of these shakers was initially applied for the harvesting of 'Valencia' oranges without abscission (Coppock 1971). By optimizing the timing of harvest and application of abscission chemicals, the overall yield loss with mechanical harvesters was significantly reduced in 'Valencia' oranges (Coppock et al., 1971, Sumner et al., 1979). Recently, a handheld limb shaker equipped with a hydraulic motor and slider-crank mechanism was developed for cherry fruit harvesting (Zhou et al., 2014), which was evaluated for the extent of damage and overall efficiency of fruit removal and recommended multiple-point excitation of the branches. Further, a semi-automated fruit harvester including a dual-motor actuator (DMA) mechanism was designed (Kleine and Karkee 2015), capable of generating infinitely variable rhythmic motions. In another recent study (He et al., 2017), the efficiency parameters, including the removal, collection, and recovery efficiencies of a localized shaking and catching mechanism were analysed, wherein the harvesting system was operated on diverse apple varieties.

Overall, the most crucial advantages of limb shakers are providing access to highest sections of the trees and a significant reduction in the harvesting time. However, various problems are also associated with their application, including, low harvesting efficiency in early and mid-harvesting seasons, and undesired detachment of immature fruits at different stages of development, underlining the scope for improvement.

Trunk shaking: Trunk shakers are predominantly applied for the harvesting of deciduous fruits, such as olives, nuts, and citrus fruits. Trunk shaking-based systems provide a sustainable alternative to fruit farmers to survive a competitive market, by reducing the harvesting cost and rendering higher yields. The point of contact of the shaking unit with the tree trunk is immediately above the bud union and below the first scaffold limbs. The design includes a padded, particle-filled clamping pad to linearly vibrate the tree trunk; thereafter the vibration energy is transmitted to the secondary and tertiary branches, leading to fruit detachment. Such straight-line shaking provides an advantage over multi-directional shaking by preventing bark damage. The vibrations are imparted for a duration that varies between 5

and 12 seconds, based on the season and fruit cultivar (Futch and Roka 2005). The operational efficiency is affected by the damping effect of the trunk and branches (Sola-Guirado et al., 2016). To attain optimal harvesting efficiency, the trunk of the fruit tree should be subjected to a high energy vibration. In this regard, trunk shakers provide a time-saving and simpler alternative to limb shakers; however, their applicability is limited to trees thinner than 50 cm in diameter, and to trees without any hanging branches (Tian-Huet et al., 2017). A recent report demonstrated the feasible application of the trunk shaker for harvesting citrus fruit, along with the positive effect of the administration of an abscission chemical on fruit detachment (Moreno et al., 2015). The study reported a collection of 70-85% of fruit by the trunk shaker independent of the orchard structure. Moreover, administration of ethephon in higher concentrations displayed a concomitant increase in fruit detachment, with the exception of the 'Clemenules' orchard, thus recommending a judicious use on abscission agents. Overall, trunk shakers are the most popular mechanical harvesters for fruit trees, owing to their superior contribution to mass production. However, trunk shaker operations are usually energy-intensive, which also poses a risk of tree damage. In addition, these harvesters are not suitable for older orchards with distinctive size and shape of the canopy.

Canopy shaking: Fruit harvesters based on canopy shaking accomplish fruit detachment by vibrating the branches at an optimal frequency with the help of multiple rods inserted into the tree canopy. Canopy shakers clamp the secondary branches and generate vertical vibrations, leading to fruit detachment (Sarkar 2021). The mechanism of canopy shaker involves transmission of energy from the inherent shaking rods directly to the canopy branches, depending on the characteristics of the shaking rod. In some cases, a group of shaking rods impact the tree canopy, although not as a single tine. In such systems, the vibrations generated by the shaking mechanism lead to direct impact of the tines on the fruits or the fruit-bearing branches. The most frequently used configuration for such shakers involves the straight shaking rod. The continuous canopy shakers are majorly used, for the harvesting of citrus fruit, and are categorized as self-propelled and tractor-drawn (Erkan and Dogan 2019). The most crucial parameters to assess the function of such harvesters are shaking frequency and stroke. Till date, the contemporary canopy shaking systems have enhanced the fruit harvesting rate to 15 times that achieved by hand-picking (Du et al., 2019).

Over the past decade, numerous modifications of canopy shakers involving straight shaking rods in various configurations have been designed to perform specific

functions for a wide range of fruits. A double-spiked-drum canopy shaker equipped with total twelve whorls was developed by Peterson 1998. Another modified canopy shaker, including 12 sets of free-floating tines radiating out of a vertical axis (Erkan and Dogan 2019) currently serves as the most popular mechanical orange harvester in Florida. Castro-Garcia et al., 2019 developed a canopy shaker for harvesting table olives, consisting of three picking-heads incorporated with straight rubber rods. Furthermore, a continuous canopy shaker, consisting of two self-propelled single drum shakers with 12 whorls of 16 straight tines each, was manufactured by Oxbow International Corporation (Byron, NY, USA) for commercial citrus harvesting (Savary et al., 2010; Spann and Danyluk, 2010). Another experimental canopy rotary drum shaker having multiple straight fiberglass rods were developed (Hong et al., 2012) for harvesting *Jatropha* fruits. A rotary harvester, Korvan 8000, manufactured by Oxbo International (Lynden, Washington, USA), containing two spindles of straight nylon shaking rods, was applied for blueberry with reduced damage. Later, Sola-Guirado et al., (2014) described the development of canopy shaker with 6 beating drums and 24 straight shaking rods and reported a fruit removal efficiency of 77.3% for olives. In the same year, a citrus canopy shaker was developed and optimized based on a progressive analytical approach devised by Gupta et al. (2016) which allowed minimal damage to the upper canopy. Overall, canopy shakers may be noted as the most efficient category of harvesters, with the capability of continuous harvesting of fruits. Although these harvesters are associated with a large amount of debris and a risk of structural damage to canopies, they in controvertibly display higher fruit removal efficiencies. Moreover, vibrations may be optimized to successfully detach fruits with minimum damage, since branch injuries are more evident at higher amplitudes.

Optimization of shaking parameters required for fruit harvesting: To achieve efficient and continuous harvesting of fruits with shakers to ensure high yield and minimal damage to tree components and fruit products, optimization of harvesting parameters is crucial. The vibration parameters to be provided as input, such as shaking frequency and amplitude, excitation location, and excitation duration, are determined on the basis of the dynamic characteristics of the tree fruit system. These parameters are usually obtained through experimentation and simulation of dynamic models and experimental data. However, most studies in this context have focused on analysing the fruit removal efficiency and extent of damage observed at varying input vibration parameters through field experiments (Leone et al., 2015, Sola-Guirado et al., 2016, He et al., 2017). Various

experiments have been conducted to determine the optimal vibration frequency, vibration amplitude, excitation duration (Colmenero-Martinez et al., 2018), excitation location (Zhou et al., 2014), and motor actuator pattern (Kleine and Karkee 2015), leading to the highest fruit removal efficiency and minimum damage. Nevertheless, although the input vibration parameters obtained so far via field experiments are effective, further optimization was required. Hence, a range of amplitude and frequency values were analysed using a laboratory unidirectional vibratory device (Ortiz and Torregrosa 2013), and the effective input vibration parameters according to the target fruit tree were successfully determined through experiments. Since fruit trees display highly variable characteristics, ideally, the input parameters need to be customized for each tree to attain high efficiency; however, such individual in situ experimentation is challenging and unrealistic.

Most of the input vibration parameters remain fixed during tree shaking, except frequency of vibration. Therefore, fruit removal efficiency may be maximized by altering the frequency, while keeping the rest of the parameters as fixed. Notably, when the excitation force is approaching the natural frequencies (Table 3), several branches experience motion at the maximum amplitude. Various approaches and techniques have been used to estimate the natural frequency of tree species, including high-speed digital video and image processing (Geice et al., 2016), pull-release experiments (Kane et al., 2014), and impact excitation experiments (Du et al., 2019). In case of limb shakers, Torregrosa et al. (2009), through his experiments for citrus crop stated that increased stroke length for less number of cycles was considered optimal for sufficient harvesting.

Use of abscission chemicals: Abscission chemicals have been extensively used in field experiments to enhance the efficiency of shaking-based harvesters. The role of various

Table 3. Natural frequencies and amplitudes of different fruit trees

Harvested crop	Frequency (Hz)	Amplitude (mm)
Strawberries	5-15	20-40
Grapes	9-10/10-20	80-140
Oranges	10-15	12-16
Cherries	10-20	15-60
Apple	15-30	8-12
Apricots	15-30	8-12
Almond	15-30	8-12
Peach	15-30	12-16
Olives	20-35	50-70

Source: Ruiz-Altisent et al., 2004, Sarkar 2021

abscission agents has been investigated in reducing the required force for detachment of fruits from the stem (Ebel et al., 2010, Moreno et al., 2015). Administration of abscission chemical increases the difference in the forces required to detach mature and of immature fruits, thus promoting selective fruit harvesting. The application of these chemicals selectively weakens the attachment of mature fruits and decreases the requisite force for their removal. Since the force required to remove the mature fruit from the tree is reduced, tree damage from shaking is also minimized and lesser power is consumed during the harvester operation (Moreno et al., 40). However, biosafety and environment-related concerns associated with the use of abscission agents have now been reported (Chen et al., 2011). These concerns have led to restrictions on the use of these chemicals, limiting their applicability for a wide range of fruit products. With these limitations, the necessity for the development of canopy harvesters capable of functioning independently without abscission chemicals has further increased, along with the importance of further refinement of existing shaker harvesters.

Catching unit: Shaking-based mechanical fruit harvesters are generally equipped with a catching unit. The catching units not only assist in easy collection of fruits, but also protect them from damage. Various materials may be used for the construction of this unit, such as canvas apron, polythene, net material, or foam. Tree shakers enable simultaneous fruit removal from the entire tree, which cause the detached fruits to scatter across the entire catching area. Therefore, the catching units are mostly attached a slow-profile collection surfaces that extend across the area encompassing the outer periphery of the tree. Since the trunk-shaking and catching system is limited to trees with trunk diameter less than 10 inches, tree heights up to 16 ft should be preferred to minimize fruit damage (Futch and Roka 2005). The commonly used catching arrangements include the inverted umbrella wrap-around type and the pained catching units. In 2002, a trunk shaker with a catch frame in the shape of an upside-down umbrella was developed (Vieri 2002). Later, lightweight under-tree nets were fabricated, which were rolled out under the tree on both sides to catch the fruits detached after trunk and limb shaker operations. Furthermore, a catching device consisting of a bounce buffer, a rolling buffer, and a collection area was innovated for apple harvesting, with the objective of reducing the speed and impact of falling fruits (He et al., 2017).

Robotic harvester: In recent times, the field of agriculture has witnessed a paradigm shift in terms of mechanization and automation. However, the number of robotic fruit harvesters developed beyond the research stage remains

surprisingly low, none of which have been utilized in open fields. Most robotic harvesters are equipped with manipulators or robotic arms which function over various degrees of freedom, ranging between 3 and 7. Such harvesters have been employed for harvesting of greenhouse-grown strawberries, apples, melons etc. The advanced versions of robotic harvesters also include rotational and prismatic joints to enhance their motility and reach. However, robotic harvesters have low economic sustainability and have witnessed limited success, given their low adjustability to terrain complexity and insufficient speed (Elfferich et al., 2022). Nevertheless, AI and deep-learning based interventions may soon enable them to navigate the orchard types and make adjustment to function over a wide range of tree types.

CONCLUSION

Horticulture is widely recognized as a labour-intensive practice in various regions of the world, including India. Mechanical fruit harvesters provide an alternative solution to manual picking, with a significantly higher rate of harvesting. Such harvesters protect the horticultural process from the influence of the demand and supply dynamics of farm labour, making it more sustainable, and improve the overall profitability and rural landscape. Vibratory harvesters, or tree shakers, are commonly used solutions, and various modifications of basic prototypes have been designed and developed to for specific applications based on fruit type, tree type, or orchard structure. Besides, various interventions, including orchard designing, use of abscission agents, and robotics-related automation have been suggested to encourage the use of tree shakers. The major limitations of mechanized harvesting approaches are the non-uniform ripening of fruit and vegetables, and high fruit and tree damage. Overall, studies suggest an impending need for innovation and customization of indigenous harvesting systems to meet the requirements specific to Indian horticultural ventures.

AUTHOR'S CONTRIBUTION

Apoorv Prakash conceptualized the review, performed the literature search, and prepared the initial draft of the manuscript. Anoop Kumar Dixit contributed to the thematic organization, critical analysis, and refinement of content. Dilwar Singh Parihar assisted in literature review, editing and formatting. Arshdeep Singh contributed to manuscript technical validation. Gursahib Singh Manes provided overall supervision, critical revisions, and final approval of the manuscript. All authors read and approved the final version of the manuscript.

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