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REVIEW ARTICLE

Tree fruit harvesting: Recent developments and future challenges for robotic harvesting

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Abstract

Tree fruit harvesting is a vital process in agriculture, involving the collection of ripe fruits from trees. This review examines manual, mechanical and automated harvesting methods, focusing on their benefits, challenges and potential advancements. Manual methods, such as hand-picking and using ladders, are highly labour-intensive and time-consuming. To address these challenges, mechanical systems like trunk shakers, canopy shakers, limb shakers and catch-and-frame methods have been introduced. These systems use vibrations and capturing mechanisms to improve efficiency and reduce labour costs. However, mechanical methods are not commonly used for fresh fruit harvesting due to the risk of damaging soft fruits and trees. To solve this issue, precise shake-and-catch systems with controlled vibration frequency and amplitude are being developed, achieving fruit removal rates of up to 93.3 %. Harvesting speeds vary, with manual pickers managing 0.5 th^{-1}, trunk shakers 10 th^{-1} and canopy shakers 25 th^{-1}. Automated harvesting offers even greater efficiency by using robots equipped with advanced technologies, such as deep learning, image processing and specialized grippers, to detect and pick fruits. These systems can complete harvesting in just 4 seconds per fruit. This review highlights the strengths and weaknesses of current methods and explores strategies to enhance fruit harvesting technologies.

Keywords: canopy shaker; deep learning; fruit harvesting; machine vision; manual fruit harvester; trunk shaker

Introduction

Fruits develop from fertilized flower ovaries, beginning with carpel fertilization. The carpel undergoes structural and physiological changes, leading to maturation and ripening. Its cells transform, forming the fruit's outer and inner layers (1).

Fruits are classified into fleshy and dry types. Fleshy fruits have a high-water content and a soft mesocarp when mature (e.g., apple, plum, avocado and watermelon). Dry fruits have a hard, dry structure at maturity (e.g., almonds, dates, figs and apricots) (1).

India is the second largest producer of fruit. India produces 331 million tonnes of fruits annually on an area of 27.23 million hectares, accounting for 11.38 % of the world's total fruit production (Fig. 1). The horticulture sector's production increased significantly in 2020-21, averaging about 331.05 million metric tonnes (2). India exported fruits and vegetables worth of Rs. 9,941 crore, of which Rs. 4,971 crore from fruits and Rs. 4,970 crore from vegetables (3). Tamil Nadu accounts for nearly 4.59 % of the area under fruits in the country. Banana (32 %) and Mango (46 %) are the leading fruit crops in Tamil Nadu (4).

Tropical and sub-tropical fruits include mango, banana, papaya, guava, citrus fruits, grapes, pomegranate, pineapple, jackfruit and jamun. Temperate fruits include apples, pears, plums and peaches (5). Some fruits grow on ground vines like watermelon, cucumber, grapes and muskmelon (6).

The most accessible and affordable sources of nutrients, including vitamins, minerals, proteins, carbohydrates and vital amino acids, are abundant in the fruits (7, 8). Fruits are rich in essential nutrients and phytochemicals that support overall health and aid in disease prevention. Their antioxidants and bioactive compounds help reduce the risk of cancer by combating oxidative stress. Regular fruit consumption provides cumulative health benefits, though nutrient content varies among different types (9). Tree fruit crops, such as apple, almond, mango and kiwi belong to various categories like drupes, pomes, stone fruits and sour fruits based on their structure. Drupes include fruits like mango and olive, which have a single seed enclosed in a pit. Pomes like apples and pears, have a core with multiple seeds. Stone fruits, such as plums and cherries, have a large seed surrounded by fleshy pulp. Sour or citrus fruits like lemon and orange are characterized by their tart taste. Representative fruits from each class such as olive, neem, citrus and mango were selected for this study and explained below.

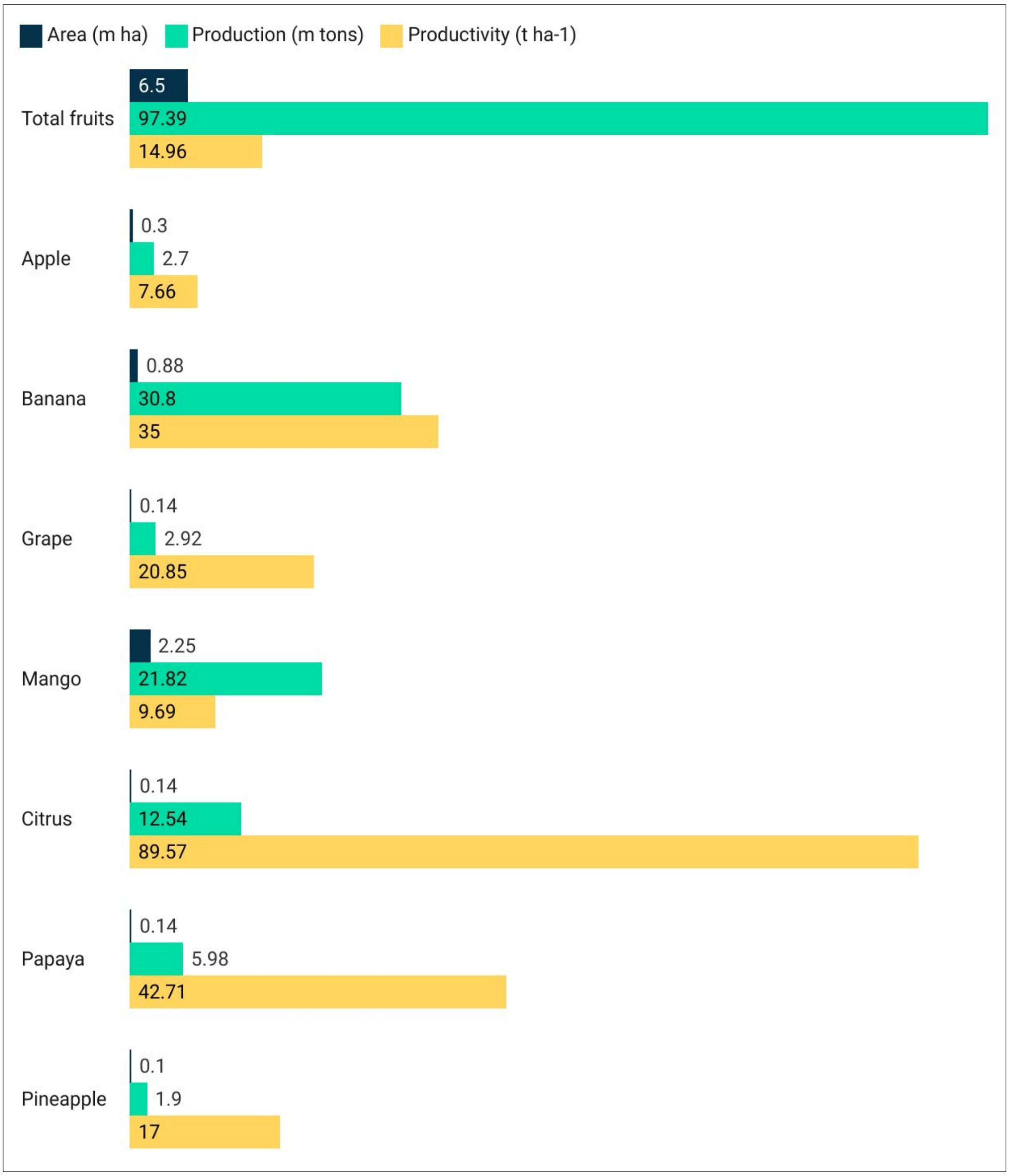

Fig. 1. India's position in world fruit production.

Olive (*Olea europaea*), which belongs to the *Oleaceae* family, is used in folk medicine across the Mediterranean, Arabia and tropical regions. It is a key oil crop, with over 70 % of olive trees grown in the Mediterranean. Spain, Italy and Greece are the top producers, with Greece averaging 300 million litres of olive oil annually (10). Over 70 % of olive trees are grown in the Mediterranean, with Greece ranking third in global production, behind Spain and Italy, averaging 300 million litres of olive oil annually (11).

Neem (*Azadirachta indica*), a common evergreen tree with a quick growth rate, has been utilized in Ayurvedic medicine for over 4,000 years (12). It is commonly called 'Indian Lilac' or 'Margosa' and belongs to the family *Meliaceae* and tribe *Melieae* (13). India is the leading producer of Neem in the world producing 4.4 lakh tonnes of neem yielding 88,440 tonnes of oil and 3.5 lakh tonnes of cake annually (15). In Tamil Nadu, Virudhunagar and Thoothukudi districts stand in the first and second position in neem plantation with 643 ha and 427 ha of cultivation area respectively (16).

India is the third highest citrus producer in the world after China and Brazil. The citrus area in India ranks third among the nation's fruit industries, after the mango and banana sectors (17). Over 64 countries worldwide cultivate citrus fruits, with an annual yield of 105.4 million tonnes among fruit crops (18). The citrus fruit group includes a diverse range of fruit species that have historically been used to treat and prevent a variety of human ailments.

Mango (*Mangifera indica*) is a large evergreen tree in the *Anacardiaceae* family, reaching heights of 10-45 m. It is the most important fruit crop in India, which leads global production, contributing over 40 % in 2021-22 with 20.7 million tonnes. Andhra Pradesh and Telangana together accounted for 28.37 % of India's mango production, totalling 5.89 million tonnes (19). Table 1 refers to the benefits of various fruits.

Cultivation practices

In India, tree fruits are cultivated using either wider spacing or closer spacing (high-density planting). Table 2 shows the

Table 1. Benefits of tree fruits

S.No	Tree fruit crops	Benefits	Reference
1	Olive	Urinary and bladder infections. It has a low incidence of chronic degenerative disease, particularly coronary heart disease and cancers of the breast, skin and colon.	(20, 21)
2	Neem	Neem leaves and paste have antibacterial activity against dental pathogens, are used to treat intestinal worm removal, fever, skin illnesses, dental disorders, inflammation, infections and mosquito-repellent tablets. Neem leaves are also used to treat chicken pox and small pox.	(22)
3	Citrus	Citrus fruits are rich in essential nutrients, bioactive compounds and antioxidants, providing a balanced diet and reducing inflammation and heart disease, with high concentrations found in juice, peel, seed and fruit.	(18)
4	Mango	Ripe mango fruits are energizing, refreshing and used for various ailments like heatstroke, asthma, hiccups, throat irritations, cracked feet and dyeing due to their tannins.	(23)
5	Apple	It is helpful for chronic diseases (asthma and cancer).	(24)
6	Custard apple	It enhances immunity, helpful in the prevention of cancer, exhibits antitumor and antibacterial properties.	(25, 26)
7	Sour oranges	Rich in Vitamin C and beta carotene, possesses anticancer properties. Helpful in asthma attacks and bronchitis.	(27)
8	Pineapple	Shows anti-diabetic, antioxidant and hypolipidemic properties.	(28)
9	Jamun	Rich source in antioxidants and calcium. It improves haemoglobin and increases the strength of gums and teeth.	(29)
10	Papaya	Antibacterial, antiviral, anti-inflammatory and antipyretic potential.	(30)

Table 2. Tree fruit crop spacing and no of plants per hectare (31)

S.No	Crops	Spacing (m)	Population ha^{-1}
1	Citrus	6×6	277
2	Lime	5×5	400
3	Mulberry	6×6	277
4	Pomegranate	4×4	625
5	Fig	6×6	277
6	Jujube	6×6	277
7	Aonla	8×8	156
8	Sweet orange	5×5	400
9	Date palm	5×5	400
10	Bael	8×8	156
11	Guava	5×5	400

spacing and population per hectare. The success of a fruit farm depends not only on the type of fruit grown but also on the location. Optimal production and profit are influenced by factors such as variety, site selection, planting and spacing systems, training and pruning, soil management, irrigation, fertilization, pollination, thinning, pest control, preservation and harvesting practices (31).

Harvesting

Harvesting is a crucial stage in agriculture, as timing is key to achieving the highest yield and quality. Various harvesting methods are utilized to optimize this process, including both mechanical and manual techniques. In horticultural crops, the traditional method of harvesting involves handpicking fruits and it is still widely used. However, this approach is inefficient and costly, especially on a large scale. To tackle this problem, mechanical harvesting systems have been explored and implemented to boost profits. Unfortunately, these systems often damage the fruits during the harvesting process, necessitating the development of methods that can remove fruits efficiently while preserving their quality. In mechanical harvesting methods, some human intervention is required, whereas fully automated robotic systems (32), require minimal or no human intervention (33). Compared to manual harvesting, automatic harvesting has several advantages, such as managing the crops quickly, requiring less labour, producing higher quality products and having better control over environmental effects (34). A fruit picker or fruit harvester robot is one of the robotic innovations in agriculture (35-37) and covers research on machine vision systems used for the automatic detection, inspection and localization of fruits for harvesting (33).

Manual tree fruit harvesting

Manual harvesting is a popular form of fruit harvesting in many regions of the world. It is more practical to harvest produce fresh, which is especially crucial for fruits with a wide range of maturity and require multiple pickings throughout the season. Six methods of manual harvesting are commonly used. These methods include farmer practice-hand picking, farmer practice -ladder climbing, pole mounted cut and hold type picking shears, secateurs and ladder climb, telescopic long reach finger type fruit picker and fruit picker harvester with basket and cushion (38). The performance of different manual harvesting significantly impacts the efficiency and output of the fruit harvesting process.

Some other manual harvesters are beaters, combs and hooks (39). This approach entails manually harvesting fruit with fruit clippers and knives, among other things. Workers who have been properly taught can harvest and handle the fruits with minimal injury. Fruit is picked and placed in little containers/baskets of various shapes and sizes or a specifically constructed picking apron, depending on its size (40). It has a net basket attached for collecting mango fruits that have been plucked. Reaching fruits from the ground is made easier by the long handle.

The harvesting operations of olive are the most expensive and they include the gathering of the detached olives and the separation of the olive fruit from the tree. Manually two workers harvest the olives by hand, gathering them into a tiny basket called a macaco that was worn around the waist (41). Olive fruits were picked up with some auxiliary tools such as rakes and combs (42).

In another method, the olive fruits are harvested either by the sticks striking olive fruits directly or by the vibrations reaching the willowy branches (43). The manual harvesting of olives is one of the costliest operations in olive fruit production and nowadays manual harvesting has been replaced by an electric hand mechanism (43).

The conventional method of harvesting neem fruits includes the collection of ground fallen fruits by using a hand and put together into a bucket, plastic bag or gunny bag normally by female labourers (44). In some areas, farmers lay a polythene sheet or tarpaulin sheet under the tree canopy. When the wind blows, the ripened fruits along with leaves and twigs fall on the sheet and the fruits are separated and collected in gunny bags (45). Manual ground collection of neem fruit is time-consuming and hard. A female labourer can earn Rs.250 per day for up to 10-15 kg of work. The expense of collecting neem fruits from the ground (Rs.30 per kg) surpasses the selling price (Rs.25 per kg). Manually harvesting neem fruits becomes unprofitable (16).

Citrus harvesting methods are done by hand plucking methods and bamboo sticks having hooks (Fig. 2) (46). Citrus harvesting methods are done by hand pulling with a ladder and gathering them in a bag. Some conventional methods like tree climbing, tree shaking and hitting by sticks are also used (38). Manually harvesting orange fruit involves cutting orange fruit pedicels using a scissor action. During operation, the operator holds the cable in one hand and the free end of the extension pipe in the other. When the fruit enters the cutting zone, the mechanism operates by pushing the rope downwards. Fruit chopped with cutting mechanisms falls into a collection bag provided below (46).

Mangoes are typically harvested by shaking, plucking with bamboo, picking by hand and climbing the tree or using a bamboo stick from the ground (Fig. 3). The basic braking mechanism used for cutting that takes advantage of the cutting parts sheared force. The upper section features two sharp blades, one fixed and one movable. A clutch wire connects the movable and fixed blades, while a hand lever regulates the operation. Mangoes can be collected after cut without bruising or tearing (47). The native mango harvester consists of a bamboo pole with a little wooden piece placed at an angle to form a 'V' shape at the end. The fruits are gathered by cutting the pedicel and dropping them on the ground (48). A significant number of labourers are steadily moving from farming to other industries. As a result, there is a labour shortage in the agriculture industry. Furthermore, there hasn't been much time for fruit harvesting during the mature stage. As a result, increasing the effectiveness of fruit harvesting is becoming more and more crucial. It's encouraging to see mechanical harvesting systems replacing human labour (33).

Manual harvesting is inefficient and costly, especially on a large scale. Manual harvesting is tedious task and time-consuming process. To tackle this problem, mechanical harvesting system have been explored and implemented to boost the profitability and efficiency of the tree fruits. Table 3 shows the manual harvesting tools.

Fig. 2. Citrus harvesting (46); **a.** Bamboo stick having hook; **b.** Hand-picking.

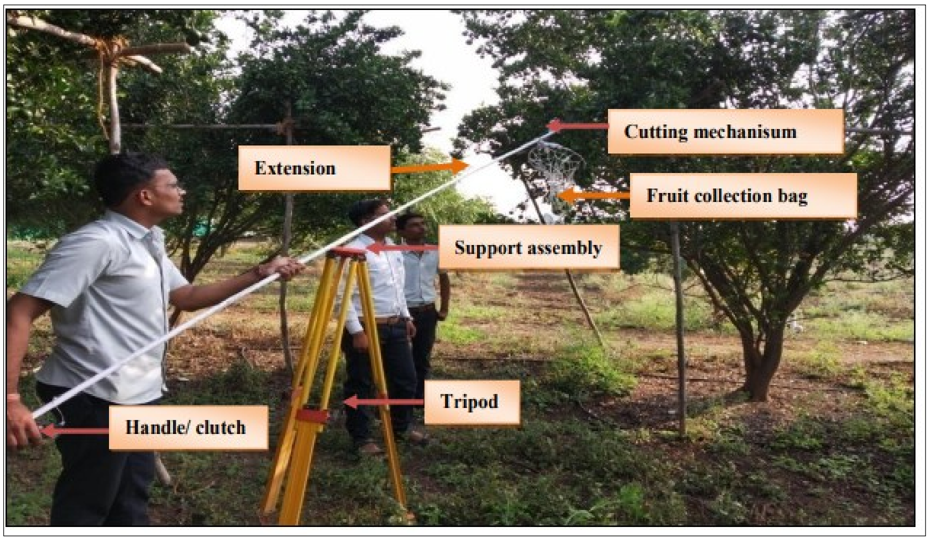

Fig. 3. Mango/Citrus harvester (47).

Table 3. Manual harvesting methods of selected tree fruits

S. No	Fruit crops	Title	Remarks	Reference
1	Olive	Hand picking	Tiny plastic rakes that are dragged alongside the trees to collect fruit. After the detachable fruit drops onto plastic nets stretched out on the ground under the olive tree's crown, it is manually gathered. The productivity of hand picking is 10 to 20 kg of olives per hour per operator.	(49)
		Hand held harvesting machine	This machine is suitable for tree height that does not exceed 4 m. This machine separates fruit from stems and branches using combs and shaking hooks; it is appropriate for trees that are less than 4 m tall. Vibrations are used for fruit separation; combs yield 90–95 % of the fruit, whereas shaking hooks yield 90–95 % at late harvest when the fruit is mature.	(49)
2	Neem	Hand picking	Collection of ground fallen neem fruits by using hand and put into the basket. Then another method is when the wind blows, the ripened fruit fall on the polythene sheet under the tree canopy.	(48)
3	Citrus	Bamboo stick with a hook	Fruit harvesting using poles with a hook at the end. Later, they manually picked the fruits using buckets and brooms.	(51)
4	Mango	Shaking, plucking	The fruits are harvested by plucking the fruits manually and shaking the fruits manually. Once the fruits have dropped to the ground, they are picked up. Fruit harvester had plucked 53 to 61 mangoes per 10 min.	(48)
		Cutting	The harvesting pole uses a scissor movement to cut the pedicle of orange fruits. The harvesting pole would be positioned so that it has access to every group of four trees by placing it on level land, with a maximum spacing of 5×5 m. When in use, the operator would grasp the extension pipe's free end in one hand while holding the cable with the other. When fruit enters the cutting zone of the mechanism, the cutting mechanism is activated by drawing the cable downward. The fruit that was chopped by the mechanisms fell into the collection bag that was placed right below it.	(46)
		Sliding	The mango harvester uses a cutting and detaching principle, utilizing a simple braking system to exploit the cutting part's shear force. The cutting section consists of two sharp blades, one fixed and the other moveable. The movable blade moves in the direction of the fixed blade and the mango is collected without bruising or rupture in the skin.	(47)

Mechanical tree fruit harvesting

Mechanical harvesting is very important to reduce the cost of production (53). The purpose of mechanical harvesting systems is to simultaneously remove the product in large quantities throughout the harvesting season. This technique has been used by shaking canopies, limbs and trunks. To improve harvesting efficiency, chemicals have occasionally been employed to create an abscission layer that loosens the mature fruits. To reduce harvest damage, the right mechanical harvesters must be selected. Compared to hand harvesting, mechanical harvesters are unable to retain the quality and size selection of many fruits. To preserve the quality, a selection procedure should be used after harvest (53).

Harvesting machinery commonly used in orchards for juice production includes canopy shakers and trunk shaking systems (54). Harvesting systems can boost worker productivity by 5-15 times compared to hand picking and reduce unit harvesting costs by 50 % or more (55). Furthermore, mass harvesting based on a canopy shaking system can obtain a harvesting rate 2-3 times higher than that examined with trunk shakers due to its continuous harvesting process (54).

An essential component of olive farming is mechanical harvesting, which lowers production costs while ensuring oil quality (56). Shaking or combing the tree are the two methods used for mechanical harvesting. The detachment force of fruits plays a major role in the performance of the shaking machine (52).

The existing hand-held olive harvester was improved for its performance. The machine productivity is 120 kgh^{-1} was achieved at a head rotating speed of 1800 rpm. Fruit removal percentage is 100 % (57). Hook type, comb type and trunk type harvesting machines are also used for olive harvesting (58).

For an 80 % removal efficiency with olive trunk shaking harvester two options are effective (59) (Fig. 4). The first option is to use a short stroke of less than 2.5 cm combined with a high frequency of over 42 Hz (2520 cycles/min). Alternatively, in second option, a long stroke of 10 cm with a lower frequency of 17 Hz (1020 cycles/min) can be used. The efficiency would be higher (60).

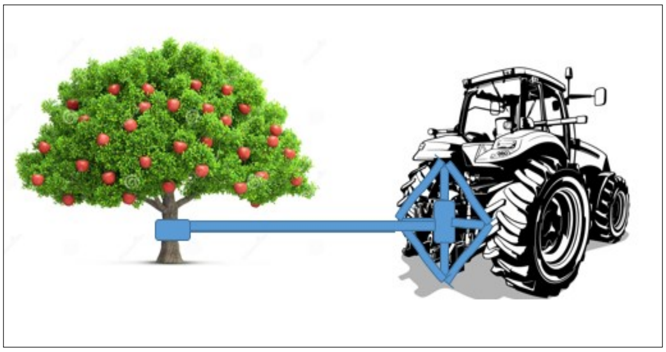

Fig. 4. Trunk shaker.

A self-propelled trunk shaker with a reversed umbrella interceptor is used for harvesting the olives (Fig. 5). Harvesting yield was very high, about 97 %. The productivity was around 302 kgh^{-1} per worker. This method was more effective. Fruit quality was also high (32).

Fig. 5. Mechanical harvesting of olives with a trunk shaker with a reversed umbrella interceptor (32).

Super high-density olive groves received more attention in recent years, mainly because of a chance to significantly boost labour productivity during harvesting by utilizing modified mechanical straddle harvesters. Straddle harvester was used for sloping terrain. In a single machine, both detachment and collection operations were combined (50).

Two types of machines were used for ground collection of neem fruits. Pneumatic suction type ground collection system and Mechanical neem fruit picker cum collector. The pneumatic suction type ground collection system (Fig. 6) for neem fruit had the following major components: power transmission system, suction unit, conveyance system, storage section and frame. The estimated collection capacity of the machine was 10 kgh^{-1}. Neem fruits are collected from the ground by suction (16).

Different combinations of these variables were used in the experiments, which were carried out using an experimental test rig. The study was conducted during 2022-2023 at Tamil Nadu Agricultural University, Coimbatore, India. A pneumatic suction device with an impeller, hose and collector was designed to pick up neem fruits from the ground after they had fallen. The ground collection system works best when neem fruits are collected efficiently with minimal suction pressure and energy use. Using a 250 mm impeller diameter, 80 mm suction hose, 4500 rpm impeller speed and 45 cm impeller height gave the best results, with 100 % picking efficiency and 99.67 % collecting efficiency. The study found that impeller speed was the most important factor for the machine's performance. Building the machine with the right settings can lower costs and reduce losses, helping farmers earn more (61).

The pneumatic suction type system is not satisfied because of the minimum coverage width (20 cm). The uneven density of the ground fallen neem fruits caused lower the suction capacity and higher fuel consumption and cost. So, to overcome this problem mechanical neem fruit picker cum collector was developed.

The mechanical neem fruit picker collector included several components, including the picker assembly, ejector assembly, collection assembly, connecting frame, handle and traction wheels (Fig. 7). It has a collection capacity of 48 kgh^{-1}, saving 97 % in time and 95 % in cost compared to conventional methods. It also saves 79 % in time and 41 % in cost compared to pneumatic ground collecting systems. The picking assembly picks the fruits from the ground and the collecting assembly collects the fruits (62).

On citrus farms with high levels of productivity, two lateral canopy shakers with a catch frame were tested to harvest the hedge's two sides separately. Nowadays, the canopy shaker systems are very large and heavy machines. So difficult to manoeuvre in small plots which are designed mainly for manual harvesting (63).

A catch frame and a conveyor system shake the tree canopy constantly at a set frequency to separate the fruits. A continuous canopy shaker with two self-propelled single drum shakers and two catch frame systems (M/s. OXBO International Corporation, Byron, NY, USA), that concurrently functioned for commercial citrus harvesting on both sides of the tree canopy (64).

Fig. 6. Pneumatic suction type ground collection system (16).

Fig. 7. Mechanical neem fruit picker cum collector (62).

The shaker was powered by a 2-stroke engine (Spark Ignition). A centrifugal clutch and a gearbox were utilized in conjunction with a slider crank mechanism to transmit power to a limb *via* a boom and a C-shaped clamp. Shakers can be controlled using the operator handle on the shaker. Limb shakers effectively remove a high proportion of fruit by applying long strokes at low frequencies (Fig. 8). This procedure can damage the tree's bark and limbs, as well as remove immature fruit (65).

Fig. 8. Limb shaker (65).

Another method was a two-section canopy shaking system for harvesting citrus fruits (Fig. 9). This system operated using a linked crank-rocker mechanism with top and bottom shaking units, each equipped with staggered front and rear shaking rods. The shaking frequency and acceleration could be easily adjusted by controlling the speed of the hydraulic motor (33).

Canopy shakers, the frequency range from 2.5 to 6 Hz was used. In trunk shaker mechanism, when using an inertial trunk shaker with reduced unbalance and eccentric mass the frequency upto 9 Hz. It was reported that the vibration frequency values in the range of 15 to 20 Hz significantly defoliated the trees (66).

The continuous canopy shaker is a kind of mechanical harvesting device (Fig. 10). Despite the excellent harvesting efficiency of the conventional canopy shaker design, its aggressive shaking action often causes significant damage to the major scaffold branches of citrus trees, leading to reduced tree health, lower future yields and increased maintenance costs. Therefore, the issue of structural damage to the tree must be addressed by either changing the design or creating a new design entirely to enhance the usage of mechanical harvesting for fruit harvests. Pareto-optimal search techniques are used to identify the best designs and the response surface approach or surrogate models are used to quantify the objective functions. To maximize fruit removal and reduce damage to trees, certain sets of settings are used (67).

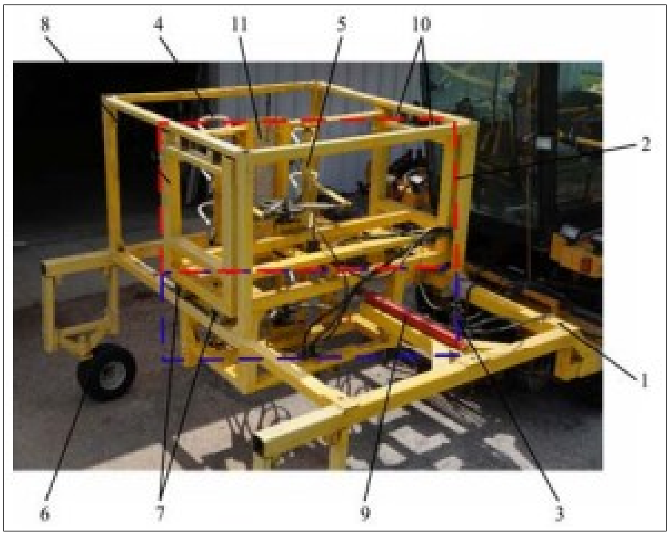

Fig. 9. Two section canopy shaking system (33).

(1. Vehicle frame 2. Top shaking system 3. Bottom shaking system 4. Shaking rod 5. Rotating plate 6. Universal wheel 7. Carrying roller 8. Body frame 9. Hydraulic cylinder 10. Upper guide roller 11. Protection grid 12. Side guide roller 13. Hydraulic motor 14. Rocker 15. Adjustable connecting rod 16. Chain 17. Flywheel)

Fig. 10. Continuous canopy shaking system (67).

For mechanical mango harvesting, battery operated mango harvester (Fig. 11) was used. The force is minimized for detaching the fruits. Picking capacity is 6 fruits per minute (68).

A trolley-mounted sorting system has been created to eliminate latex stains and burns, as well as harvesting losses caused by fruit fall and human error. The device employs a sensory feedback-based automatic cutting mechanism and a sorting facility based on mango size to reduce latex leakage and free fall. The equipment is intended for continuous processing, minimizing harvesting time and effort and may be operated by semi-skilled individuals. The performance evaluation demonstrates that it is a viable alternative to traditional pickers for medium to small-scale growers (69).

Mechanical systems are rarely employed for harvesting fresh fruit due to fruit injury and tree damage (33). Mechanically harvesting machine is best suited for fruit processing industry where mass fruits are harvested. However, the machine operation cost is higher due to harvesting untrained and non-pruned trees (70). Table 4 shows the mechanical tree fruit harvesting machine.

Autonomous/robotic harvesting

Automating the harvesting process enhances efficiency by allowing robots to operate continuously without breaks. Advanced sensors and AI enable real-time ripeness assessment, ensuring selective harvesting that reduces waste and delivers high-quality produce. Harvesting crops at the optimal time improves taste, nutrition and shelf life, benefiting both consumers and retailers. Additionally, data collected on robotic systems helps farmers analyse patterns to optimize planting, irrigation and pest control. Over the time, this technology supports sustainable farming by reducing labour costs, minimizing waste and ensuring efficient utilization of resources (71).

Harvesting robots offer an affordable solution to labour shortages and growing expenses. Harvesting robots enable control, traceability and customization of the harvesting process. They can analyze temporal, geographical and individual data on target fruits, including ripeness, harvest time, location and pose and defects (72). The technology status of harvesting robots is divided into two main categories: fully integrated systems, which combine all components such as vision, gripper and control systems into one cohesive unit and individual harvesting subsystems. These subsystems, such as vision (73) for object recognition, grippers (74) for fruit harvesting and control systems, are developed separately and can be integrated into larger systems as needed. Fully integrated systems aim to provide a more seamless, automated approach to harvesting, while subsystems allow for flexibility in system customization and development (72).

Robotic harvesting systems use two main strategies: selective harvesting and bulk harvesting. Selective harvesting employs robotic manipulators with specialized end-effectors and machine vision to identify and pick individual ripe fruits. These robots are typically mounted on mobile platforms, ensuring precise and gentle harvesting to maintain fruit quality (75). In contrast, bulk harvesting uses mechanical vibration to shake the tree and detach fruits forcefully. This method is highly efficient for large-scale operations, significantly reducing labour costs and harvesting time (76). However, it may cause fruit damage and is more suitable for crops where minor bruising is acceptable, such as olives and nuts. The choice between these methods depends on the crop type, required quality and farm size (63).

An autonomous fruit harvester with machine vision is designed to detect and pick fruits from trees without human intervention, making it highly beneficial for large-scale farms with limited labour (Fig. 12). The primary function of these robots is to accurately identify and harvest ripe fruits using computer vision, which relies on advanced cameras and image processing techniques (77). Fruit detection methods include machine vision (based on colour and shape), 3D imaging, light sensing and ultrasonic sensing, ensuring precision in identifying harvestable produce (78).

Several 3D visual sensors, such as Light Detection and Ranging (LiDAR) sensors, RGB-D (RGB-depth) cameras and stereo cameras (79, 80), enhance fruit recognition. Stereo cameras, which capture images using two or more RGB cameras at fixed distances, provide depth perception to improve accuracy.

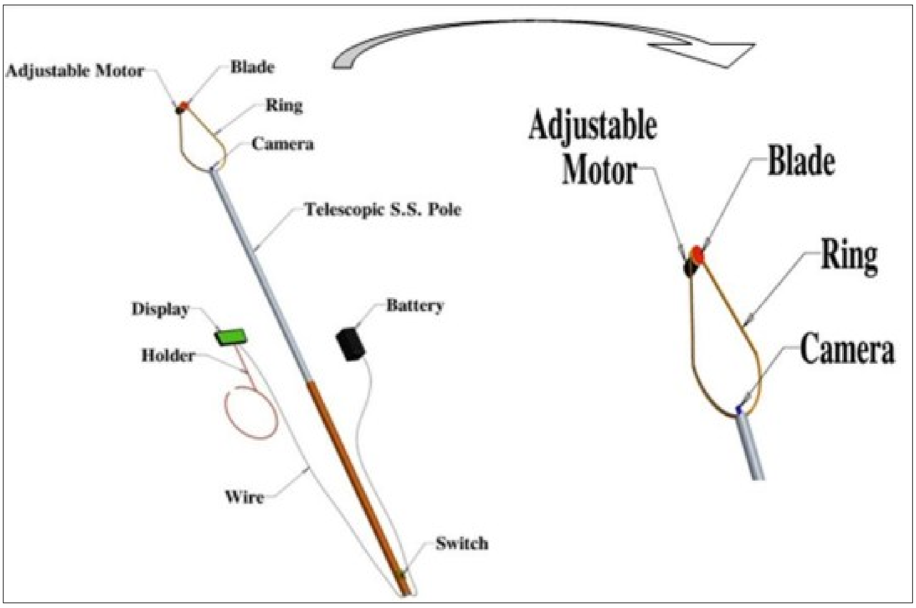

Fig. 11. Battery operated mango harvester (68).

Table 4. Mechanical harvesting of tree fruits

S. No	Fruit crops	Title	Mechanism	Reference
1	Olive	Trunk shaker with a reversed umbrella interceptor	A self-braking system, engine power of 77 kW, a very high frequency vibrating head is 1800-2000 vibrations per min and an umbrella opening diameter is 6 m. The harvesting yield is 96.58 % which is very high.	(32)
		Straddle harvester	Straddle harvester equipped with an anti-levelling and antiskid system to ensure stability on sloping terrain. This machine combines both detachment and collection operations. Straddle harvesters have a high harvesting efficiency of about 90-95 % of the fruits to be removed. The productivity is 1000 -1500 kg of olives per person per hr.	(49)
2	Neem	Pneumatic suction-type ground collection system	A pneumatic neem collector consists of a power transmission system, suction unit, conveyance system, storage section and frame. In power transmission 0.82 hp air-cooled, single-cylinder, two-stroke petrol engine was used. The machine's suction blower used a plastic forward-curved type impeller with a casing. When the operator has finished sucking the neem fruit from beneath a neem tree, they can open the shutter by pushing the lever on the right handle against the spring pressure, which will release the sucked fruit. When the lever is released, the spring and suction pressure cause the shutter to close. The collection was 10 kgh^{-1}.	(16)
		Mechanical type picker cum collector for neem fruits	Consists of picking assembly, ejector assembly and collector assembly. The picking assembly consists of a picking roller with bristles. These bristles are used to harvest neem fruits as the roller moves across the ground in a clockwise motion. The ejector assembly consists of an array of fruit ejecting rods mounted on the rear side of the collection box. It is used for removing fruits from the roller. Collector assembly used for collection and storage of fruits picked and removed from the roller. The collection capacity was 48 kgh^{-1}.	(62)
3	Citrus	Limb shaker	An engine with a 2-stroke (spark ignition) powered the shaker. Power was transferred to a limb via a boom and C-shaped clamp using a slider-crank mechanism, a gearbox and a centrifugal clutch. The maximum number of fruit detachment was 97.9 %.	(65)
		Two section canopy shaking	A hydraulic motor powers a flywheel's crank motion, driven by an adjustable connecting rod. The system removes the entire shaking system, then inserts a shaking rod into the tree canopy. The rods strike one side of the canopy, dislodging fruits. The shaking frequency is 4.7 Hz, with an 82.6 fruit removal percentage and 5.4 % tree damage rate.	(33)
		Self-propelled continuous shake and catch system	A self-propelled CSC system employs six people, including two harvester operators and four field truck drivers. The system transports fruit to a field truck, with catch frames capable of holding upto 60 boxes. Each unit separates fruit from leaves and stems, reducing waste. The system's productivity exceeds 100 boxes per hr, ten times higher than hand harvesters.	(54)
		Tractor-drawn continuous shake and catch system	The tractor-drawn continuous canopy shaker can handle uneven tree canopies. When it comes to trees that haven't been skirted to the first scaffold branches, this shaker has shown good fruit removal.	(54)
4	Mango	Battery operated mango harvester	An 11-foot stainless steel pole was used in the development of a mango harvester because of its strength and longevity. To keep the motor at a 45 ° angle, an over ring was made and the blade was made of GI sheet. The brass welding was used to fix the motor and blade. A 12-volt battery was utilized to power the mounted 5 MP camera. A wire was used to connect the conveyor and motor switch. On the over ring, there is a conveyor to move the fruit.	(68)

Fig. 12. Fruit harvesting robot by machine vision (78).

In high-value crops like olives, real-time detection is crucial for maximizing efficiency. The YOLOv5 model, a compact and fast AI-based system, enables high-speed, real-time fruit localization. It can identify over 95 % of olives on a tree, significantly enhancing harvesting efficiency, reducing waste and improving farm productivity and crop quality (81).

To simplify the implementation of the olive detection model, Fig. 13 illustrates the key phases of the process. This includes three core stages:

Data preparation

Images of olive trees are collected, pre-processed, annotated and augmented to build a robust dataset, which will be used for training, validation and testing of the YOLO model.

Model implementation

A suitable deep learning model is selected and trained using the training and validation datasets. The model's performance is then thoroughly evaluated on the test data set to ensure optimal accuracy.

Model inference

The finalized detection model is deployed for real-world applications, enabling the accurate identification of olive trees in life or practical imagery (81).

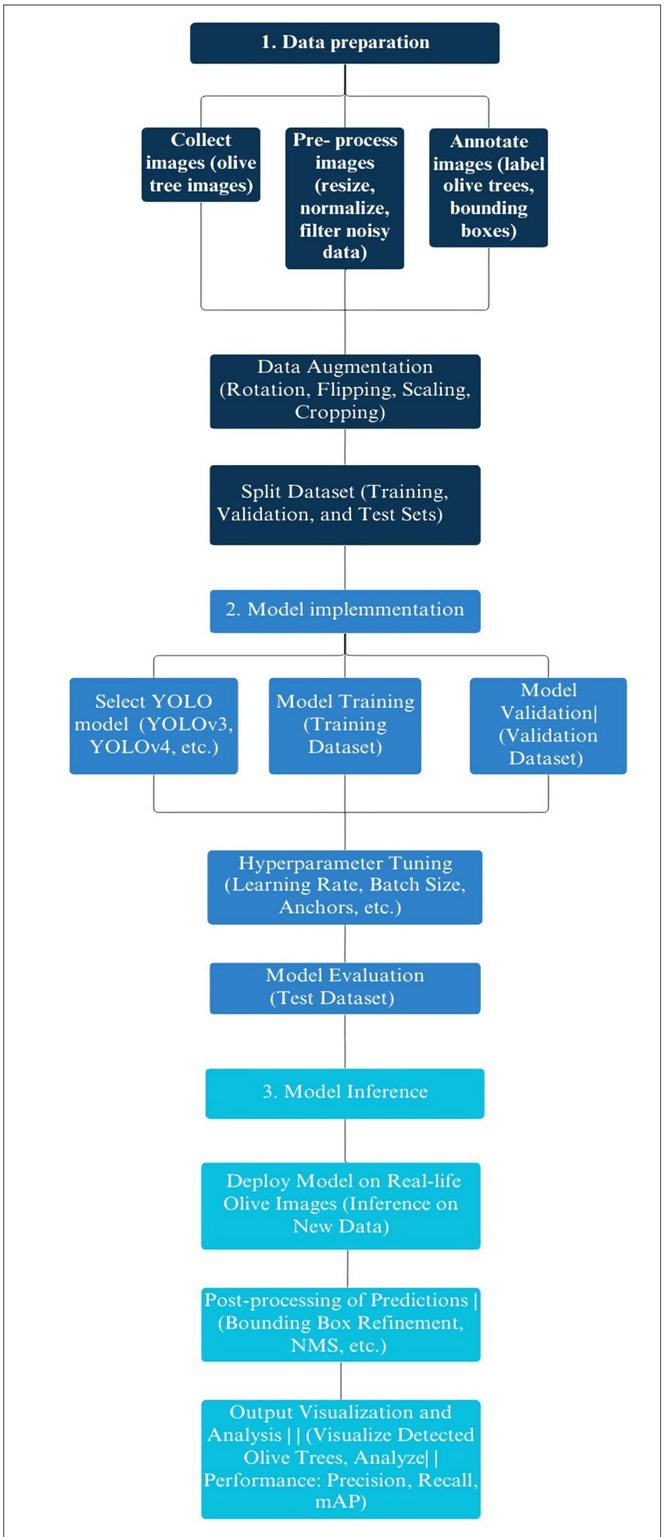

Fig. 13. Olive detection model implementation (81).

A robotic manipulator was created, simulated, built, programmed and tested to pick olives. The robot, which runs on energy and does not emit pollutants was created utilizing robot arm theory and numerical matrix methods. Simulations were done in Solidworks™ and MATLAB™, while the experimental model was produced with a 6-DOF manipulator and mechanical gripper. Python and MATLAB were used to program camera image analysis and inverse kinematics calculations. Testing was done solely with the mechanical gripper. A high percentage of fruits were plucked successfully (82).

Automatic fruit harvesting by a robot follows five key steps

(i) fruit detection (ii) fruit localization (iii) integration of camera data (iv) inverse kinematics and (v) path planning. First, RGB-D cameras, which capture both RGB and depth information, are used to detect and locate fruits. Deep learning is applied to the RGB images to identify fruit positions and their 3D locations are determined by combining RGB and depth data. To minimize occlusion caused by leaves or overlapping fruits, multiple cameras are employed. The gathered data is then integrated and reordered for efficient harvesting. Since an articulated robotic arm requires joint angles for movement, inverse kinematics is used to convert the 3D fruit positions into the necessary joint angles. Finally, a path is planned based on these calculations, enabling the robot to execute precise harvesting motions (83).

An end-effector (EE) is a specialized tool mounted at the wrist of a robotic manipulator, designed for harvesting fruit. It operates by either grasping or gripping the fruit or its peduncle (the attachment to the plant), carefully detaching it from the parent plant and seamlessly transferring it to a storage location for collection (84). The four types of end-effectors are the clamping type, air-suction type, suction-holding type and envelope type (Fig. 14) (85).

The primary concept of a clamping-type end-effector is to use the integrated shearing device to complete the picking process after grabbing the produce using either mechanical jaws or flexible fingers. This end-effector has shown usefulness for items that require a high degree of stability. Particularly with gripper-style end-effector picking, apples are the ideal fruit to use (86).

The air-suction-type end-effector works on the principle of sucking produce into the storage structure after the produce has finished being sheared, with the produce being drawn inside the end-effector *via* an inhaling mechanism. The air-suction end-effector is appropriate for lighter, smaller targets that require less suction to pick. An end-effector designed for greenhouse harvesting, featuring a centrally positioned adsorption mechanism to maximize suction force and enhance clamping performance, ensuring secure handling and improved operational efficiency (87).

Based on the idea of using negative pressure to create suction, the suction-holding end-effector combines an air-suction end-effector and a clamping end-effector. It attaches the produce to the actuator and then uses the device to shear it off. This type of end-effector is useful when handling fragile, delicate or irregularly shaped food, because it reduces the pressure on the product, lowering the chance of damage (85).

A circular or cylindrical mechanism is used by the envelope-type end-effector to cover all agricultural goods. Wrapping mechanisms distribute force throughout the whole surface of an agricultural target, in contrast to clamping-type end-effectors, which apply force on both sides or at many spots. Its benefit is that most agricultural goods may be handled more steadily using this 'full wrap' method, which also lessens damage by lowering the single point of pressure on the products' surfaces. The envelope-type end-effectors exhibit more flexibility and adaptation when handling delicate, fragile or unusually shaped agricultural goods such as apples and oranges, despite being more challenging to design and build (85).

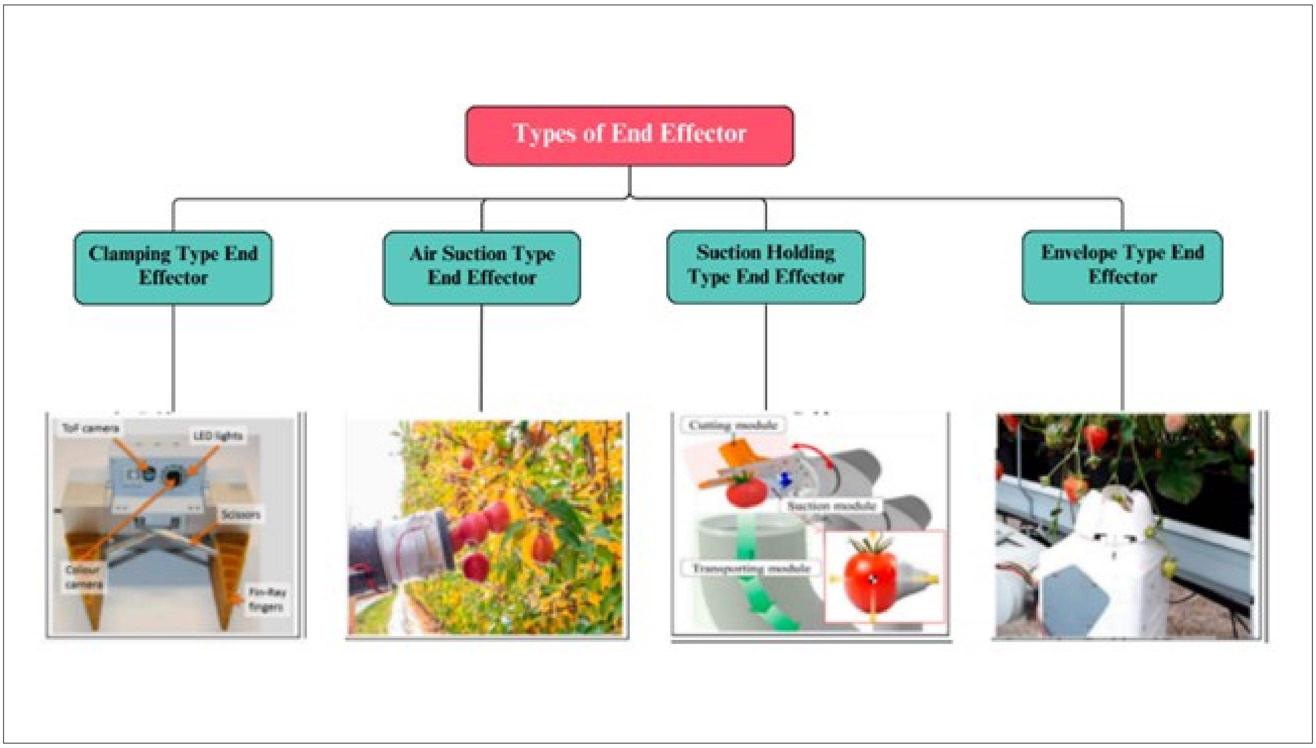

Fig. 14. Types of end effector (85).

Automated fruit harvester using machine vision to recognize and collect orange fruits from a tree. The system comprises a six-degree-of-freedom (6-DOF) robotic arm mounted on a four-wheeled electric kart. The kart employs a ZED camera to measure long-range distances and the green detection algorithm to recognize trees. Image processing is carried out using Microsoft Visual Studio and the Open CV library. The trees x and y coordinates, as well as its distance, are sent to an Arduino microcontroller, which controls the wheels' motor. When the kart is less than or equal to 65 cm from the tree, the robotic arm with its vision system algorithm takes control and searches for orange fruits in the tree (88).

Deep learning (DL) based techniques for fruit identification and recognition are extensively utilized for reliable, quick and accurate fruit identification and recognition (Fig. 15). These techniques can be divided into two categories: two-stage techniques (AlexNet, VGGNet, ResNet, Faster R-CNN, FCN, SegNet and Mask R-CNN) and single-stage techniques (YOLO, SSD). Because of its fast identification speed and good recognition accuracy, faster R-CNN is a widely used technique. When it comes to high recognition speed requirements and mobile deployment, the most popular approach is YOLO. Because of their distinct qualities, size, weight and hardness, apples and citrus are the main subjects of research because they are perfect for automated harvesting (89).

Before any human-in-the-loop picking experiment, the vision system uses the manipulator to identify and locate the apples' work area. On the monitor, all these apples will be displayed and users must manually click the during each harvesting cycle screen to select the desired apple. After the intended apple is established, the manipulator is directed to get close to the apple after which the vacuum-based end-effector is turned on to take the apple off. At last, the manipulator makes a comeback to the home posture with the fruit separated (90).

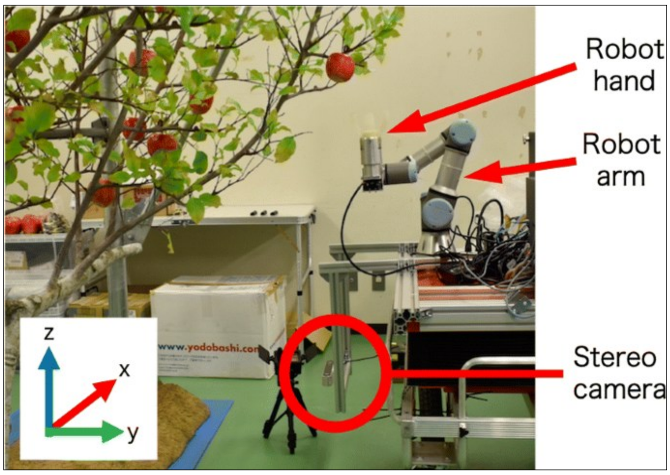

Fig. 15. Deep learning methods (89).

Fig. 16 shows that an effective path-planning model must be able to identify a path, avoid obstacles, create optimal routes and need little processing time. It reduces the robot's travel time by determining the closest path between two options. It can manage changeable settings, is effective and stays clear of obstacles (91).

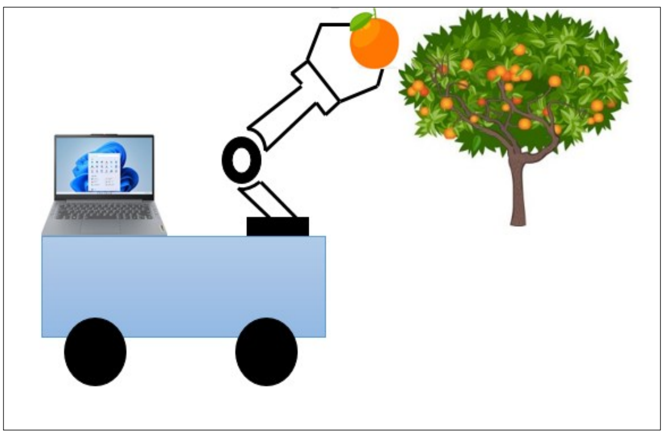

Fig. 16. Path determination using RRT* algorithm.

A robotic apple harvesting tool was developed, featuring a manipulator, end-effector and an image-based vision servo control system. The spoon-shaped end-effector, equipped with a pneumatically operated gripper, was specifically designed for apple picking. The robot used a vision-based module to autonomously identify and harvest apples. Visual C++ 6.0 was chosen as the programming tool for the host computer. The system's effectiveness was evaluated through 100 picking trials conducted at 10 different positions, achieving a 77 % success rate and an average time of approximately 15 sec per apple. These results suggest the prototype and control system have significant potential for outdoor apple harvesting operations (92).

Autonomous flying fruit-picking robots were introduced in 2019 by a cutting-edge startup called Tevel. On the prototype, the end effector was a two-finger cup-shaped gripper. The same team introduced a full harvesting system in 2021. Three-finger grippers were the recommended end effectors for harvesting apples (90); no further details or analysis were provided. This technique was used for apples as well as other comparable-sized fruits, such as mangoes and oranges (93). Fig. 17 shows the machines used for tree fruit harvesting.

Automatic harvesting can reduce cost for large orchards with right plucking system, ripening identification, reducing harvesting wastage and automation of manual processes. Autonomous tree fruit harvesting methods are furnished in Table 5. Table 6 provides a comparison between manual, mechanical and autonomous tree fruit harvester.

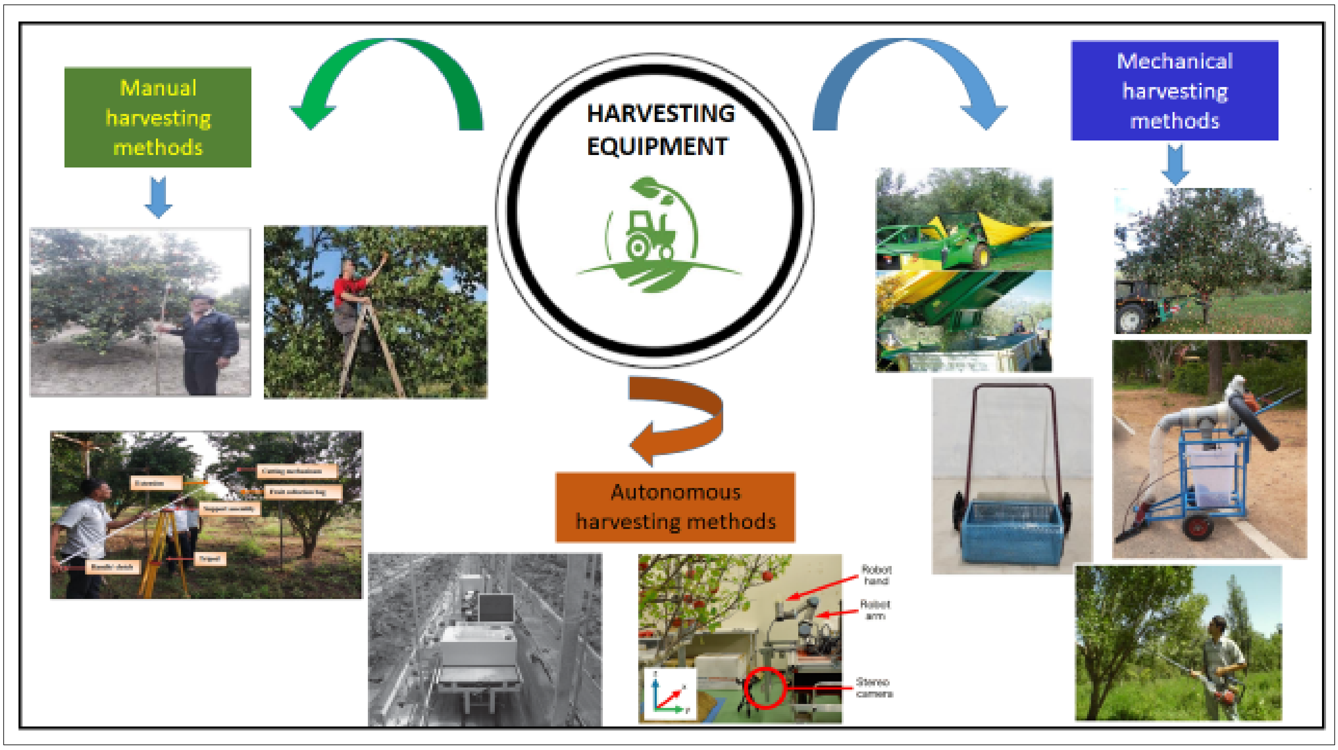

Fig. 17. Types of tree fruit harvester.

Table 5. Autonomous tree fruit harvesting methods

S.No	Fruits	Title	Remarks	Reference
1	Olive	A real-time olive fruit detection for harvesting Robot based on Yolo Algorithms	You Only Look Once (YOLO) is a new object detection method that uses a single glance to identify and locate objects in an image. It divides the input image into N equal-sized S×S grids, with each grid responsible for identifying and localizing objects. The olive detection model involves three steps: data preparation, model implementation and model inference, where the detection model is deployed on real-life olive images.	(81)
2	Citrus	Deep learning	Convolutional neural networks (CNNs) are being explored for fruit recognition, detecting ultimate targets through high-level qualities and low- and high-level features. Kinect v2 deep pictures can achieve an average precision of 0.613, but point-based strategies are needed for stem retention and length control.	(72)
		Machine vision system	The fruit harvester with machine vision system consists of a kart, a 6-DOF robotic arm and machine vision. The system uses stereo vision and a green colour identification algorithm to identify tree leaves. An Arduino microcontroller receives tree location and distance to operate the kart's motor. Orange colour recognition is used when the kart approaches the tree, controlling the robot arm's motor to pick orange fruit.	(88)
3	Mango	Suction gripper	The use of a quadcopter for mango harvesting is challenging due to potential damage to fruit and sap oozing out. The system requires human labor to collect the fruit from the capture nets, which is made possible by a suction gripper.	(93)
4	Apple	Deep learning based fruit detection	The process of identifying and locating fruits in photographs takes an average time of 0.3 sec. The process also involves a manipulator taking 2.5 and 2 sec to get close to an apple and return to its home position. The fruit detachment time is 4.0 sec, but future technologies may shorten this. The total apple harvesting cycle takes 8.8 sec.	(90)

Table 6. Comparison between manual, mechanical and autonomous tree fruit harvester

S. No	Methods	Olive	Neem	Citrus	Mango
1	Manual	Hand picking, shaking, sticks, ladder	Hand picking, shaking	Hand pulling with a ladder, tree climbing, tree shaking and hitting by sticks.	Shaking, plucking with bamboo, picking by hand and climbing the tree or using a bamboo stick from the ground.
2	Mechanical	Trunk type harvester, self-propelled trunk shaker with reversed umbrella interceptor. Shaking frequency = 25 Hz	Pneumatic suction type ground collection system, mechanical neem fruit picker cum collector	Trunk shaker, canopy shaker, two section canopy shaking system Shaking frequency = 19 Hz	Battery operated mango harvester, trolley mounted shaking system
3	Autonomous	Robotic manipulator		Automated fruit harvester with machine vision system, deep learning methods.	Autonomous flying fruit picking robots

Future aspects

Future advancements include a speedier robot, a closed-loop control mechanism and a larger robot that will be manufactured and tested on a real tree (82). Robotic arms for picking fruit will concentrate on optimizing the structure to increase maneuverability and precision. Maneuverability will be improved by advances in articulation; linkage mechanisms and kinematics and gentle fruit handling will be guaranteed by torque and force sensors. Ripe fruits will be identified by advanced 3D cameras and machine vision technologies and picking trajectories will be optimized by AI-powered algorithms. End effectors will be adaptable and versatile, revolutionizing fruit harvesting with unprecedented speed and precision.

Conclusion

The tree fruit harvesting systems, include mechanical and automated harvesting technologies. It highlights key applications, including machine vision and deep learning for fruit detection and localization. In mechanical harvesting, the shake-and-catch frame system has proven highly effective for fruit detachment. Automated harvesting technologies help balance the trade-off between mechanical and traditional manual harvesting, improving efficiency and reducing labour dependency. The design of harvesting end-effectors and detection algorithms is optimized for specific fruit types, incorporating crop attributes such as colour, shape and size. Additionally, environmental factors and precision crop maintenance practices are essential in developing practical harvesting robots. The precision of automated harvesting systems has been validated, with a shaking mechanism achieving a fruit removal efficiency of 93.3 %. Independent parameters such as shaking frequency, amplitude, applied force and actuator positioning have been optimized to enhance the selective removal of ripe fruit while minimizing damage to unripe fruit. The maximum harvesting rates were found to be 0.5 th^{-1} for manual pickers, 10 th^{-1} for canopy shakers and 25 th^{-1} for trunk-shaking harvesters, demonstrating that mechanized harvesters can replace 20-50 human pickers. For autonomous tree fruit harvesting, microcontrollers, MATLAB-based simulations and deep learning techniques are integrated to enhance object detection, motion planning and real-time decision-making, improving harvesting efficiency and adaptability across different orchard conditions.

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

Author(s) hereby declare that generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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