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Review

Classification, Advanced Technologies, and Typical Applications of End-Effector for Fruit and Vegetable Picking Robots

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Abstract: Fruit- and vegetable-harvesting robots are a great addition to Agriculture 4.0 since they are gradually replacing human labor in challenging activities. In order to achieve the harvesting process accurately and efficiently, the picking robot's end-effector should be the first part to come into close contact with the crops. The design and performance requirements of the end-effectors are affected by the fruit and vegetable variety as well as the complexity of unstructured surroundings. This paper summarizes the latest research status of end-effectors for fruit- and vegetable-picking robots. It analyzes the characteristics and functions of end-effectors according to their structural principles and usage, which are classified into clamp, air suction, suction holding, and envelope types. The development and application of advanced technologies, such as the structural design of end-effectors, additional sensors, new materials, and artificial intelligence, were discussed. The typical applications of end-effectors for the picking of different kinds of fruit and vegetables were described, and the advantages, disadvantages, and performance indexes of different end-effectors were given and comparatively analyzed. Finally, challenges and potential future trends of end-effectors for picking robots were reported. This work can be considered a valuable guide to the latest end-effector technology for the design and selection of suitable end-effectors for harvesting different categories of fruit and vegetable crops.

Keywords: Agriculture 4.0; agricultural robot; fruit and vegetable picking; end-effector; advanced technologies

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1. Introduction

The demand for agricultural resources, such as water, food, and farmland, will increase dramatically as the world's population continues to grow, posing a challenge to the development of modern agriculture [1]. Smart agriculture technology is a highly integrated, precise, and intelligent modern agricultural technology supported by technologies like the Internet of Things, big data, artificial intelligence, and automated robots. It is a solution to improve agricultural productivity and rationally utilize agricultural resources for sustainable agricultural development. Agricultural robots, especially used for picking and harvesting, play an essential role in developing Agriculture 4.0 [2]. In the field of agriculture, picking fruits and harvesting vegetables sounds simple, but it is a tedious and uninteresting job, which makes it challenging to motivate people to work [3]. To reduce the risk of farm workers suddenly quitting their jobs, many researchers have turned to agricultural robots to reduce the reliance on manual labor and increase overall productivity. Agricultural robots can perform tasks faster and more accurately than manual labor, reducing the misuse and waste of production materials due to human error [4,5]. The

end-effector is a crucial part of agricultural picking robots, which can automate many repetitive and tedious agricultural tasks, such as fertilizing, spraying, and harvesting. The end-effector of an agricultural picking robot is the manipulator at the end of the robot and its attached devices for positioning, gripping, and collecting crops such as fruits and vegetables [6]. During the initial research of agricultural picking robots, the design of the end-effector was limited by technology, and simple mechanical grippers or fixtures were usually used. These mechanical end-effectors are light in structure, simple in operation, and low in cost, and they can realize basic picking operations for most fruits [7]. However, when working with fragile and bruise-prone fruits, vegetables, or plants in unstructured agricultural environments, traditional mechanical grippers cannot meet the requirements of modern intelligent agricultural robots. Driven by smart agriculture technology, the new end-effector must have an open control system, highly intelligent algorithms, and an optimized end-effector structure for different crops [8]. First, various agricultural products (e.g., apples, strawberries, etc.) have different surface characteristics and physical properties, which require different materials for the end-effector, and soft grippers may be a better choice for fruits and vegetables with soft surfaces [9]. Second, different agricultural products have different shapes and sizes, and in order to be able to accurately grasp fruits of varying shapes and sizes, and to avoid slipping and damage during the gripping process, the robot end-effector requires a different structure and principle design [10].

Moreover, since the robot operates in a complex agricultural environment in the field, changing conditions, such as weather, light, and temperature, coupled with the complex growth posture of the fruits themselves and the existence of obstructions, overlap. These conditions bring significant challenges to the design of the new end-effector. Therefore, with the advancement of technology, more flexible and precise end-effector designs have emerged, and intelligent end-effectors equipped with a variety of sensors and complex picking control strategies are a hot spot for many scholars, such as the use of visual sensors, tactile sensors, force sensors, and other sensors [11]. End-effector integration of various sensors can measure temperature, force, position, slip, etc. Through the combination of sensors and control technology, more intelligent operation can be realized, which has an essential impact on the picking efficiency, picking quality, and stability of agricultural robots.

With the continuous improvement of agricultural picking robot technologies and the expansion of their application range, the end-effector plays an increasingly important role in modern agricultural production. The end-effector must simulate the movement of the human hand to perform the required functions, and it must have more stable control over the crops and the environment during the production process [6]. Although the end-effector's operation performance and perception ability are far from reaching the human level, these technical difficulties are being overcome one by one, which will provide a reliable technological guarantee for the design and use of agricultural picking robots in the future. Many researchers have focused on reviewing harvesting end-effectors for agricultural robots [12]. For example, Zhang et al. described the development of industrial robot fixtures and their application in agriculture [13]. Vrochidou et al. reviewed separation methods and design principles for robotic harvesting systems [14]. Navas et al. described recent advances in designing and applying soft fixtures for crop harvesting [15]. The end-effects of robotic harvesters also face challenges and debate. Some researchers believe that the traditional mechanical claw design meets the requirements. In contrast, others advocate using more advanced sensing and control technologies, such as artificial intelligence and machine vision, to improve gripping efficiency and minimize damage [16]. Furthermore, with the rapid development of picking robots, picking end-effectors of different varieties, shapes, sizes, and characteristics have been developed and applied in a large number of applications. Therefore, it is necessary to provide an overview of the development and application of various types of fruit- and vegetable-picking robot end-effectors, which will assist other scholars in improving and utilizing the latest research results and reducing the search time.

The paper's main contributions are as follows. (1) The development history of end-effectors for picking robots is described in detail and categorized based on existing cases. (2) Key technologies for end-effector design are described, including structural design, grasping strategies, sensors, and new material applications. (3) Typical end-effector applications in fruit and vegetable harvesting are discussed.

The main categories of end-effectors and their applications in fruits and vegetables are shown in Figure 1. Finally, this paper also reported on end-effector challenges and potential future trends to raise the amount of attention on end-effectors in developing agricultural robots.

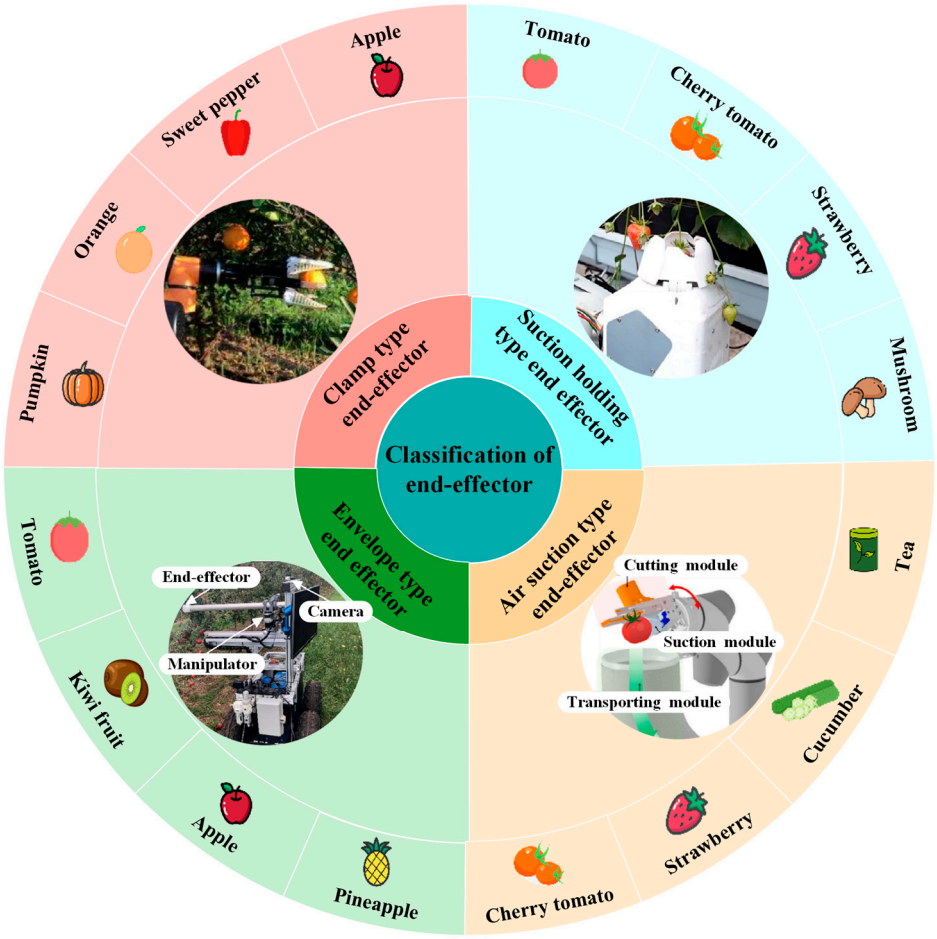


Figure 1. Diagram of end-effector categories and typical applications [17–20].

2. Development, Classification, and Advanced Technologies of End-Effector for Fruit and Vegetable-Harvesting Robots

2.1. Development History of End-Effector

In 1968, the American scholars Schertz and Brown first proposed the application of mechanical equipment for fruit and vegetable harvesting, which is considered by academics to be a milestone in the beginning of agricultural harvesting robotics research [21,22]. However, the harvesting robots that were initially developed were mainly vibratory, with low levels of automation and intelligence. Since the 1980s, based on the rapid development and mature application of industrial robotics and vision-processing technology, a variety of fruit- and vegetable-harvesting robot research has been carried out in Europe, the United States, Japan, and other countries [23]. Japan developed a five-degree-of-freedom articulated robot for tomato-harvesting research, marking the birth of the first picking robot. In 1996, the Netherlands Institute of Agro-Environmental Engineering developed a seven-degree-of-freedom, multi-articulated cucumber-picking robot arm equipped with an end-effector that can be changed at any time. With the continuous development and

improvement of the picking robot technology, the robot end-effector equipped with the end-effector is also synchronized with the birth of the development process, which is divided into two phases. Figure 2 shows the development of the end-effector from its inception to the present day, mainly listing the important technologies and features involved in the end-effector.

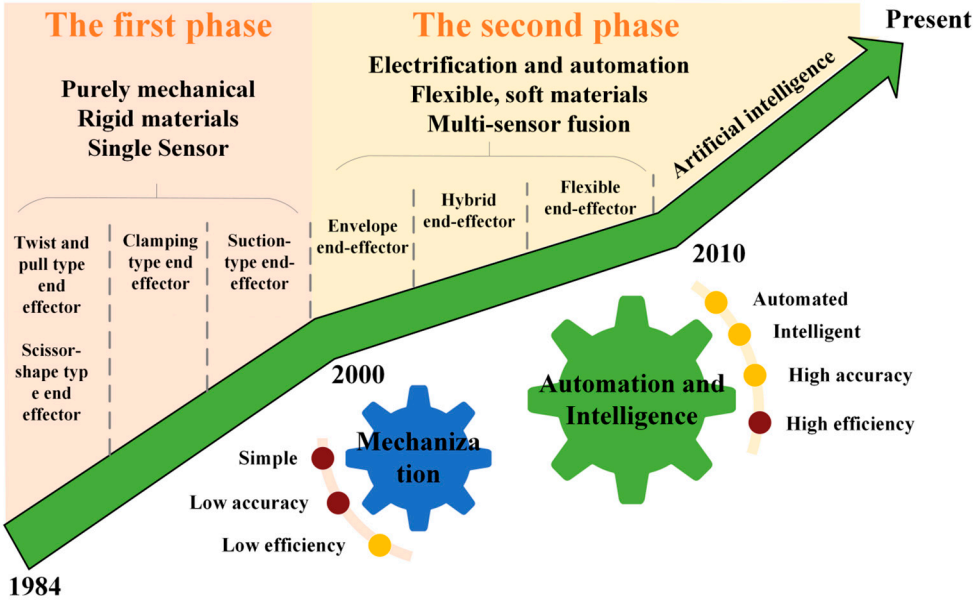


Figure 2. Schematic diagram of the development history of the end-effector.

The first stage of end-effector development was from the beginning of its birth to around 2000, and the end-effectors in this stage were mainly mechanized structures. As a result, picking robot end-effectors mainly used mechanical gripping methods, usually scissors or gripping structures. Pool et al. introduced a citrus-picking robot end-effector with a rotating lip mechanism to capture the fruit. However, this mechanical stripping method had a high damage rate to the fruit (up to 37%) [24]. Kondo et al. developed a pneumatic end-effector for small-tomato picking in 1994 [25]. Monta et al. developed a robotic end-effector with a suction-cup structure based on the tomato plant's physical properties, consisting of two parallel plate fingers and a suction cup [26].

In addition, cucumber- [27], citrus- [28], and strawberry- [29] oriented robots have also emerged, carrying end-effectors mostly of a mechanical gripping type, which has the advantages of simple structure, low cost, etc., but do not have the inability to adaptively adjust according to the size, shape, and position of the crop adaptive adjustment. Hence, the precision and efficiency are relatively low. With the gradual development of industrial robotics, some well-known robotics companies (e.g., Agrobot, Aarhus Robotics, etc.) have started to develop more advanced end-effectors, and the robotic end-effector used for agricultural harvesting has been greatly improved. Among them, the clamp-type and the air-suction-type end-effectors are the two most widely used types. In 2000, Hayashi et al. designed two types of gripper-type end-effectors for eggplant picking [30]. The end-effectors include a fruit size judgment mechanism, a fruit grasping mechanism, and a fruit cutting mechanism, which can selectively pick fruits according to the lengths of the fruits. Compared with the mechanical gripping method, the air-suction-type end-effector has the advantages of an advanced structure, little damage to the target, and a high picking success rate. The air-suction-type end-effector generally consists of a gripping mechanism and a suction device. The electric or pneumatic pressure powers the gripping mechanism, and the gripping function is achieved by varying either the motor's speed or the pneumatic pressure. The suction device adopts a vacuum negative pressure device, which grabs the target through the adsorption force of air pressure. Johan Baeten et al. designed an

air-suction-type end-effector for apple picking that only needs to be close to the apple and then closes the vacuum port in order to pick it up [31]. However, the air-suction-type end-effector has limitations in dealing with different shapes of crops that require different structural designs depending on the crop, especially for targets with large masses and fragile skin, such as strawberries and tomatoes. Therefore, the air-suction-type end-effector and envelope-type end-effector are born synchronously and gradually as new types of clamping methods. The advantages are that they can be adapted to different sizes and shapes of crops, and the precision and efficiency are higher.

The suction-holding-type end-effector generally adopts pneumatic or electric suction through the control of air pressure or motor speed to realize the clamping. The adsorption clamping method has been widely used in practical applications. Peter P et al. designed the tomato-picking end-effector, using vacuum suction cups to suck the target with a motor-driven cable for clamping [32]. Tanigaki et al. developed the cherry-picking end-effector, first through the adsorption device to suck the fruit and then through the two symmetrical fingers to intensify its fracture [33]. Kondo et al. reported a grading robot with a three-degree-of-freedom manipulator and suction cups as the end-effector, which can ground fruits, such as peaches, pears, apples, etc. [34], from the container and can grade three fruits per second by rotating the suction cups to obtain four side images of each fruit. However, it should be noted that the suction-holding method has some differences in adsorption performance for different crops. For large-mass fruits, such as apples, oranges, peaches, etc., a larger adsorption force and adsorption area are needed, while for strawberries and tomatoes with lighter mass targets, less adsorption force is needed. But more advanced sensors and control technologies are needed.

After 2000, with the large-scale application of artificial intelligence, machine vision, new sensors, and other new technologies, the development of picking end-effectors for agricultural robots ushered in the second stage, which is automation [35]. Since agricultural robots used for picking fruits or vegetables need to consider efficiency, accuracy, reliability, safety, and other indicators, the automation of the picking end-effector, or even intelligence, cannot be separated from the fusion of artificial intelligence technology and multi-sensor technology. Sensors include vision sensors, force sensors, tactile sensors, and ultrasonic sensors, which are installed on the outside or inside of the robot end-effector to detect the size, shape, position, color, and other information of the crop target and then realize the automation of the robot's clamping mode adjustment [36]. Vision sensors that have been applied on a large scale include Kinect sensors, binocular cameras, time-of-flight cameras, etc. These are non-contact sensors that are best suited for robotic end-effectors to recognize or locate target positions and pick points and obstacles in the workspace [37]. Jochen Hemming et al. used a combination of a color camera and an aircraft time camera to design a robotic vision system for sweet-pepper picking with good results [38]. The application of mechanical sensors can improve the safety and stability of the robot and avoid accidental injury situations in the robot's gripping process. Bao et al. designed a flexible pneumatic bending joint with both contact rigidity and gripping flexibility based on a flexible pneumatic actuator (FPA). They utilized the joint to design a fruit-picking end-effector that is capable of generating sufficient force to grasp fruits, such as apples, with sufficient active adaptability [39]. In addition, due to the complexity of the agricultural environment, a single sensor cannot meet the needs of agricultural robots. Multi-sensor information fusion technology is also the key to agricultural harvesting robots. A spherical fruit-harvesting-robot end-effector was developed by Liu et al. This end-effector is mainly for spherical fruits, using a two-finger gripper for fruit gripping and positioning and a laser device for fruit stalk cutting [36]. Meanwhile, the end-effector is equipped with different types of sensors, including a vacuum pressure sensor, a distance sensor, a proximity sensor, and a force sensor, which improves the reliability of the end-effector's work.

Since the 21st century, due to challenges such as light, branch and leaf shading, and fruit ripening of crops grown in field environments, the development of agricultural robotic end-effectors has gradually transitioned from mechanization to automation and moved

towards intelligent development [40]. The end-effectors have been developed from two finger to multi-finger, from rigid mechanical structure to soft materials, and from no sensor to carry the vision, mechanics, and other sensors. The robot end-effector moves toward the direction of less damage to fruits and vegetables and with higher precision. Overall, the robot-picking end-effector is developing and improving constantly, and its application range is also expanding. In the future, with the continuous updating and application of agricultural robotics, the robotic picking end-effector will be more efficient, diversified, and even intelligent, making a greater contribution to the development of agriculture and improving the efficiency of agricultural production.

2.2. Classification of End-Effectors

In the operation of fruit- and vegetable-picking robots, the end-effector is the first component that directly contacts the target of agricultural products and performs the task. Its material, structure, and working method have a significant impact on the productivity, operational precision, and quality of the target agricultural products of the fruit- and vegetable-picking robot. Thus, it also becomes the key component of the fruit- and vegetable-picking robot [41]. In a complex agricultural environment, different agricultural targets have various colors, sizes, surfaces, and other characteristics. Taking fruit picking and vegetable cutting as an example, researchers and scholars at home and abroad have developed a variety of end-effectors [42]. These end-effectors are categorized into four types in this paper, including a clamping-type end-effector, air-suction-type end-effector, suction-holding-type end-effector, and envelope-type end-effector. More detailed information is shown in Figure 3. Among them, the clamping end-effector realizes the target grasping through the mechanical clamping mechanism, including two finger, three finger, multi-finger, and other types. The air-suction end-effector fixes the target by means of the vacuum principle combined with suction cups and then realizes target picking, which is suitable for crop targets with a relatively small picking force. The pneumatic suction-type end-effectors act through the suction cup and other ways through the vacuum principle of negative pressure on the target for sucking to realize the target picking of the fruits. This way is suitable for the target where the picking force is relatively small. The suction-holding-type picking end-effector is a combination of a clamping type and an air-suction type. The suction cup will suck the fruit, and then, the clamping will further stabilize the fruit. This is suitable for the cluster growth of the fruit to avoid damage to the other fruits, as well as the leaves and branches. The envelope end-effector uses a cylinder structure on the target for wrapping and built-in scissors for picking; its versatility is relatively strong and suitable for the majority of fruits.

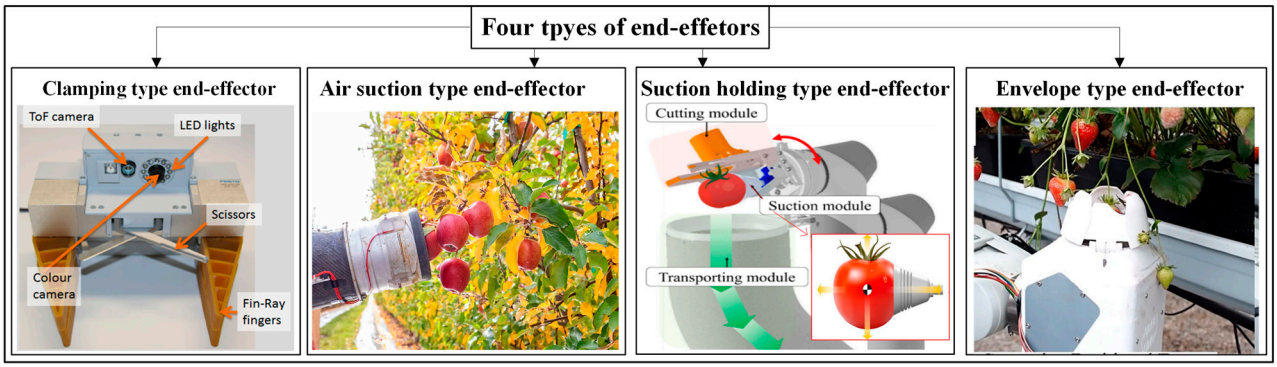


Figure 3. The schematic diagram of the four end-effector types.

2.2.1. Clamping Type End-Effector

The principle of the clamping-type end-effector is to hold the produce by mechanically gripping jaws or flexible fingers and to complete the picking by utilizing the built-in shearing device. This end-effector has been shown to be effective for products with high

stability requirements [43]. Applications have targeted larger, simple-shaped fruits, such as oranges, sweet peppers, and pumpkins. Apples, in particular, are the most suitable type of fruit for gripper-type end-effector picking. Prof. Manoj Karkee's team at Washington State University has made a great contribution to the research on mechanized apple harvesting and was the first to carry out large-scale field trials and applications of apple harvesting [44]. The literature [45] introduced a novel pneumatic 3D-printed soft robotic end-effector, which is mounted in a five-degree-of-freedom robotic system to achieve apple separation with the advantages of simple and low-cost separation steps. In addition, Sliwal et al. developed a seven-degree-of-freedom apple-harvesting robot, which first used a depth camera combined with a Hough-transformed circle to acquire apple information and then used a gripper end-effector with an open-loop three-finger structure to harvest apples with a harvesting success rate of 84% [46]. Miao et al. described a robot capable of picking apples automatically. The robot uses a gripper end-effector equipped with a high-definition camera and a depth camera, which allows for the identification and localization of ripe fruits by means of a target detection algorithm [47]. The end-effector is equipped with pressure sensors, displacement sensors, and a curved flexible structure that reduces the fruit damage caused by picking during the clamping process and stabilizes the apples by means of a two-finger gripper. In addition, Bac et al. evaluated a sweet-pepper-harvesting robot for the purpose of realizing the application of agricultural robots in commercial greenhouses, which have two types of end-effectors (Fin Ray and Lip) [48]. It demonstrated excellent performance in a complex environment with light variations, shading, and densely spaced obstacles, increasing harvest success from 6% to 26% for the Fin Ray and from 2% to 33% for the Lip Type. Goulart et al. developed a mango-harvesting robotic end-effector and, for the actuator's operation, evaluated the harvesting area, harvesting volume, and harvesting force [49]. In the research of agricultural picking robots, the gripper-type end-effector is the most researched and applied, and this type of end-effector has the advantages of effectively preventing shaking or falling during the shearing process and having a high shear force [50]. However, the picking speed may be slowed down by the gripper type of end-effector's limited adaptation to a variety of agricultural products, including tomatoes, watermelons, and others.

2.2.2. Air-Suction-Type End-Effector

The principle of the air-suction-type end-effector is that the produce is sucked inside the end-effector by means of an inhalation device, and after the shearing work is completed, the produce is sucked into the stowage structure. The air-suction end-effector is suitable for smaller-sized, lightweight targets, such as strawberries, tomatoes, and tea leaves, which require less suction for picking. Chiu et al. developed an end-effector for greenhouse-grown tomato picking that has an adsorption device at the center of the end-effector, which provides an optimal suction force to assist in enhancing the clamping performance [51]. The test results showed that the average adsorption success rate was 95.3%. A robot that can go deep into the canopy to pick apples was proposed by Zhang et al., who used a vacuum device to suck the apples tightly and then a rotating mechanism to pull them for picking [17]. The apples entered the storage device with the air ducts after the separation, and the buffer material in the air ducts can reduce the risk of damage to the apples due to bumping.

In fact, cotton and tea are the most suitable agricultural products for an air-suction-type end-effector due to their lightness. Fue et al. present a mobile vehicle for cotton harvesting, fitted with an end-effector that provides a vacuum suction, with the bolls being pumped into the hose by means of a 90 cm flexible plastic hose placed close to the bolls and connected to the end-effector at the other end. The other end is connected to the end-effector [52]. It can be seen that pneumatic suction has certain advantages for lightweight crops, and for fruits that are difficult to clamp, pneumatic suction devices that can enter deep into the fruit tree are a better choice. However, air-suction-type end-effector

systems usually require high power to generate sufficient suction force, which may increase the robot's energy consumption.

2.2.3. Suction-Holding-Type End-Effector

The suction-holding end-effector is a combination of an air-suction end-effector and a clamping end-effector, which is based on the principle of utilizing negative pressure to create suction, which attaches the produce to the actuator and then shears it off with the device. This type of end-effector is advantageous when handling soft, fragile, or irregularly shaped produce, such as strawberries, cherry tomatoes [53], and mushrooms [54], because it reduces the pressure on the produce, thereby decreasing the likelihood of damage.

The cherry-tomato-picking mechanism designed by Yonghyun Park utilizes an integrated design of cutting, suction, and transportation modules [18]. The end-effector works when the suction-cup vacuum sucks the fruit for fixation, the blade cuts the stems for picking, and the combination of cutter and suction cup is used to separate the fruit compared to clamping and direct pulling, which reduces damage to the fruit due to stress concentration. However, the device collection and picking time are slower; the average time of the whole picking process is 13.5 s. Saleh et al. fabricated three soft pneumatic end-effectors using 3D printers and worked on translating them into agricultural applications for fruit picking [55]. Fujinaga et al. introduced a suction-holding end-effector for tomato-picking robots and reported harvesting experiments in a tomato greenhouse [56]. The end-effector consists of a suction part and a cutting part. After the suction part sucks up the target fruit, a photoresistor determines whether the target fruit is harvestable or not. When the fruit is assessed to be harvestable, the cutting part cuts off its stems. The final experiment showed a success rate of 85%. Jun et al. proposed a tomato-harvesting robot that combines 3D sensing and manipulation. The end-effector was developed with suction pads for grasping individual tomatoes in a cluster [57]. The robot was validated and evaluated on a laboratory test bed and showed excellent results.

2.2.4. Envelope-Type End-Effector

The envelope-type end-effector uses a cylindrical or circular mechanism to cover all the agricultural products. Unlike clamping-type end-effectors, which apply force on both sides or at several points, wrapping mechanisms distribute force over the entire surface of an agricultural target. Its advantage is that through this "full wrap" approach, most agricultural products can be controlled more stably while reducing the single point of pressure on the surfaces of agricultural products, thus reducing damage. Although the envelope-type end-effectors are more difficult to design and manufacture, they show greater flexibility and adaptability when handling soft, fragile, or irregularly shaped agricultural products, such as apples, tomatoes, pineapples, and kiwifruit. Baeten et al. were the first to apply advanced industrial components to agricultural machinery, designing a flexible gripper for apple picking that consisted of a silicone funnel and a camera mounted inside [31]. In order to improve the robotic harvesting efficiency of fresh tomatoes, Feng et al. designed a tomato-intelligent picking robot [58]. The robot used an envelope-type end-effector to pick tomatoes, and a pouch filled with constant-pressure air was used inside the end-effector to prevent fruit damage. The test results illustrated that the successful rate of harvesting tomatoes was 83.9%. Guo et al. analyzed an enveloping end-effector for pineapple picking, which has a flexible and stable mechanical structure that allows the whole pineapple to coincide with the entire face of the fixture and reduces the stress concentration [59]. The end-effectors were also equipped with distance and force sensors for the precise positioning, gentle picking, and efficient collection of pineapples. However, the design and manufacture of this type of end-effector are more difficult, requiring a sophisticated mechanical structure and complex control system. For large and heavy agricultural products, a stronger holding force and finer control are needed to ensure the stable operation of the end-effector. The reasonable design of the picking end-effector not only affects the picking efficiency of the robot and the quality of agricultural products but

also directly relates to the operating performance and adaptability of the robot in a specific environment. With the speedy development of agricultural robotic technology, picking robots for different agricultural products have been developed, and the categories and working principles of end-effectors are also various.

Therefore, in addition to the four types of end-effectors mentioned above, there are various categories of end-effectors according to different categorization criteria. In the following, the end-effector of agricultural picking robots will be further categorized and discussed according to different categorization methods, as shown in Figure 4, to help the readers understand and select an end-effector suitable for specific agricultural product-picking work. Meanwhile, Table 1 further lists the end-effector's principles, characteristics, and operating objects, which will help scholars better design or select them to meet the targeted needs.

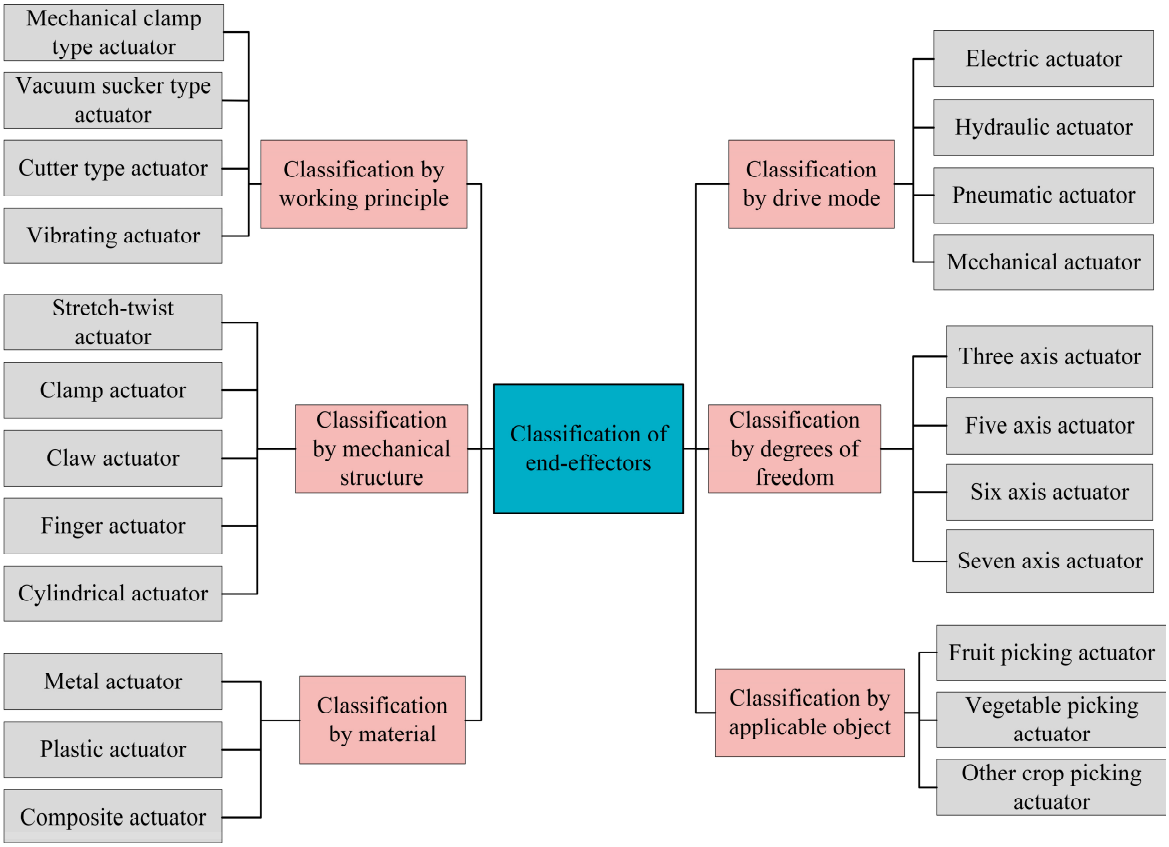


Figure 4. Classification chart of end-effector based on different criteria.

Table 1. Summary of detailed information on references in the end-effector category, including principles and application objectives.

Classification Criteria	Types	Application Objects	Principles	References
By working principle	Clamp type	Citrus, Sweet pepper, etc.	The motor controls claw opening and closing through a spring system	[60,61]
	Vacuum-sucker type	Strawberries, cherry tomato	Negative pressure is generated by the air pump so that the sucker is adsorbed to the target object	[17,18]
	Scissors actuators	Pineapple, guava, etc.	Cutting crops with blades that rotate or reciprocate at high speeds	[62,63]
	Vibrating actuator	Apple, jujube, oil tea, etc.	To shake trees or bushes by mechanical vibration to cause ripe fruit or fruit to fall	[64,65]

Table 1. *Cont.*

Classification Criteria	Types	Application Objects	Principles	References
By driver mode	Electric actuator	Blueberries, corn, etc.	The movement of the claw is controlled by the motor or the generator set	[66,67]
	Hydraulic actuator	Rice, corn, etc.	The hydraulic system provides power to control the fixture movement	[68,69]
	Pneumatic actuator	Pick, carry, etc.	A pneumatic system (helium) provides power to control fixture movement	[70]
By end mechanism	Clamp actuator	Sweet pepper, citrus, etc.	Through the clamping principle to grasp or cut the products	[43]
	Finger actuator	Apples, tomatoes, etc.	Composed of several small "fingers", including two fingers, three fingers, or more fingers	[71]
	Bionic actuator	Kiwi, citrus, etc.	Use the characteristics of plants or animals interface to imitate the design	[72]
By degrees of freedom	3 DOF	Cherry tomato	Including *x*-axis, *y*-axis, and *z*-axis, moving up and down, left and right, and rotating motion	[73,74]
	5 DOF	Sugar snap peas, etc.	Including three rotational motions and two translational motions	[75]
	6 DOF	Apple, etc.	Including three rotational motions and three translational motions	[76]
	7 DOF	Grape, etc.	Compared with 6DOF, more degrees of freedom of fixture	[21]
By material	Metal actuator	Pineapple, etc.	Made of high-stiffness steel, aluminum alloy, and titanium alloy	[77]
	Plastic actuator	Cotton, etc.	Made of thermoplastic materials such as polyimide (PI) and polypropylene (PP)	[78]
	Composite actuator	Apple, etc.	Made of high-strength and microweight materials such as carbon and glass fiber and aramid fiber	[53]
By applicable object	Fruits	Fruits	Design based on the characteristics of the fruit	[54]
	Vegetables	Vegetables	Design based on the characteristics of vegetables	[14]
	Other crop actuator	Mushroom, tea, etc.	Special end-effector designed for special crops	[79]

3. Advanced Technology for End-Effectors

The end-effector is one of the most commonly utilized components of agricultural picking robots. The end-effector's primary responsibility during the picking robot operation is to locate, select, and gather the target. End-effectors differ in their structural designs and operational principles depending on the agricultural application object and the working items they encounter [80]. However, the ultimate goal and standard of end-effector design are to guarantee product quality and safety, lower labor costs and working errors, and increase the picking robot's accuracy and efficiency. This necessitates that the end-effector has the following: (1) a simple, efficient, and suitable mechanical structure for the working object; (2) a fast and accurate target-recognition algorithm and intelligent grasping and control strategy, and (3) advanced sensors and new materials. This chapter will focus on the key advanced technologies involved in end-effectors.

3.1. Structural Design

The design goal of the end-effector is to achieve the automated harvest of the crop target, and it can be designed into different structural forms when facing different applica-

tion scenarios [81]. The first end-effectors to be developed were vibrators or pullers, which grabbed the ripe fruit, shook it directly from the tree, or violently separated it from the branch. This end-effector is therefore unfriendly towards fragile fruits or vegetables, causing damage to fruit and vegetable targets and reducing shelf life [82]. Therefore, the design process of high-quality end-effectors should comply with standard environment-based design specifications. We have classified the most studied and applied end-effectors in Section 2.2. The design process of these end-effectors mainly includes:

(1) Analysis of target requirements and mechanical characteristics. The demand analysis refers to the method of market research used to determine the picked objects, consider the needs of the market economy, and design the end-effector to ensure that it meets those needs. Target mechanical characteristics analysis refers to the mechanical tests performed on the pressure, shear, and torque resistance of the harvested object or fruit stem [43];
(2) End-effector structure and cutting scheme design. The structural design points to selecting the appropriate type of end-effector for the picking object. When the strength of the fruit stem of the picking object is low, the fruit stem should be selected as the working object. When the fruit is large, bright, and easy to identify, it should be selected as the working object. Cutting-plan design refers to when the strength of the stem is high and the strength of the fruit is low, the blade should be used to cut. When the strength of the stem is low and the strength of the fruit is high, anthropomorphic hand-cutting should be selected [19,83];
(3) Comprehensive design and mechanical analysis. The comprehensive design includes the choice of freedom, drive mode, and the design of the transmission chain, which should be analyzed and designed according to the size and shape of the operating object. Mechanical analysis is the use of analytical and experimental methods of mechanical synthesis of the manipulator to determine the working range, sensitivity, and size of the end-effector [84];
(4) Hardware and software design. Research and select hardware devices, such as plastics, metals, motors, tools, sensors, and batteries. Others include the design of hardware connections, mounting, and driving, as well as control electronic circuits (schematics and printed circuit board (PCB) design). Then, in order to effectively control the end-effector system, it is necessary to develop C++ or Python 3.0-based driver algorithms, navigation, and control strategies [85];
(5) System simulation and testing. Design the necessary components with known computer-aided design (CAD-2016) software applications. At the same time, a virtual model of the end-effector system can be constructed using the robot operating system (ROS), and the performance of the end-effector can be evaluated in the Gazebo simulation environment. Test the effectiveness of the end-effector through the test procedure, including recording applied forces, payloads, pressure control, energy requirements, control algorithm performance, etc. Measure the selected performance indicators (damage rate, picking time, etc.). Finally, by optimizing and fine-tuning the design of the end-effector, re-testing, and measuring the performance indicators, it is determined whether it is considered to be potentially usable.

3.2. Steps for End-Effector Grasping

Fast and accurate identification and positioning technology is the premise of robot automatic picking and the basis for ensuring the completeness of picking and improving the success rate. The end-effectors of picking robots developed by many scholars are equipped with corresponding visual cameras or sensors (also called eye on hand). The traditional method uses sensors or ordinary cameras to identify and locate target crops, which usually involves image acquisition, preprocessing, feature extraction, and target recognition. Cameras or optical sensors capture the visual information of crops [86]. The preprocessing includes image enhancement, noise reduction, and other operations to improve image quality and processing efficiency. Feature extraction extracts the crop's

visual features through various algorithms, and target recognition uses these features to train machine-learning models and builds models for analysis and detection [87]. With the update of computer-vision and image-processing technology, object-detection algorithms based on deep learning and the combination of 3D point cloud processing technology have inspired the problem of end-effector positioning in complex environments. The grasp of the end-effector also requires the technology of fixture pose planning. The robot uses kinematic planning and path-planning algorithms to determine the best path and fixture pose to reach the target object. Global path planning is responsible for finding a feasible route from the robot's current location to the target location.

In contrast, local path planning optimizes the robot's motion path to achieve smooth and efficient grasping based on global planning. Pose planning needs to determine the optimal attitude of the fixture in contact with the target object, which usually involves the calculation of the robot kinematics and inverse kinematics [81], followed by the control of the clamping force once the path and attitude are determined. The robot needs to adjust the clamping force according to the quality and weight of the target object and the physical characteristics of the fixture. This usually requires an exemplary force feedback system and complex control algorithms to achieve real-time monitoring and adjustment of the force, ensuring that the grasping process is stable and does not cause damage to the target object. A team from the University of Patras, Aeronautics, has developed a fuzzy controller-based layered control scheme for picking robots equipped with pressure profile sensors to improve the efficiency and successful rate of a strawberry-harvesting robot [88].

3.3. Artificial Intelligence (AI) Technology for End-Effector

With the rapid development of smart agriculture, artificial intelligence technology is widely used with the gripping scheme of the end-effectors of picking robots. The development of this gripping scheme started with the earliest static path planning and predefined fixture control. This scheme is simple, but in the face of small changes in the environment, such as small shifts in fruit maturity and location, it may decrease operational effectiveness. As machine-learning algorithms and deep-learning technology are introduced into the grasping strategy, the end-effector of the picking robot can identify and adapt to different farming products and environments. By analyzing the sensor data, the machine-learning models can identify the shape, size, and ripeness of fruits or vegetables, providing targeted control guidance to end-effectors [89]. Researchers employed the particle-swarm optimization approach in a paper titled "Optimizing UAV Agricultural Protection Operations" to plan the robot's course, which greatly increased the robot's productivity [90]. On the other hand, during the picking process of the robot, the position, shape, and surrounding environment of agricultural products may change, so the robot needs to respond quickly. The adaptive control system analyzes sensor feedback in real-time, uses instant decision-making, and adjusts the posture and strength of the robot to ensure that picking tasks can be completed efficiently and accurately in different situations. Deep-learning technology and reinforcement-learning (RL) technology have begun to play an important role, among which convolutional neural networks (CNN) and recurrent neural networks (RNN) have shown superior performance in target recognition and localization.

For example, the apple-picking robot visual inspection project from Jia et al. uses deep-learning methods for fruit identification and positioning, effectively improving the robot's operational accuracy [91]. In addition, some research also attempts to use imitation learning to teach robots human grasping strategies. Yi et al. introduced a humanoid robot arm grasping system, which trains the robot by allowing it to imitate human grasping movements, thus improving the robot's ability to grasp various objects, including agricultural products [82]. Moreover, deep reinforcement learning (DRL) optimizes the robot's motion path and fixture posture. The robot grasping project introduced by You et al. uses the Actor–Critic framework in DRL and priority experience replay (PER) to train the robot [92]. In conclusion, the gripping scheme of the end-effector of a picking robot has gone through

a process of development from simple rules to AI technology. It will continue to evolve more efficiently, accurately, and flexibly.

3.4. Additional Sensors for the End-Effector

Sensors are essential for fruit and vegetable-picking robots to sense target objects. The end-effector is equipped with various sensors, such as visual sensors, force/torque sensors, and tactile sensors, to obtain information about fruits and vegetables so that precise grasping can be carried out in actual operations [93]. Vision sensors are some of the most important sensors, including RGB cameras, depth cameras, spectrum cameras, etc. They can help robots obtain image information of fruits and vegetables and visual information from the surrounding environment [94]. Using computer-vision algorithms such as object detection, image segmentation, feature extraction, and deep learning, the robot can identify the target agricultural product from the original image and determine its location, shape, and size [80]. The application of force/torque sensors is mainly to control the clamping force of the mechanical clamps accurately. They can modify the clamp's strength to avoid damaging the crop by continuously monitoring the force the clamp is applying to it. At the same time, the force/torque sensor can also be used to detect the stability of the robot's grasping and provide real-time feedback on the grasping process to ensure the integrity of the crops. Tactile sensors can provide detailed sensory information on the crop's surface, such as avoiding excessive pressure on the crop and maintaining stable clamp gripping. The laser range finder can be used to measure the distance between fruits and vegetables and the robot, thereby determining the position and direction of the robot and providing a data basis for subsequent path planning and control strategies of the gripper.

3.4.1. Vision Sensors

Vision sensors, also known as optical sensors, rely on light to obtain information. Vision sensors can help agricultural robots accurately locate and identify targets by capturing information, such as the shape, color, and texture of crops [95]. For example, red–green–blue (RGB) cameras are usually used to capture red, green, and blue light colors to form full-color images, which can identify the color and texture of crops and determine whether the fruit is ripe. With the development of sensor technology, depth cameras (RGB-D cameras) have gradually replaced ordinary RGB cameras because they can provide more accurate depth information and scene-perception capabilities [96]. Especially with the improvement of deep-learning technology and algorithm computing power, it has been widely used in agricultural picking robots and other fields. RGB-D cameras can capture red, green, and blue colors of light and obtain depth information (D stands for depth) through infrared projection and infrared cameras or through ToF (time of flight) technology. Li et al. used an RGB-D camera and a deep-learning segmentation network, combined with a new cone point cloud processing method, to accurately locate occluded fruits and optimize agricultural robots' picking efficiency and accuracy in orchards [97]. In agricultural robots, infrared cameras can work at night or in dark environments. For example, Rath et al. developed an automated system for picking Gerbera jamesonii peduncles. The system uses image-analysis methods and a binocular stereo camera equipped with a near-infrared filter to identify peduncles [98]. Especially outdoors and in natural environments, infrared filters can help increase the contrast of an image, making specific details more visible. Hyperspectral cameras can capture a more comprehensive spectral range than conventional RGB cameras, which can be used to detect the physiological conditions of crops, such as detecting the moisture content or nutrient content of fruits by analyzing the reflectance spectra. Cho et al. use a support-vector classifier and snapshot hyperspectral imaging technology to develop a model that accurately identifies and classifies the maturity of hydroponic tomatoes, aiming to promote the automated development of greenhouse agriculture [99].

Vision sensors are frequently used in agricultural robots, but lighting conditions quickly affect their performance. For example, strong sunlight or dark light at night may

affect their recognition capabilities. In addition, the speed at which vision sensors process image information is limited by image quality and computing power, which may involve the work efficiency of agricultural robots.

3.4.2. Force/Torque Sensor

The force/torque sensor is a device capable of measuring and monitoring mechanical forces. Its primary operating principles are derived from capacitive, piezoelectric, or magnetoelectric effects, as well as resistive strain gauges. The force sensor is mostly employed on end-effectors in agricultural robot development to help manage the robot's clamping power and minimize the damage to crops caused by excessive clamping [100]. In particular, robotic arms equipped with force sensors can precisely control the clamping force on fruits, thereby achieving damage-free picking of fruits of various shapes and hardnesses. Among them, pressure sensors are most widely used in agricultural robots because they can accurately measure the pressure of liquids or gases at a low cost. In some particular agricultural scenarios, unique robots use hydraulic or pneumatic systems, and pressure sensors can be employed to monitor the system's working state [101]. Zhang et al. introduced a cherry-tomato-picking robot system, which establishes an optimal clamping model based on the information of the pressure sensor, reducing the damage caused by fruit slippage and uneven picking force [102]. You et al. showed a citrus-fruit-picking robot [80]. The robot uses various sensors to quantify multiple indicators of the picking process, including a vacuum pressure sensor to monitor the pressure in the suction cup and then perform precise control to reduce damage to the fruit.

The advantage of the force sensor is that it can monitor and adjust the operating force of the robot in real time to protect the safety of crops. However, the performance of force sensors is affected by environmental conditions, such as humidity, temperature, and electromagnetic interference, which requires close cooperation with the robot's control system to achieve precise force control.

3.4.3. Tactile Sensor

A tactile sensor is a sensor that can simulate the touch of human skin. Its working principle is mainly based on resistance, capacitance, or the piezoelectric effect [103]. In agricultural robots, tactile sensors are used as the end-effectors of agricultural picking robots, which can help the robot sense and control the force of contact with crops, thereby preventing damage to crops. The difference from mechanical sensors is that tactile sensors imitate human tactile sensation and can detect detailed force-distribution characteristics on the contact surface; they can not only measure the force's size but also sense its direction and change. Therefore, tactile sensors can provide richer information to help agricultural robots better understand their interactions with crops. Xie et al. tested a flexible gripper integrated with a multi-sensor network for safely grasping fragile fruits and other agricultural products to avoid slipping and damage [104]. Among them, tactile sensors play an essential role between the fingers of the gripper, improving the sensing and grasping capabilities. The advantage of tactile sensors is that they can provide rich contact information, which helps to enhance the operational accuracy and safety of agricultural robots. However, due to its advanced technology and high price, the prospect of large-scale application in agriculture is still worth looking forward to.

The application of sensing technology in agriculture has experienced rapid development. Modern picking robot end-effectors are equipped with essential vision and force sensors and more advanced sensors, such as 3D cameras, multispectral cameras, high-sensitivity force/torque sensors, and complex tactile sensors, making the picking operation more precise and efficient. Recent research has begun to explore combining deep-learning techniques with sensor technology. For example, deep-learning algorithms are used to process the output data of visual sensors to achieve more accurate target recognition and localization [105]. At the same time, reinforcement-learning algorithms are used to optimize the generation and execution of grasping strategies by receiving feedback from

force/torque sensors and tactile sensors. In addition, the development of new sensors also brings new possibilities for agricultural robot grasping strategies. For example, flexible and conductivity sensors can provide richer object surface information, while 3D cameras and lidar can provide more precise spatial information. These new sensors offer new tools for achieving more efficient and precise grasping strategies. For future agricultural robots, it is expected that more sensor types and modes will be developed, including more sophisticated tactile sensors, accurate depth sensors, and even olfactory sensors capable of sensing odors to identify better and assess crop maturity and quality.

3.5. New Materials for End-Effectors

As part of direct contact with agricultural products, the surface material of the end-effector is crucial for achieving the protection of farm products and efficient picking [106]. In recent years, the application of soft materials has attracted more and more attention in agricultural robot end-effectors. The flexibility and softness of soft robot end-effectors enable them to better adapt to irregular crop shapes and characteristics and reduce the risk of crop damage [107]. Through research on the application of soft materials, the design of deformable mechanical structures, and the integration of perception and control, agricultural robot end-effectors are developing in a more intelligent, adaptable, and precise direction in operation. The development process of the new materials of agricultural robot end-effectors is as follows.

(1) In the initial development stage of agricultural picking robots, the end-effectors mainly adopt rigid structures, such as mechanical grippers. Although these rigid structures can complete basic operating tasks, they have problems with the risk of damage and insufficient adaptability to weak, fragile, or deformed crops. Due to difficulties in using materials, in the initial stage, fruit-picking robots' identification and action sites were mostly at the fruit stems. The fruit stems are not easily damaged by clamping, but the identification is complex, and the efficiency could be higher. Bulanon et al. proposed an apple-picking end-effector made of aluminum [108]. During the picking process, the robot pinches the fruit stem with two fingers to pick. Generally, mechanical rigid structures are widely used in crops that are not easily affected by rigid materials. Ali Roshanianfard et al. have invented an end-effector for harvesting pumpkins. This end-effector has an electrically driven and internal impact gripping mode with a five-finger anthropomorphic manipulator that can be used to pick heavy crops with radii ranging from 76.2 to 265 mm [109]. This rigid material multi-finger manipulator has the advantage of harvesting a large mass of produce compared to soft manipulators;

(2) With the development of soft robot technology, people have begun to explore the application of soft materials (such as silicone, foam plastic, etc.) in the end-effectors of agricultural robots. Soft materials are soft, deformable, and adaptable and can better adapt to irregular crop shapes and terrains, reducing the risk of crop damage. Using soft grippers to grip crops provides better grip and protection. The current research on agricultural picking robots includes tomato-picking mechanisms [110], apple-picking end-effectors [111], etc.;

(3) As scholars conduct in-depth research on soft robots, people have begun to explore more complex soft structure designs. These structures are elastic and deformable, allowing the robot to better adapt to the shape and characteristics of various crops. For example, materials with adjustable hardness and elasticity can deform crops using motor drive or pneumatic methods to adjust to different shapes of crops and provide better gripping and operation capabilities. Zhou et al. proposed a flexible picking mechanism based on tomato characteristics [112]. The flexible clamp uses a fluid elastic material as an end-effector to realize the clamping action of tomatoes by adjusting the inflation pressure. Under static conditions, the optimized design of the gripper can successfully grip tomatoes 100 percent. Furthermore, by integrating advanced sensor technology and control systems, robots can better perceive crops' shape, position, and status and achieve precise control and operation.

4. Typical Application of End-Effector in Fruit and Vegetable Picking

4.1. Typical Fruit Picking

4.1.1. Apples

The apple is a fruit with rich nutritional value and has a wide planting area. It is also the main object of application when picking robots [47]. Most of the end-effectors used for apple picking are two-finger, three-finger, envelope, and air-suction types. Bulanon et al. proposed using visual servicing and laser ranging sensors to position apples and designed a two-finger end-effector (Figure 5a) to pick by twisting [108]. However, pulling or twisting end-effectors must avoid excessive picking force, which may cause apple damage. To solve these challenges, flexible end-effectors with force control and visual recognition have become the mainstream direction of research. Chen et al. designed a soft manipulator for apple picking (Figure 5b), which reduces the potential risk of damage to the apple skin during robotic picking by providing constant pressure clamping and avoiding fruit damage during the sliding process [113].

On the other hand, the apple tree trunk is tall, with many messy branches, and the location of complex fruits is widely distributed and shaded. Therefore, the end-effector must have a sufficiently large workspace and an adaptive adjustment function to ensure that it does not damage the target fruits during the picking process and make adjustments to ensure no or minimal damage to the fruit during picking. Xiong et al. proposed an apple-picking robot with a dual robotic arm configuration to adapt to the research and development needs of a typical "elevated" apple tree shape, ensuring coverage of the canopy area with the most compact mechanical structure [114]. They designed a dual robotic arm based on Cartesian coordinates (Figure 5c), with two sets of vertical synchronized operations and a three-degrees-of-freedom motion range to adapt to the spatial distribution characteristics of typical canopy fruits of dwarf and dense planting. When the manipulator cannot accurately approach the apples, the adsorption end-effector is also a good solution. Zhang et al. designed a vacuum-based adsorption end-effector for apple picking, which can move at a certain distance when sufficient vacuum flow is provided [17]. It attracts fruits internally and has the characteristics of zero error, as shown in Figure 5d. The back end of the end-effector is connected to the vacuum pump via flexible and expandable bellows, allowing for the appropriate flow rate and vacuum pressure to be used to grasp and separate fruits of different sizes while maintaining the agility to navigate inside and outside the canopy. The robot developed by Yu et al. uses a binocular vision system to detect apples and achieves picking effects through a mobile vehicle platform and a humanoid dual-arm system [115]. The apple recognition accuracy and harvest success rate are 82.5% and 72% (Figure 5e). Damage to the target during robot-picking operations is also a factor that needs to be considered. Therefore, more and more soft robot grippers have been developed. To reduce the fruit damage caused during picking, Miao et al. set up the end-effector [47]. A quadratic sequential programming method is utilized to optimize the compliant mechanism, enabling the end-effector to lessen the output force on the fruit. Taking apple picking as an example, it can provide a constant tightening force of 7.9 N, and the grasping success rate is approximately 95.3% (Figure 5f). The end-effector studies mentioned above are from schools and research institutes, but they are not sufficient for commercial applications.

It is worth noting that a number of mainstream companies have already commercialized apple-picking robots. Abundant Robotics, a mainstream agricultural robotics company, has automated apple picking using a vacuum-type end-effector combined with computer vision [116]. The company's self-developed vacuum-type end-effector is simple, and efficient and reduces losses to apples (Figure 5g). The picking robots developed by FFRobotics from Israel use multiple arms with forked "fingers" to grasp and pick apples from trees [117], and their gripper-type end-effector adds three-dimensional motion to the existing torsional motion for cleaner apple picking (Figure 5h). The robots have been sold to growers and are commercially available with a payback in three years.

In conclusion, apples have the characteristics of complicated skin and easy separation of the fruit and fruit stem. They can be harvested by pulling, twisting, or shaking without the use of scissors. The end-effector for apple picking has gone through a design process from vibratory picking to mechanical picking, to soft actuators carrying flexible materials. More and more scholars have made technological breakthroughs in the recognition accuracy, picking success rate, average harvesting time, and maximum gripping force of apple-picking end-effectors, so the apple-picking robots are most promising for realizing large-scale applications and making a greater contribution to the development of agricultural automation robots.

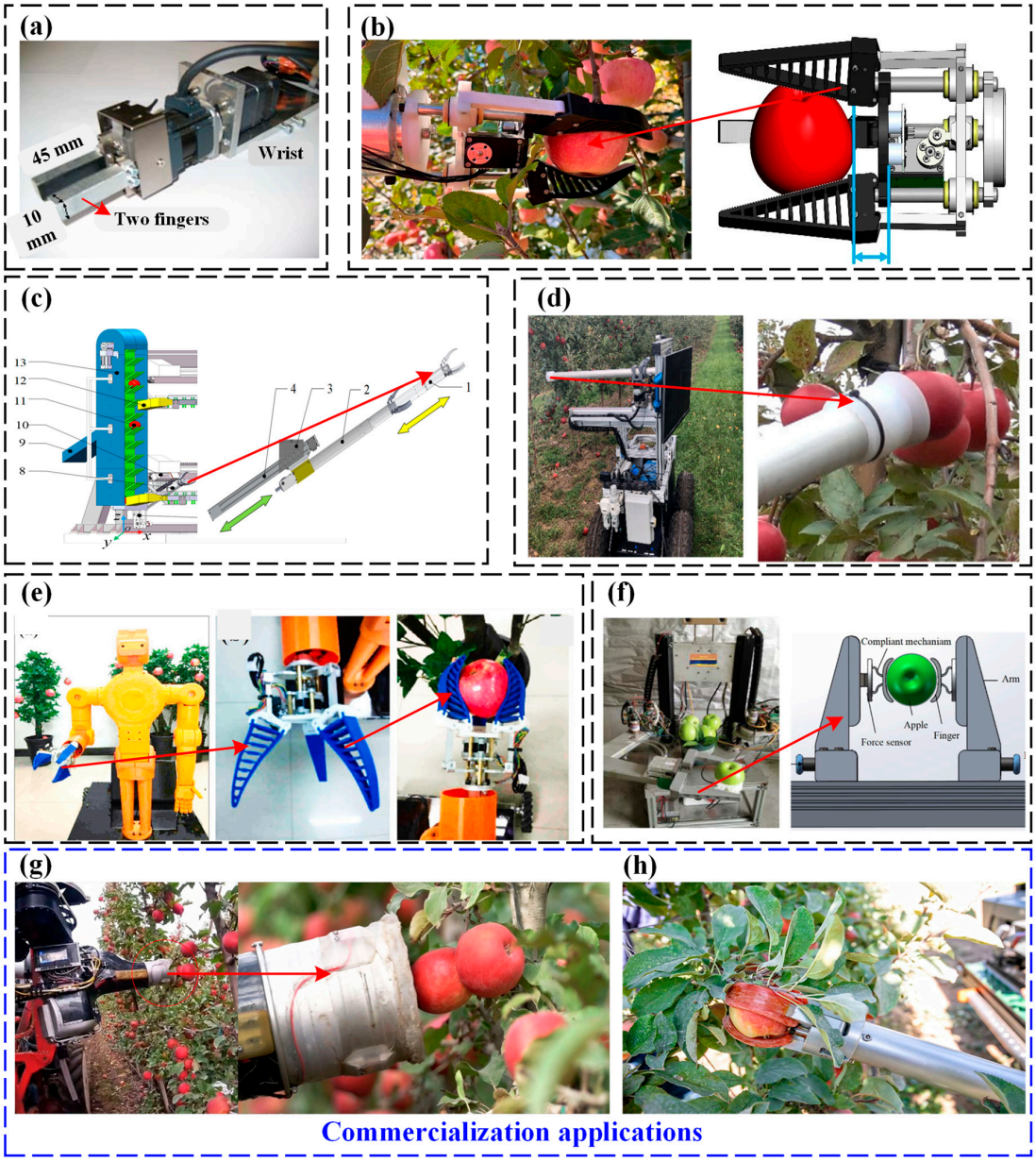


Figure 5. Typical application of end-effector for apple picking. (**a**) A sample two-finger end-effector proposed by Bulanon et al. [105]. (**b**) A soft three-finger end-effector for apple picking designed by Chen et al. [109]. (**c**) An apple-picking robot with a dual robotic arm developed by Xiong et al. [110]. (**d**) A vacuum-based adsorption end-effector for apple picking designed by Zhang et al. [17]. (**e**) A humanoid dual-arm system developed by Yu et al. [112]. (**f**) A two-finger end-effector with a force sensor [47]. (**g**) An apple picking end-effector developed by Abundant Robotics [116]. (**h**) An apple picking end-effector developed by FFRobotics [117].

4.1.2. Citrus and Oranges

Citrus and orange are also representatives of hard fruits. Unlike apples, citrus and oranges have soft skin, an effective buffer for the mechanical end-effector to grasp, and can reduce damage. Considering citrus's shape and surface characteristics and its growth characteristics on fruit trees, suction-holding and clamping-type end-effectors are most commonly used in citrus research scenarios. You and Burks developed a suction-holding gripper device (Figure 6a), which utilizes a gripping force controller to grasp oranges or tangerines firmly and safely and then uses rotating and pulling actions to target the fruit [80]. In addition to the suction-held end-effector, the clamping end-effector is the most used in citrus-picking robot research. To improve the success rate and consistency rate of citrus stem picking, Yin et al. designed a new end-effector with a fork-shaped cutting mechanism (Figure 6b) [118]. The end-effector can imitate the action sequence of manual picking and cut the harvested citrus stems into standard lengths. In particular, a linear radar is installed at the bottom of the end-effector to measure the feeding depth of citrus with a resolution of 1 mm, and then the stepper motor is controlled to cut the fruit.

The overall picking success rate reaches 87.2%, effectively solving the problem of stiff citrus stems—short and hidden questions. To shorten the robot's working time, Tang et al. designed a simple three-finger end-effector combined with a robotic arm motion-planning algorithm, which can effectively perform picking [119]. Mehta et al. developed a citrus-picking robot based on vision control using a three-finger end-effector [120]. Interestingly, the end-effector is equipped with a near-infrared sensor to detect the presence of fruit and performs picking based on a visual servo controller. Also, with a three-finger end-effector, Chen Meng et al. designed a universal spherical fruit-picking end-effector based on adaptive [121] flexible force clamping (Figure 6c). The end-effector is a pneumatic structure and is equipped with a variety of sensors. The visual sensor is used to identify the type of fruit. The pressure sensor adjusts the pressure output in real time, and the torque sensor adjusts the strength of the torsional fruit. It has good versatility and flexibility. Xiao et al. designed a three-finger clamping end-effector (Figure 6d) based on the principle of manual citrus picking [122]. The end-effector can stably grasp citrus fruits and effectively cut them. The picking action includes rotating and pulling the fruits to improve the success rate and reduce peel damage. The end-effector excels in time efficiency and success rate. The end-effector that You and Burks built performs exceptionally well regarding fruit removal rate, particularly when handling fruits with unusual shapes. It also offers more substantial benefits in terms of design freedom. In addition, bionic picking is also an emerging research topic. Wang et al. described the growth direction of citrus in natural orchards. They designed a citrus-picking end-effector with a bite structure by simulating the head mechanism of a snake, which effectively improves the performance of citrus picking [123].

In particular, the working errors of picking robots are accumulated from visual positioning errors, robotic arm control errors, end-effector system errors, etc., which will seriously interfere with the picking work of the robotic arms. Studying the systematic errors of the picking end-effector is also a focus. Nowadays, some end-effectors cannot tolerate these errors and are unsuitable for use. Zou et al. designed an end-effector with a universal fault-tolerant structure to solve the problem of binocular vision positioning error [124]. By modeling the relationship between the end-effector and the picking tool, a fault-tolerant mathematical model was established. The citrus- and lychee-picking experiments were completed within the error range, and the indoor picking success rate exceeded 84%, verifying the applicability of the fault-tolerant design. From the above literature, it can be concluded that the suction-holding end-effector can achieve stable picking of citrus by utilizing vacuum suction, especially when the surface of the citrus is smooth and easily forms a seal. This method will not produce excessive pressure on the surface of the citrus and better protect its integrity. However, the environment, such as temperature, humidity, etc., may affect this method and the adsorption force. In addition, if there is dirt on the surface of the citrus, it may affect the contact between the suction cup and the surface of

the citrus, reducing the adsorption force. In contrast, the clamping end-effector is more suitable for handling citrus with rough surfaces or irregular shapes. This method grabs and releases citrus by closing and opening the mechanical claw. The advantage of the clamping-type end-effector is that the gripping force is stable and not easily affected by the environment. The claw's strength and shape can be adjusted to adapt to citrus of different sizes and shapes, including two-finger or three-finger types. However, the clamping-type end-effector may exert pressure on the surface of the citrus, which may damage the citrus if the force is too great. Therefore, the research focus will be end-effectors with strong picking versatility, stable clamping, and no damage to fruits.

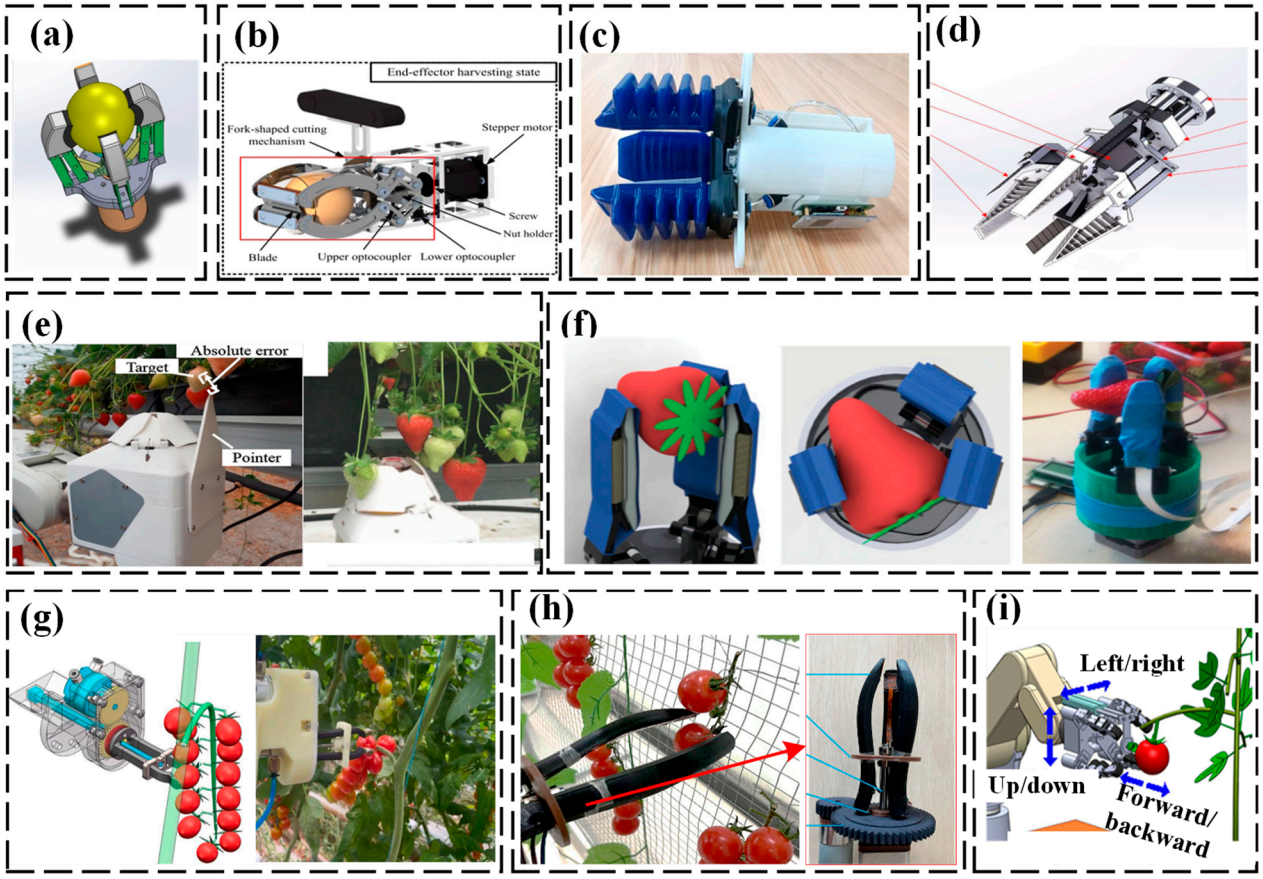


Figure 6. Typical application of end-effector for other fruit picking. (**a**) A suction-holding gripper device that utilizes a gripping force controller [80]. (**b**) A new end-effector with a fork-shaped cutting mechanism [118]. (**c**) A pneumatic structure with a variety of sensors [121]. (**d**) A three-finger clamping end-effector [122]. (**e**) A suction cup-type end-effector for strawberry picking [20]. (**f**) A flexible three-finger end-effector for Strawberry picking [88]. (**g**) A pneumatic finger-like end-effector for cherry tomato picking [68]. (**h**) An end-effector by 3D printing [102]. (**i**) An integrated design of cutting, suction, and transport modules [18].

4.1.3. Strawberries

Strawberries are one of the leading commercial crops in greenhouses. Due to the remarkable color characteristics of its fruits (ripe and immature) and its ease of large-scale cultivation, many research results have been achieved for the mechanized picking of strawberries. However, strawberries are soft and do not have a hard shell. After the skin is damaged, it deteriorates straightforwardly. Therefore, mechanical picking end-effectors are unsuitable, and air-suction-type end-effectors have received more attention. Ya Xiong et al. developed an air-suction-type end-effector (Figure 6e) [20,125]. The picking principle is to suck in the target strawberry from below to avoid damaging the front branches and

immature strawberries. In addition, the built-in infrared sensor can correct the shape and position errors, thereby improving accuracy and efficiency. Satoshi Yamamoto et al. designed a hybrid envelope and suction-cup end-effector that includes a suction cup, two fingers, three nozzles, an air claw, and an air slider [126]. The end-effector detects and fixes the target fruit through the suction cup and fingers. Then, it uses a nozzle to separate the fruit from its pedicle and pull it out at an angle of 70°. Fotios Dimeas et al. designed a flexible three-finger end-effector (Figure 6f) to reduce the clamping force on strawberries, using three identical fingers to distribute the contact force evenly [88]. The finger clamp is made of polyurethane foam. It picks up strawberries and disperses the force according to their characteristic geometry to prevent damage to the fruit. In addition, the sensor array on the finger can detect and reposition issues such as offset and uneven force distribution. Shigehiko Hayashi et al. developed a cylindrical cutter-type end-effector that combined machine-vision technology to determine the location and maturity of the fruit and then positioned and cut the strawberry pedicels [127]. The picking success rate was 54.9%. Because strawberries grow intensively and mature and unripe fruits grow close together in clusters, the effectiveness of the sensing systems currently on the market still needs to be improved. Therefore, Soran Parsa et al. developed and designed a novel end-effector that can remove occluded or overlapping fruits and collect target strawberries without any contact with the fruits with a success rate of 83% and avoid collision problems [128]. The strawberry-picking end-effector invented by Yaohui Zhang has excellent maneuverability and adaptability and can efficiently and automatically pick strawberries in complex and rugged planting environments [129]. By accurately building the kinematic model and solving the Jacobi condition number, the accuracy and stability of the robotic arm in strawberry-picking operations are guaranteed.

Each end-effector designed for strawberry picking has its unique structure and picking principle. The unified goal is to improve picking accuracy and efficiency and reduce the damage to strawberries [130]. At the same time, performance metrics are essential for evaluating these systems. For the study by Ya Xiong et al., the picking success rate is as high as 96.8%, and the picking cycle time is also relatively short, indicating that it performs well in terms of accuracy and efficiency. The end-effector Satoshi Yamamoto and associates designed has a slightly longer average picking time but exhibits good stability and a modest picking mistake. At the same time, the end-effector uses complex combinations such as suction cups, fingers, and nozzles and can also handle fruits of different types and ripeness levels. The design by Fotios Dimeas and others focuses on reducing stress on the fruit and avoiding damage to the fruit during the picking process. Their innovative design of fingers and considerations of force distribution may show advantages in specific application scenarios, such as for fragile or specially shaped fruits. The system of Shigehiko Hayashi and others is innovative for combining machine vision and end-effectors. The entire picking process is automated through machine vision to determine the location and maturity of the fruit, as well as the cutting and confirmation operations of the end-effector. Although the test results show that the strawberry harvest success rate is slightly lower, this may be related to factors such as the actual operating environment and fruit maturity.

Unlike the end-effector mentioned above, the strawberry-picking end-effector invented by Yaohui Zhang and others was designed with a fully considered rugged mountain planting environment. It adopts a P-R-R-P-R-R structure design and optimizes the movement trajectory, making it easier to adapt to narrow spaces. At the same time, it adopts a sturdy and durable structure to withstand torque enough to ensure the long-term stable operation of the robot in the mountains. In addition to the problem of strawberry picking, strawberry yield estimation is also a problem encountered by large strawberry farmers during the picking process. Farangis Anjom et al. introduced the development and application of a strawberry-picking vehicle in yield mapping [131]. After the strawberries are harvested manually, they are placed in trays on picking trucks. The “smart” picking vehicles they designed include sensors such as load units, real-time kinematics (RTK), global positioning systems (GPS), microcontrollers, and inertial measurement units (IMUs) to

assist in synchronizing work with pallet-transport robots during the strawberry-harvesting process, and they created the yield diagrams of the strawberry field. In short, for a particular fruit like the strawberry, different design systems have their advantages and areas for improvement, and which system to choose may need to take into account the needs of practical applications. At the same time, to evaluate these systems more comprehensively, more field test data and long-term operational feedback may be needed.

4.1.4. Cherry Tomatoes

The biological characteristics of cherry tomatoes are similar to strawberries; they are easily damaged fruits. Care must be taken to avoid damaging the fruit during the picking process, so most research on air-suction-type end-effectors has been conducted. Jin Gao et al. designed a pneumatic finger-like end-effector (Figure 6g), which combines RGB-D cameras and force sensors to pick cherry tomatoes by clamping and rotating [71]. The maximum movement speed is six cm/s. The experimental results show that the picking success rates of the end-effector in the right, rear, left, and front directions are 84%, 83.3%, 79.8%, and 69.4%, respectively. The end-effector (Figure 6h) designed by Fu Zhang et al. uses a multi-stage picking strategy to imitate the process of human hands grabbing cherry tomatoes [102]. The material of this end-effector is made by 3D printing, with a picking success rate of 95.82% and a damage rate of only 2.9%. Yonghyun Park et al. adopted an integrated design of cutting, suction, and transport modules, using visual, tactile, and infrared sensors to achieve the goal of efficient harvest [18]. Kehong Zhou and others used physics and genetic algorithms to optimize the design of a specially designed flexible robot finger based on tomato characteristics and the simulation results of the fingers, which can be used to clamp and handle tomatoes while avoiding damage to them accurately [112].

The above four end-effectors have specific differences in design concepts, working methods, and manufacturing materials. These differences lead to changes in their performance indicators. Jin Gao et al. used a pneumatic finger-like design. Although this design is relatively stable during the picking process, its success rate could be much higher compared with other end-effectors. This may be attributed to its design, with a maximum distance of 38 mm and a minimum distance of 20 mm between the fingers, which may cause difficulty in the handling of larger or smaller tomatoes. In contrast, Fu Zhang et al. used a two-stage movement strategy and adopted finger grasping. Its fingers are designed with sinusoidal contours to mimic grasping a cherry tomato with a human hand. This design concept performs well in terms of picking success and damage rates but may also lead to possible challenges when handling tomatoes of different sizes. The flexible end-effector designed by Jin Gao adopts a fluid elastomer end-effector, which enhances its picking flexibility to a certain extent. Yonghyun Park and others adopted a design that integrates cutting, suction, and transport modules, which is more efficient in the processing process but may require more equipment support and a more complex control system. The end-effector designed by Kehong Zhou could clamp tomatoes successfully, with a success rate of 97%, without causing damage to the tomatoes in either static or dynamic clamping tests. However, when the inflation pressure is lower than optimal, the four-chamber finger will be in a static state, which may affect its average working efficiency. Also, Yurni Oktarina et al. introduced an agricultural robot for picking red and green tomatoes [132]. They used a simple image-processing method to adapt to the partial computing resources of the processor while customizing the end-effector according to the size of the tomato tree and tomatoes. The results showed that the average time for collecting red tomatoes was 4.932 s and 5.276 s for green tomatoes, proving the effectiveness of this design as an agricultural robot. In addition, a more interesting end-effector was designed by Azamat Yeshmukhametov et al. They created an end-effector with a hemispherical shape by calculating the average size of cherry tomatoes, and they designed a cutting blade on the edge of the effector to cut tomatoes and other spherical objects passively [133]. Chiu et al. aim to develop a grip-type end-effector for tomato-picking robots grown in greenhouses [51]. The end-effector is designed with four fingers, and there are foam sponge pads inside the fingers to reduce

the damage to the fruit when grabbing (Figure 6i). The center of the end-effector is a fruit suction device, which can fix the fruit inside the end-effector, improving grip performance. Qunwen Vu et al. analyzed the advantages and disadvantages of existing tomato-picking grippers, proposed an enhanced solution for vacuum combined with suction manipulators, and developed a four-finger manipulator end-effector with a vacuum nozzle inside. The innovation lies in the vacuum [134]. The system uses linear motion and is independently driven, improving the end-effector's flexibility.

In summary, for soft and juicy fruits like cherry tomatoes [135] and strawberries, the design of picking end-effectors needs to consider the fruit's biological characteristics to ensure that the fruit is not damaged during the picking process. The leading solutions are summarized as follows: (1) consider using flexible materials, such as soft robotics, to make end-effectors to reduce the pressure on the fruit; (2) design an end-effector with an adaptive adjustment function, which can adjust the gripping force and gripping space according to different sizes and shapes of target fruits to realize the versatility of this end-effector; (3) use image-recognition and deep-learning techniques to ensure that the end-effector can identify fruits with moderate maturity and avoid picking immature or overripe fruits while, simultaneously, the end-effector can accurately position fruits in complex environments; (4) design an end-effector with precise force control that can apply appropriate force to the fruit during picking to avoid damage; and (5) design a small, precise cutting mechanism to cut off the connection between the fruit and stem to ensure the fruit is intact.

4.2. Typical Vegetable Picking

4.2.1. Sweet Peppers

The wweet pepper is one of the most consumed vegetables suitable for large-scale greenhouse cultivation. Sweet peppers are large and round, and their stems are thick and difficult to pull or twist. This requires the end-effector to have robust grasping and shearing capabilities. Therefore, an envelope-type picking device can be designed. Grasp and use a sharp knife to cut the stems one at a time. On the other hand, the stems of sweet peppers are short, and sweet peppers often grow densely, which also requires the end-effector to pick accurately.

Wageningen University and the Research Center have made good progress in the mechanized harvesting of sweet peppers. Bac and Hemming et al. developed and evaluated an autonomous robot for commercial greenhouse sweet-pepper harvesting using two types of end-effectors (Figure 7a). The performance of the end-effector was tested in complex environments with different lighting changes, weather conditions, and occlusion. The test results included the number of picked fruits, positioning errors, execution times, cutting failures, and other indicators. In addition, the impact of picking posture on robot picking was also discussed. Habegger et al. also designed two end-effectors [136]. One is a two-finger end-effector (Figure 7b), which uses a pneumatic slider and a rubber clamp to directly grasp the stems of sweet-pepper fruits and is equipped with a high-torque brushless direct current (DC) motor. Then, a driven blade is used to cut the stem. This design ensures the plant or fruit is not damaged while achieving the correct fruit stem cutting at a slight angle. However, the missed harvest rate of this equipment is about 25.32%, and the fruit damage rate is approximately 38.38%. The picking effect needs to be improved. Another four-finger end-effector uses an arc-shaped gripper to hold the fruit and is equipped with a pneumatic valve-driven scissor-type mechanism to cut the fruit handle. However, this design is unsuitable for handling densely grown sweet-pepper fruits due to the increased number of fingers. The performance is poor, with a missed harvest rate of approximately 25.53% and a fruit damage rate of roughly 40.16%. When cutting the fruit stems, the stems are prone to being squashed, requiring multiple cuts to succeed. The end-effector developed by Christopher Lehnert performed well in sweet-pepper harvesting, with a separation rate as high as 92%, effectively overcoming the problems of large sweet-pepper fruits and thick fruit stems that are difficult to cut [137]. This kind of end-effector has a gripping, solid force. The fruit handle clamping or enveloping device can firmly grasp the fruit and cut off

the fruit handle at one time, achieving efficient and reliable harvesting. Image-recognition auxiliary end-effectors are often used to position the fruit stem accurately to avoid damage to other fruits. However, when it comes to different varieties, there are more challenges due to having shorter, thicker fruit stalks, so the success rate is lower. Boaz Arad et al. developed a vibrating knife-type end-effector, which relies on a six-degrees-of-freedom mechanical arm and a motor-driven vibrating knife to cut the fruit handle [138]. It is equipped with a six-finger metal clip covered in soft plastic, but its workability needs to be evaluated in further trials.

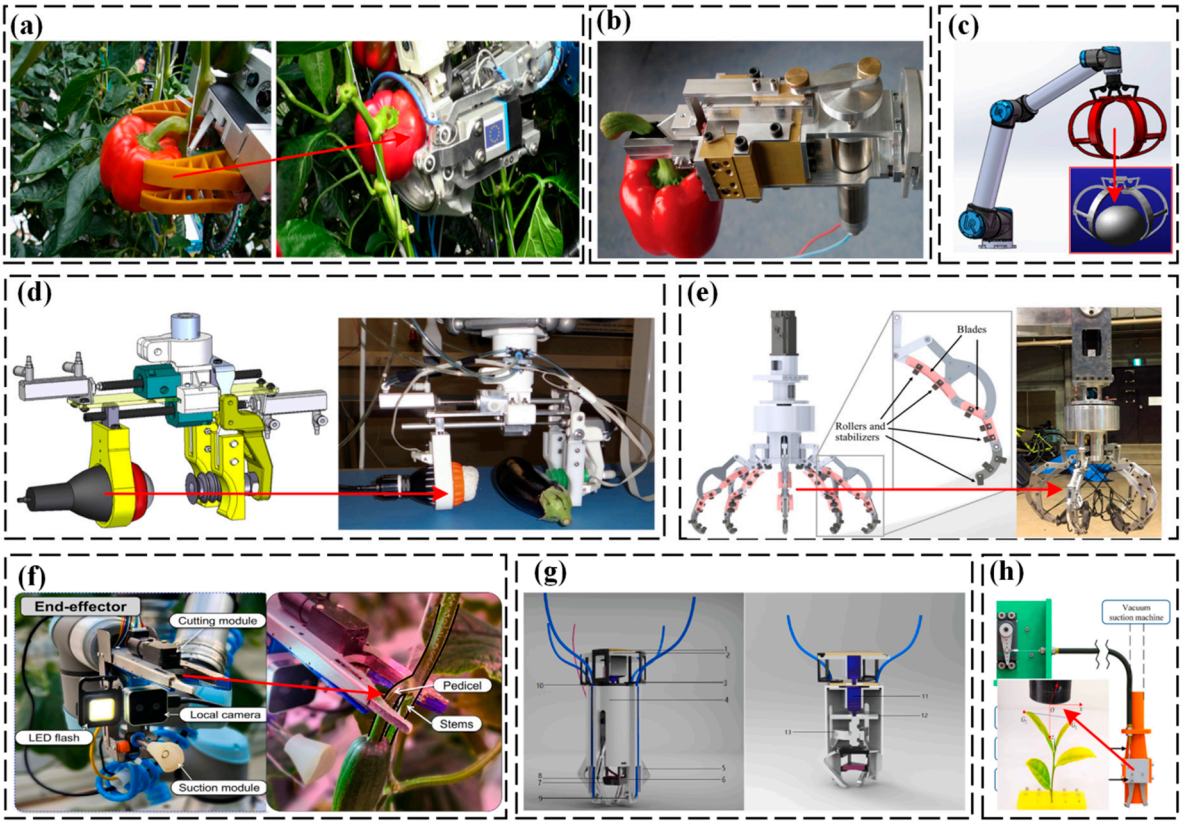


Figure 7. Typical application of end-effector for vegetable picking. (**a**) The end-effector (fin ray; lip type) was designed by Bac and Hemming et al. [48]. (**b**) A new two-finger end-effector for sweet-pepper picking [136]. (**c**) An end-effector for pumpkin picking [139]. (**d**) A three-finger end-effector with an additional tactile sensor for eggplant picking [140]. (**e**) An anthropomorphic end-effector for pumpkin picking [61]. (**f**) A suction-holding end-effector for cucumber picking [18]. (**g**) An envelope-type end-effector for tea picking [141]. (**h**) An air-suction-type end-effector for tea picking [142].

In conclusion, the design options regarding the end-effector for sweet-pepper harvesting have their advantages and disadvantages. However, they all strive to improve the efficiency and accuracy of automatic sweet-pepper harvesting while minimizing the damage. At the same time, they can provide valuable references and insights for the development of automatic harvesting technology for sweet peppers.

4.2.2. Eggplants

Eggplant is a common vegetable crop in greenhouses, and its shape is usually oblong or oval. Eggplants change significantly in size during their growth. Therefore, when designing a harvesting end-effector for eggplants, several key factors need to be considered, including adapting to targets of various shapes, sizes, and occlusion environments while having a certain degree of adaptability and flexibility. Therefore, clamp-type or finger-type end-effectors are most suitable for eggplant picking. Due to eggplants' irregular shape

and considerable weight, envelope-type or adsorption-type end-effectors are limited. An eggplant-picking robot system based on visual detection and a manipulator control model was developed by Shigehiko et al. This system developed an end-effector composed of a fruit-grabbing mechanism, a size judgment mechanism, and a cutting mechanism that can successfully cut the eggplant [30]. The eggplant harvesting robot designed by Delta Sepulveda et al. consists of a dual-arm robot system and sensors [143].

The additional three-finger end-effector can provide a maximum clamping force of 40 N. After the robot's vision system detects the eggplant by capturing infrared light from the surrounding environment and combining it with the planning algorithm, the fingers perform a contraction movement to grab the eggplant, and the subsequent cutting device cuts off the fruit stem to achieve the picking function. The test performance indicators showed that the eggplant-recognition success rate was as high as 97.4%. Even if leaves and other debris block the eggplant, it can achieve a recognition success rate of more than 94%. The picking success rate is as high as 91.67%, realizing automated picking of eggplants to a certain extent. Carlos Blanes et al. designed a three-finger end-effector with an additional tactile sensor (Figure 7d), which uses three mechanical fingers to grasp eggplants with a vacuum suction cup between two fingers [140,144]. The mechanical fingers can be inflated until the value returned by the tactile sensor reaches a particular value and then stops, working together with the vacuum suction cup to grasp the eggplant. However, performance metrics for this design have not yet been given, so more empirical data is needed to evaluate its effectiveness and potential. In short, eggplants are usually picked by shearing with a clamping end-effector, and the shearing point is located at the stem of the eggplant. This part is challenging and requires greater force to cut; in addition, inappropriate cutting positions may affect the eggplants' quality and later storage. Although the skin of the eggplant is thick and has specific pressure resistance, the internal tissue of the eggplant is relatively delicate, which requires high picking intensity and method. Excessive picking intensity may cause internal damage to the eggplant and even affect its commercial product—value and storage life. Therefore, on the one hand, the end-effector has precise positioning and cutting capabilities to cut at the correct position. On the other hand, it needs to have exact force control capabilities to ensure that the eggplant can be effectively separated from the plant during the picking process. It will not cause damage to the eggplant.

4.2.3. Pumpkins

Pumpkin is a particular food. Because its skin is relatively thick, it has a high tolerance for picking force. Therefore, the end-effector for picking pumpkins can be loose regarding force control. However, pumpkins are relatively giant in size and weight, usually with a mass of 3 kg. Therefore, the end-effector needs to have a sufficient load-bearing capacity and stability, which places higher requirements on the picking end-effector. The end-effectors currently used for picking pumpkins are mainly of the envelope type because the envelope-type end-effectors can provide sufficient carrying capacity to ensure that the robot can pick pumpkins safely and stably. Ali Roshanianfard et al. designed an anthropomorphic end-effector based on a pumpkin's shape, appearance, and other characteristics [145], as shown in Figure 7e. Featuring an electric drive and an internal impact-grabbing mode, this end-effector can grab and harvest heavy crops with a radius ranging from 76.2 to 265 mm, considering the sustainable force distribution. Its control unit consists of a programmable logic controller (PLC) system, computer, positioning board, amplifier, servo motor, switch device, and emergency switch. By inputting the coordinates of the pumpkin into the PC, and after analysis by the control algorithm, the PC sends relevant commands to the servo motor and switch unit to achieve precise control. This end-effector can harvest different varieties of pumpkins because its radius, volume, and mass size range can cover the physical parameters of other varieties of pumpkins.

In addition, since pumpkins may be covered by leaves and other plants, causing them to be obscured, it is necessary to research and design end-effectors that can work with

visual recognition systems to find and pick pumpkins accurately. Liangliang Yang et al. optimized the design of the pumpkin-picking end-effector based on the size parameters of pumpkins (Figure 7c) [139]. By establishing a four-bar linkage model, the Automatic Dynamic Analysis of Mechanical Systems (ADAMS) was used to simulate the grabbing and releasing actions of the end-effector. Finally, the end-effector can be mounted on the robotic arm with the camera to pick pumpkins.

4.2.4. Cucumbers

The cucumber is a vegetable grown on a large scale in greenhouses. Due to its elongated shape and little color change, cucumber-picking robots mainly use clamping end-effectors. Qian et al. designed an end-effector for picking cucumbers. Parameters such as the compressive characteristics of cucumbers and the fruit stalk cutting resistance were determined, and an end-effector consisting of a pneumatic end-effector and a cutter was developed. The relationship between the value of the pneumatic pressure in the pneumatic end-effector and the grasping capacity was analyzed, which improved the ability of the end-effector to grasp cucumbers [146]. Yonghyun Park developed an efficient cucumber-picking robot solution using a vision system to identify cucumber-picking stems and designed a suction-holding end-effector (Figure 7f) [147]. This end-effector uses a compact circular saw-type end-effector. The circular saw-type mechanism at the upper end of the end-effector is used to cut cucumber stems, and the adsorption device at the lower end is used to fix the cucumbers. However, it can imitate a human manual collection mechanism but with a larger picking end-effector due to the introduction of a servo motor. Yuseung et al. further improved the suction-cup soft robotic gripper, which can adjust its shape and surface parameters according to the surface and shape characteristics of the cucumber, increase the effective radius related to the gripping force, and improve the adsorption force on the surface of the cucumber. The experimental test results showed that the success rate reached 86.2%, and the damage rate was 4.7% [148].

Therefore, for cucumber crops with a larger mass and appearance, envelope-type end-effectors are the best choice because they can provide sufficient support. On the contrary, this brings troubles to the robot's structural design and the manipulator's load-bearing capacity, so the optimal design of the flexible material and structure of the end-effector should be the subject of great interest.

4.3. Other Special Crops

4.3.1. Mushrooms

Mushrooms are an exceptional fungus crop cultivated on a large scale in greenhouses because of their rich nutritional value and high price. Research on mechanized mushroom harvesting started early, but mushrooms are characterized by their small size, soft texture, and large growing area, which exerts challenges for manual harvesting. When machine harvesting of mushrooms is used, the end-effector must accurately separate the mushroom from the base to prevent damage to the mushroom. Reed et al. have achieved some critical results. The end-effector they designed has a high mushroom-positioning accuracy of more than 90%, significantly improving picking accuracy and efficiency [149,150]. At the same time, their equipment allows the suction cup to rotate approximately 120°, improving the flexibility and adaptability of the device. In addition, an appropriate strength is also a critical evaluation index in the mushroom-picking process. The suction-holding end-effector uses the adsorption force generated by the vacuum to achieve precise picking without damaging the mushrooms. Shuzhen Yang et al. proposed a new type of mushroom-picking end-effector that adopts the vacuum negative pressure picking principle [151]. It can fully use the smoothness of the mushroom's surface to generate a strong adsorption force and stably grasp the mushrooms. Mingsen Huang et al. concluded through experiments that bending picking is the most effective picking method, requiring the least amount of force and the least complexity. The end-effector they designed uses a vacuum cup, a flexible

chuck, and a flexible pad [152,153]. The load-bearing capacity of the vacuum cup reaches 11 N, showing high stability and practicality.

In summary, mushrooms have irregular shapes and smooth and fragile surfaces, so suction-holding end-effectors are often ideal for the mechanized picking and harvesting of mushrooms. The suction-holding end-effector can effectively control it to avoid unnecessary friction or collision during the picking process and protect the integrity of the mushrooms. However, there are some challenges with the suction-holding end-effector. For example, it must maintain stable adsorption under various environmental conditions, including humidity, temperature, contamination on the mushroom surface, and other factors that may affect its performance. In addition, the maintenance and energy consumption of the vacuum system are also factors that many scholars need to consider. In short, using robots for mushroom picking has the advantages of high efficiency and a low injury rate. Through scientific design and optimization, the performance of the end-effector can also be significantly improved, which provides a new solution for the modernization and automation of the mushroom-picking industry.

4.3.2. Tea Leaves

Tea is an indispensable drink in people's lives due to its rich nutrients, such as amino acids and caffeine. However, tea is petite, light in weight, and has a complex growth environment [154]. Its unique growth characteristics pose considerable challenges to robotic picking. In particular, precisely picking famous tea leaves has become an emerging hot research field [155]. In countries such as Japan and Israel, large-scale integrated picking machines are mainly used to harvest tea leaves [156]. This kind of machinery can pick a large number of tea leaves in a short time, reducing the labor intensity and cost of manual picking. However, this large-scale picking machine is mainly aimed at bulk tea leaves. Due to the one-size-fits-all picking method, it is not easy to distinguish between high-quality and low-quality tea buds on the tea trees, leading to decreased quality of the picked tea leaves [157]. Therefore, large machinery is unsuitable for selectively picking famous tea. The selective picking of famous tea requires automated robots that can accurately pick. The focus of research for this kind of tea-picking robot is mainly on China. Chuangyu Wu conducted an in-depth study on the intelligent picking of famous teas [158]. They developed an intelligent tea-picking robot with a high picking success rate and positioning accuracy. This advanced robotic technology can accurately identify and pick tea buds. The particular end-effector can ensure the high quality of tea leaves and the healthy growth of tea trees. The tea-bud-picking system developed by Yingpeng Zhu et al. uses a vacuum suction cup to generate negative pressure under the pick-up tube, forming an air flow to attract the tea buds [159]. After the shearing mechanism cuts the tea buds, the tea buds follow the rising airflow into the pick-up tube to complete picking. This picking method can increase the success rate of tea-bud picking, effectively reduce internal interference in the tea tree, and improve picking efficiency, as shown in Figure 7h. The tea-picking system developed by Xu et al. [142] uses machine vision recognition and a microprocessor-controlled drive device to drive a robot to perform picking work. The end-effector of the system includes a pair of meshing gears, a pair of slender shearing fingers, and a pipe. A stepper motor drives the gears and drives the shearing fingers to achieve the precise picking of tea leaves. The pipe will shear the collected tea leaves. In addition to the traditional mechanical claws used to pick tea leaves, flexible picking manipulators are also employed in designing famous tea-picking robots. The famous tea-picking end-effector designed by Chunlin Chen et al. uses highly elastic silicone-wrapped mechanical claws (Figure 7g) that can effectively avoid damage to tea buds [160]. However, there is also a problem with the error that the vision system causes. Chen et al. designed a four-finger clamping end-effector to compensate for the positioning error. A servo motor drives the end-effector's upper part to realize the actuator's overall rotation for picking. Recently, laser alignment and color sensors feed signals back to a microcontroller, improving the picking efficiency. In short, the critical problem for an intelligent tea-picking robot is to develop a fast and

accurate recognition algorithm, which is the core of improving the speed of tea-bud picking. Similarly, developing an end-effector suitable for tea picking is also an essential part of the robot, which has the adsorption end-effector with bellows as the preferred solution because the tea leaves are light and easy to suck away. Therefore, improving the cutting efficiency of the end-effector scissors is the focus of the following research step, which will significantly increase the possibility of developing and applying tea-picking robots.

In conclusion, we discuss the research and technology comparison of end-effectors for picking robots targeting typical fruits and vegetables and present critical reflections and recommendations. More detailed information about references on fruit and vegetable picking end-effectors is shown in Table 2.

Table 2. Summary of detailed information on references for fruit- and vegetable-picking end-effectors.

Application Object	Actuator Type	Harvesting Method	Driving Mode	Additional Sensor	Material	Successful Rate	Damage Rate	Reference
Apple	Two-finger gripper	Pull and rotate	Electrical motor	Pressure and displacement sensor	3D printing of polyformaldehyde	95.3%	/	[47]
	Vacuum sucker type	Pull and rotate	Pneumatic	RGB-D	Soft silicone	80%	/	[17]
	Three-finger gripper	Pull and rotate	Electrical motor	Force sensor and IMU	Rigid gripper	84%	13%	[46]
	Two-finger gripper	Rotate	Electrical motor	CCD camera and laser distance sensor	Rigid gripper	89%	/	[108]
	Three-finger gripper	Rotate and pull	Electrical motor	Pressure sensor	3D printing ABS	/	/	[141]
	Three-finger gripper	Horizontal pull with bending	Electrical motor	Binocular sensor	Soft silicone	82.93%	/	[161]
Citrus and orange	Three-finger gripper	Cut	Electrical motor	Pressure sensor	3D printing ABS	95.23%	1.11%	[122]
	Three-finger gripper	Rotate	Pneumatic	Pressure and torque sensor	3D printing ABS	/	/	[121]
	Suction-holding type	Cut	Vacuum pneumatic	Pressure sensor	Chloroprene	95%	/	[80]
	Bionic type	Bite and cut	Pneumatic	Vision sensor	Rigid gripper	89%	/	[123]
	Four-finger gripper	Cut	Electrical motor	/	3D printing plastic	/	/	[162]
Strawberry	Envelope type	Tooth cutting	Electrical motor	Vision sensor	Plastic	69%	/	[163]
	Three-finger gripper	Rotate	Electrical motor	Pressure sensor	Foam	60–80%	/	[88]
	Envelope type	Cut	Electrical motor	Infrared sensor	Plastic	59%	5.4%	[20]
	Three-finger gripper	Pull and rotate	Pneumatic	Vision sensor	Soft gripper	78%	23%	[164]
Kiwifruit	Two-finger gripper	Flexural rotation	Electrical motor	Fiber optic sensor	3D printing plastic	80–100%	10–20%	[165]
	Envelope type	Cut	Electrical motor	Color detection sensor	Rigid gripper	89.3%	6%	[166]
	Two-finger gripper	Rotate	Electrical motor	Infrared sensor	Plastic	88.89%	/	[167]

Table 2. *Cont.*

Application Object	Actuator Type	Harvesting Method	Driving Mode	Additional Sensor	Material	Successful Rate	Damage Rate	Reference
Cherry tomato	Two-finger gripper	Rotate and pull	Pneumatic	RGB-D	Nylon and silicone	84%	1.9%	[71]
	Three-finger gripper	Pull	Pneumatic	Pressure sensor	Silicone	97%	/	[112]
	Vacuum adsorption type	Cut	Pneumatic	Pressure sensor	3D printed silicone	80.63%	/	[18]
	Three-finger gripper	Pull and rotate	Electrical motor	Pressure sensor	Soft gripper	95.82%	2.9%	[102]
Grape	Two-finger gripper	Cut	Electrical motor	Vision sensor	Rigid gripper	83%	/	[168]
	Two-finger gripper	Inflorescence thinning end-effector	Electrical motor	Vision sensor	3D printing plastic	86%	5%	[169]
Sweet pepper	Two-finger gripper	Cut	Brushless Direct Current Motor	No	Metal	./	/	[136]
	Six-finger gripper	Vibratory Cutting	Electrical motor	RGB-D	Soft plastic and metal	61%	/	[138]
	Two-finger gripper	Cut	Electrical motor	RGB	Plastic	26%	13%	[48]
	Vacuum sucker type	Cut	Pneumatic and electrical motor	RGB and pressure sensor	Metal	33%	/	[48]
	Vacuum sucker type	Vibratory Cutting	Pneumatic	RGB-D and pressure sensor	Soft silicone	90%	/	[137]
Eggplant	Four-finger combined the suction pads	Cut	Air compressor	Photoelectric sensor	Soft plastic and metal	62.5%	12.5%	[30]
	Suction-holding type	Pull and rotate	Electrical motor	Pressure sensor	3D printing plastic	90%	/	[144]
Pumpkin	Envelope type	Cut	Electrical motor	No	Metal	/	/	[139]
	Five-finger gripper	Cut	Servo motor	Vision sensor	Metal	79%	5%	[145]
Cucumber	Suction-holding type	Cut	Direct Current Motor	Local camera	Soft plastic and metal	86.2%	4.7%	[148]
	Vacuum adsorption type	Cut	Pneumatic	Vision sensor	3D printed silicone	90%	/	[146]

5. Discussion on Challenges and Future Trends

With the arrival and development of Agriculture 4.0, agricultural harvesting robots continue to play an important role. In particular, the end-effector technology of harvesting robots plays a crucial role in promoting the automated harvesting of various fruits and vegetables. The end-effector is the actuator of the harvesting robot and a critical component in direct contact with agricultural products, playing the role of "operator". In recent years, schools and enterprises have developed various end-effectors to realize the automated harvesting of different varieties of fruits and vegetables. They have undergone updates from the traditional vibration and mechanical scissor types to the intelligent sensing type—application scenarios that transfer from agricultural greenhouses to wild planting

fields. However, considering the large-scale diffusion and commercial application of end-effectors, they still face some challenges in the harvesting of fruits and vegetables.

First, improving work efficiency and the success rate are still the biggest challenges for end-effectors. Currently, most end-effectors pick fruits individually, which takes a long time, and the picking success rate is also low. Meanwhile, ensuring the accuracy and safety of operations is required in automated fruit and vegetable operations. For example, fragile fruits, such as strawberries and tomatoes, will suffer collision damage when faced with mechanical picking end-effectors, shortening the storage period. In addition, different agricultural products have various sizes and shapes. They have different surface hardnesses and can withstand different gripping forces. Achieving accurate, safe, and damage-free harvesting operations is also a thorny issue. Then, the end-user must be able to adapt to unstructured agricultural environments. As the end-effector has to face complex scenarios, such as occlusion, overlapping, and light changes, when working, it is equally difficult to adopt advanced new sensor technologies and efficient recognition algorithm fusion.

Second, the development of an end-effector under controlled conditions (greenhouse) is different from field conditions. The environment under greenhouse conditions is controlled, allowing the end-effector not to be highly adaptable to changing environmental conditions [170]. Crops in greenhouses are usually neatly arranged, allowing the end-effector to focus on high-precision operations without the need for complex picking path-planning techniques. Greenhouse environments are cleaner, with fewer contaminants, and end-effector materials can be chosen to be lighter and finer, reducing the need for redundant protection and sealing designs. However, field environments are complex and variable, with harsh weather conditions such as high winds, heavy rain, and mud. The end-effector needs to be highly durable and water and dust resistant. The structural design of the end-effector needs to take into account vibration and fatigue resistance to face large mechanical shocks. With the wide variety of crop arrangements and growing environments in the field, the end-effector needs to incorporate a variety of sensors to provide a high degree of flexibility and adaptability. These design differences are to ensure that the picking robot can operate efficiently and stably in different environments.

Third, end-effector applications in greenhouse conditions face a number of challenges and limitations. With relatively small spaces and narrow aisles in greenhouses, end-effectors need to operate efficiently in limited spaces. The presence of human–machine collaboration in greenhouses requires end-effectors to be designed for safety. Crops grow uniformly in the greenhouse, requiring the end-effector to be able to carry out high-precision, high-sensitivity operations to avoid accidental harvesting or damage to crops. Regular maintenance and low-cost control are also factors to be considered. However, the field environment is an unstructured environment full of great complexity and uncertainty. Weather, lighting conditions, and obstacles cause great interference to the robot, and the end-effector needs to be specially designed to cope with all kinds of adverse weather conditions and maintain efficient operation. There is a wide variety of crops in the field, and different crops have different morphologies and growth characteristics. The end-effector must have a high degree of flexibility and recognition to cope with the demands of picking different types of crops. These are great challenges for end-effector design and development.

Finally, there are many social, economic, and policy constraints on the diffusion and application of picking robots in modern agriculture. For example, the ability of picking robots to significantly reduce the reliance on manual labor can bring about tensions and uneasiness at the social level, especially with low acceptance in communities that rely on agricultural labor for employment. Also picking robots usually involve high initial investments and long economic payback cycles, which is a reason for farmers to remain cautious. Thus, the lack of policy support and financial incentives may slow down the diffusion of the technology and may limit its widespread adoption.

In conclusion, end-effectors for fruit and vegetable harvesting will continue to play a key role in the future development of agricultural robots, which are mainly used in greenhouse conditions and real field scenarios. Potential future trends in end-effector

categories, structural design, sensor applications, and advanced technology developments may be as follows:

(1) Lightweight, adaptive end-effectors are the primary potential development trend. In the future, the design of end-effectors will be lightweight on the one hand and use an under-actuated structure to reduce the mass of the end-effector. On the other hand, more emphasis will be placed on flexibility and deformability to adapt to different forms of fruits and vegetables while reducing damage to the plants, improving picking efficiency and quality;
(2) The research and development of bionic manipulators is a popular research trend. Drawing on the characteristics and structures of organisms in nature, robotic manipulators with similar structures and functions are designed and developed. This R&D method aims to realize a more flexible, intelligent, and efficient mechanical system, and it can also solve the problem that traditional manipulators have limited applications in complex environments;
(3) Fusion of multi-sensor technologies. At present, some advanced end-effectors have begun to integrate simple visual and tactile sensors to achieve more accurate gripping action. The future end-effector integrates visual, mechanical, tactile, and even olfactory sensors, which will be equipped with more accurate sensing ability and will be able to identify the location, shape, and ripeness of fruits and vegetables in real time to achieve intelligentization;
(4) A more intelligent control system: People will study perception, decision-making, and human–machine collaboration methods based on artificial intelligence and machine learning and develop intelligent terminal control algorithms suitable for selective harvesting scenarios, which can adjust picking strategies according to the real-time environment and fruit and vegetable morphology and gradually achieve strong adaptability and high efficiency harvested autonomously;
(5) Design of flexible end-effector. The current design of an end-effector is mostly based on rigid materials, although it has durability and reliability. However, there are limitations in the face of damage-prone crops, the design of a flexible end-effector will improve the limitations of rigid structure. The combination of flexible materials and flexible end-effectors is the future trend, which can make up for the error of excessive stress brought by traditional mechanical materials and reduce the risk of damage;
(6) Design for modularity and reconfigurability. The current end-effector design has been able to realize the basic gripping and picking functions, mostly using mechanical fingers or pneumatic devices, but it mainly relies on the fixed form of the components for gripping. The scope of application is relatively limited; modularity and reconfigurability of the trend will make the current design not universal to become more compatible and to enhance the functionality of the equipment to expand and adapt to market capabilities.

6. Conclusions

The end-effector of agricultural robots plays a vital role in the process of people moving towards the Agriculture 4.0 era and shows enormous development potential in the future. After conducting a thorough analysis and investigation of agricultural picking robot end-effectors, it can be commented that end-effectors have significantly improved agricultural production capacity, decreased labor demand, and optimized the quality of agricultural products in the decades since they were developed. Various end-effectors have been developed for harvesting fruits and vegetables of different varieties, sizes, and shapes. End-effectors are categorized into four types: clamping end-effectors, air-suction end-effectors, suction-holding end-effectors, and envelope end-effectors. These categories are based on the various structural forms, driving forces, and control strategies of the end-effectors. Advanced technologies for end-effectors include introducing soft materials, flexible materials, and bionic structural designs that significantly optimize the functionality and adaptability of end-effectors. In addition, advanced sensor technology and intelligent

control strategies bring more powerful perception and decision-making capabilities to picking robots, thereby improving the efficiency of autonomous operations. In short, the main challenge for the end-effector is to increase its efficiency and reduce its cost when operating in greenhouse and field conditions. This is a complex problem influenced by a number of factors, including the use of modular and repeatable structural designs, the application of flexible and soft materials, and the use of artificial intelligence techniques and sensors, which are the main research trends for the future.

In summary, this paper serves as a comprehensive overview of the development of end-effectors for picking robots, advanced technologies (including structural design, gripping steps and strategies, sensors, and new soft materials), and their typical applications in fruit and vegetable picking. The advantages and disadvantages of different types of fixtures are compared and discussed. In addition, challenges and potential future trends in fixture development and application in agriculture are reported, and the need for further research and development work to meet the challenges of Agriculture 4.0 is emphasized.

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