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Seedling Picking Devices for Automatic Transplanters: A Systematic Review

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Abstract

The performance of the seedling picking device, as a core component of transplanting machines, is directly related to the efficiency, quality, and cost of the transplanting operation, and plays an active role in promoting the development of automatic transplanters. At present, a contradiction exists between the seedling picking speed and the success rate of seedling picking. With the increase in the vegetable planting area, the quality requirements for seedling picking are gradually increasing. Efficient and high-quality seedling picking has become the focus of scholars. In order to provide scholars with a comprehensive and profound understanding of seedling picking devices, this study searched and screened the literature, and the CiteSpace literature quantitative analysis software was employed to analyze the research hotspots and trends by using a knowledge graph. Three kinds of seedling picking devices and pot seedling detection technologies were discussed. The working principles, advantages, and disadvantages of these seedling picking devices and detection technologies were analyzed, and the problems with current seedling picking devices were summarized. Results show that, the automatic seedling picking device has a complex structure, weak versatility, difficulty in fully matching diversified agronomic needs, low intelligence level, large research and development investment, high cost, and difficulty in promotion. Solutions are given for these corresponding problems: the seedling picking device should adopt a modular design to improve its versatility; the creation of unified standards for the production of pots, the growing of seedlings, and the development of sensors must be accelerated; and computer vision, artificial intelligence, deep learning, intelligent control algorithms, and other technologies must be integrated into seedling picking devices to improve their level of intelligence, ensure transplanting efficiency, and reduce damage to pot seedlings. A universal high-speed, low-loss seedling picking device should be the main research direction in the future. This study provides a good reference for the further development of automatic transplanting machines.

*Keywords:*Automatic transplanter, Seedling picking device, Seedling transplanter, Transplanting, Plug seedling

1. Introduction

Vegetables are a vital element of the human diet, offering essential nutrients such as fiber, vitamins, antioxidants, and minerals [1]. The increasing global population has resulted in a surge in demand for vegetables [2]. In recent years, the sown area of vegetables in China has continued to rise, reaching 22,434 thousand hectares in 2022, and the yield of vegetables reached 791 million tons. The vegetable planting mode has gradually changed from scattered planting to large-scale agricultural production. Transplanting is an indispensable part of large-scale vegetable planting. At present, vegetable planting mainly includes open-field direct seeding and film mulching sowing. Although direct seeding in open fields is simple, ensuring the quality of planting is difficult because of other reasons such as soil condition and soil depth, and the amount of seeds used is one to two times higher than that used in seedling transplanting. Frost, cold weather in late spring, and other bad weather conditions also need to be avoided. Plastic film is difficult to clean up, which has a great influence on soil quality. Given its obvious advantages, the application of seedling transplanting technology in vegetable planting has gradually increased [3], and the yield has increased by 20.8% and 16.5%, respectively. Compared with open-field direct seeding and film mulching seeding, manual transplanting entails high labor intensity and low efficiency and cannot complete large-scale operations. Semi-automatic transplanting is carried out by manually picking up seedlings, and then the seedlings are placed on a conveyor belt or directly placed in the planting device. The limited speed of manual seedling picking makes this method unsuitable for large-scale transplanting in a short time, and the advantages of mechanization are not obvious. In addition, the shortage of labor in areas with small populations and extensive cultivation areas has prevented the spread of semi-automated transplanting [4]. As the main direction of vegetable transplanting in the future, an automatic transplanting machine can not only significantly improve transplanting quality and working efficiency but also reduce the labor intensity of workers [5][7].

Agricultural mechanization is an important basis for transforming the mode of agricultural development and improving rural productivity, and it is an important support for implementing the strategy of rural revitalization. The development and progress of automatic transplanting machines is the key to realizing the mechanization of vegetable planting [8]. Japan and some countries in Europe have conducted works on transplanters as early as the 1920s, achieving a high degree of automation [9]-[11]. China's introduction of policies related to agricultural modernization has led to the rapid development of automatic transplanters.

China has proposed a strategy for the coordinated development of agricultural machinery products and key

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components. The performance of the automatic seedling picking device, as a core component in the development of automatic transplanting machines, determines the transplanting efficiency, quality, and stability of transplanting machines [12]. Study on automatic seedling picking technology plays a positive role in promoting the development of fully automatic transplanting machines [13]. Therefore, the development of intelligent high-speed and low-loss seedling picking devices has become the key to improving the effect and quality of seedling picking.

To intuitively show the research progress on the seedling picking device, this study adopted the CiteSpace literature analysis tool to search and analyze the relevant literature since the new century in the core database of China National Knowledge Infrastructure (CNKI) and Web of Science (WoS). The search time interval was limited to January 1, 2000, to December 31, 2024. The curve of the number of Chinese and English literature published in the range of statistical retrieval years is shown in **Fig. 1**.As shown in the figure, the number of Chinese-language documents reached its peak in 2023, and the number of English-language documents peaked in 2022. Although the number of publications on the seedling picking device fluctuated after 2020, the overall number of publications was relatively balanced, remaining basically stable at about 30.

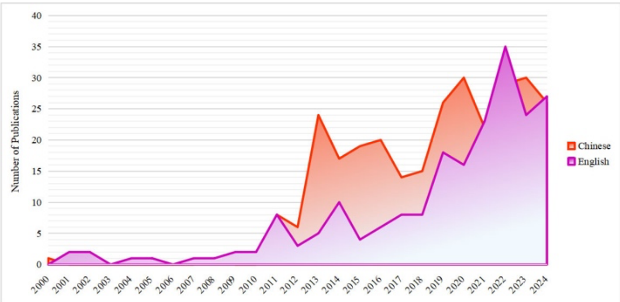

Fig. 1. Number of publications

Keywords are selected on the basis of the high generalization and conciseness of the theme of the literature. Through the analysis of the high-frequency keywords in the literature, the research hotspots, trends, and the relationship between the research topics in this field can be revealed. For the effective literature, CiteSpace software was employed to analyze the high-frequency keywords in Chinese and English literature. The collinear map of CNKI database and WoS database in the research field of transplanter picking device from 2000 to 2024 are shown in **Fig. 2** and **Fig. 3**, respectively. Nodes are presented in the form of a tree ring history. The size of the annual ring reflects the frequency of keywords; a large annual ring corresponds to a high frequency of keywords. The color of the annual ring represents the time interval in which the keywords were active. The color change from the inside to the outside indicates the time frame in which the keywords were published, from the earliest period to the present. The thickness of the annual ring is proportional to the frequency of keywords in the corresponding time zone. “Transplanting,” “seedling pick-up device,” “seedling pick-up mechanism,” and “transplanting machine” are the main keyword nodes, occupying the core position in the literature collection and generating a wide range of radial connections around them, forming a complex structural network.

Fig. 2. CNKI literature keyword co-occurrence map

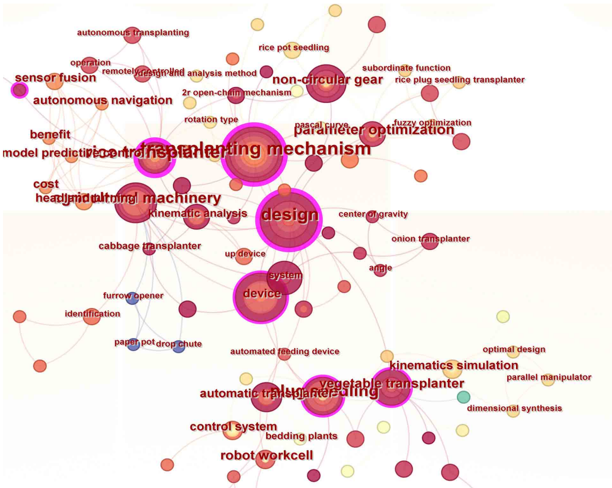

Fig. 3. WoS literature keyword co-occurrence map

This study systematically summarizes and sorts out the relevant studies and patents of existing automatic transplanter seedling picking devices and summarizes the relevant research progress in this field. The advantages and disadvantages of various seedling picking methods were summarized by comparing and analyzing the existing research progress,. Subsequently, the detection methods of pot seedlings were discussed. Finally, the future trend of automatic seedling picking devices was analyzed and prospected. The automatic seedling picking device is mainly divided into clamping type, ejection type, and straight drop type.

2. Clamping Type

The clamping-type seedling picking device typically employs the motion characteristics of mechanisms such as linkages, non-cylindrical gears, and cams to synthesize the movement trajectory of the extraction needle [14]. The clamping type can be categorized into two types: insertion clamping and direct clamping.

2.1 Insertion Clamping

The insertion clamping seedling picking device operates by utilizing an extraction needle that engages the seedling pot through the insertion and clamping of the substrate in a continuous motion [15]-[18]. Upon the release of the seedling, the extraction needle loosens its grip on the pot, allowing the seedling to detach from the tray either due to gravitational forces or through the assistance of a seedling pushing ring.

Viscon of the Netherlands developed a needle-type transplanting device, as shown in **Fig. 4**, in which the individual seedling picking mechanisms were equipped with an independent control system, thus increasing the success rate of seedling picking and the frequency of transplanting. The PAIA and PF2R vegetable transplanters produced by Yanmar Agricultural Machinery Co., Ltd. in Japan, the MA-1 and PF-1 automatic vegetable transplanters produced by the Mitsubishi Corporation, and the Urbinati RW32 transplanter produced in Italy, as shown in **Fig. 5**, also picked up seedlings in this way [19]-[21].

Fig. 4. Viscon automatic transplanter[20]

Fig. 5. RW32 Automatic transplanter[21]

Davood Mohammad Zamani [22] developed a seedling picking robotic arm with two pairs of seedling pins at the head of the arm, which were inserted vertically into the potting bowl to complete seedling picking. However, as the speed of the transplanter increased, the seedling picking targeted the stalks, leaves, and root system of the seedlings, causing serious injuries. W. C. Choi [23] designed an insertion and clamping seedling picking device. After arriving at the extraction point, the potting seedling is placed into the planter through the push ring. The success rate of seedling extraction of this device reached 97%, but the seedling extraction efficiency was low, extracting only 30 seedlings per minute, which does not satisfy the current demand of high-speed transplanting. Jin Xin [24] investigated an automatic tomato potting seedling picking device that uses the insertion clip pick-up method. The seedling extracting claw consisted of a pair of seedling clamping needles, two rings, and a pusher. The device caused minimal damage to potting seedlings, but the optimal transplanting frequency of the device was 60 plants per minute, which was not up to the standard of high-speed transplanting machinery. Yu Yaxin [25] discussed a rotating seedling picking mechanism that uses planetary gear trains with non-circular gears combined with incompletely eccentric circular and non-circular gears. The trajectory of picking seedlings is shown in **Fig. 6**, and the trajectory ABCDEFA was formed by the tip of the picking arm. The laboratory prototype test showed that the success rate of seedling picking was 93.8% at a seedling picking frequency of 60 plants per minute per row. Han Shuai [26] combined the fuzzy PID algorithm with the picking device, which improved the stability of the seedling picking device and had higher control accuracy.

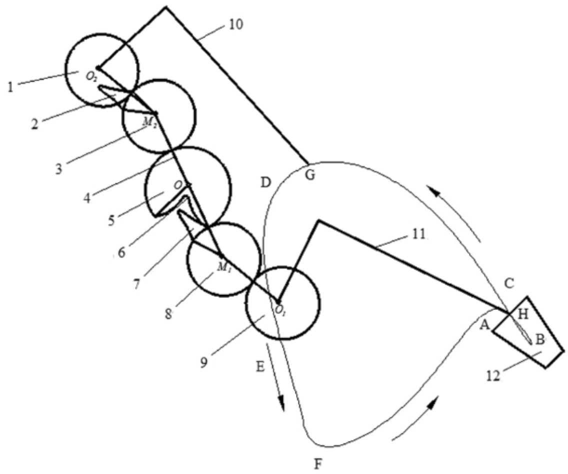

Fig. 6. Seedling picking mechanism of the planetary gear train with combined non-circular gear transmission[25]
1, 9 planetary non-circular gear; 2, 7 incomplete non-circular gear; 3, 8 non-circular gear; 4 planetary carrier; 5 incomplete eccentric circular gear; 6 incomplete non-circular gear; 10, 11 seedling picking arm; 12 plug seedling tray

The seedling picking device has a straightforward design and compact dimensions. However, when extracting seedlings with larger leaf spans, the insertion of the extraction needle into the substrate may inadvertently damage the stems and leaves or compromise the integrity of the pot, potentially affecting the subsequent growth of the crops, particularly for seedlings housed in trays with more extensive leaf spans. Furthermore, the insertion of a clamping seedling picking device necessitates precise control over the movement trajectory of the extraction needle, as well as the specific positions for both extraction and planting. The stability of seedling delivery also warrants further investigation [27].

2.2 Direct Clamping

The seedling picking clamps the stem of the seedling directly and pulls out its seedling roots along with the substrate. When it reaches the designated seedling casting position, the end executing part loosens, the seedling falls down because of its own weight, and the casting of the seedling is completed [28]-[31].

Abhiijit Khadatkar [32] designed a small transplanting robot with a seedling picking device that worked by driving a robot via servo motors to move to the location of the potting seedling and grabbing the potting seedling. After transporting the potting seedling to the top of the conveyor tube, the robot opened and released the potting seedling, completing the seedling picking action. The success rate of seedling extraction was 95.1%. Vikas Paradkar [33] developed a three-degrees-of-freedom tandem robotic arm seedling picking device, which detected the position of potting seedlings through light-emitting diodes and photoresistors, drove the manipulator to clip the potting seedlings that reached the seedling pickup position, and transported them to the seedling drop-off point to complete the drop-off. The success rate of seedling picking was 94.7% in the field. However, these two seedling picking devices are not suitable for Chinese transplanting methods and are difficult to apply in China.

Han Changjie [34] designed a seedling picking device with a pneumatic control manipulator. The seedling clamp was subjected to the elastic force of the compression spring and the pressure of the limit bearing, forcing the seedling clamp to close and clamp the seedling. When the seedling clip lost the limit of the limit bearing and was bounced off by the compression spring, the seedlings were accurately placed in the planting system. To reduce stem damage by seedling pickers during transplanting, Hu Shuangyan [35] designed a flexible clamping mechanism with a crab pincer function using the bionic principle. Finite element analysis was carried out, and silicone was selected as the clamping material. The clamping damage test results showed that the clamping damage rate of the silicone gripper was 3.28%. Wang Xiu [36] devised an automatic seedling picking device that uses pneumatic control. When the seedling clamping device clamped the pot seedlings, the seedling separating device, which featured a multi-level scissor mechanism, placed the pot seedlings in a seedling cup separately to complete seedling picking; the seedling picking process is shown in **Fig. 7**. When the seedling picking frequency of the device increased, the machine vibrated strongly, thereby decreasing the success rate of seedling picking and rapidly increasing the matrix damage rate.

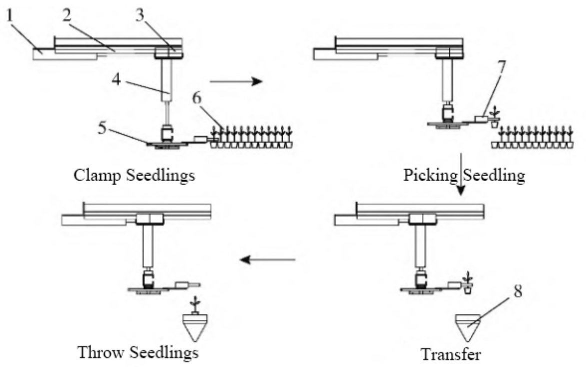

Fig. 7. Schematic of the seedling picking process of the seedling picking device[36]
1. shifting cylinders 2. shifting guide rails 3. shifting sliders 4. lifting cylinders 5. shear fork seedling dividing mechanism 6. potting seedlings 7. seedling clamping devices 8. seedling cups

The seedling picking device has a simple principle and a high transplanting efficiency, and it almost does not affect the substrate. However, this seedling picking method is greatly affected by the external environment, such as the growth position of the seedlings in the potting, the stem strength of the seedlings, and the adhesion between the seedlings and the potting tray. As a result of these factors, the potting seedlings might become unable to be taken out or the quality of the seedling extraction may be affected, thereby damaging the potting seedlings and increasing the seedling retardation period. Therefore, this seedling picking method is more suitable for potting upright seedlings with strong stems.

3. Pushing Type

Conventional seedling trays are equipped with drainage holes at the bottom, through which a push rod interacts with the lower surface of the root–substrate composite to eject the seedlings from the tray. The ejected seedlings are then systematically delivered into a planting device by a seedling distribution mechanism, thereby completing the transfer process [37]. The push mechanism can take various forms, including cam systems, crank–slider mechanisms, high-speed servo electric cylinders, pneumatic cylinders, or jet systems.

The 2ZLX-2 series transplanting machines developed by the Italian company Ferrari utilize a push-out method for seedling extraction [38], as shown in **Fig. 8**. The push-out rod was designed to sequentially eject seedlings from their pots, which were subsequently grasped by a robotic arm for collection. This series of transplanting machines is capable of achieving a planting speed of up to 9,000 plants per hour per row, and it incorporates sensor technology to enhance the automation level. Through the application of advanced automatic control technologies, precise seedling extraction was facilitated, improving the operational efficiency considerably compared with other transplanting machines, thereby addressing the demands of modern agricultural practices. However, the high cost of this machinery and the challenges associated with its maintenance contribute to increased production costs in vegetable farming. Similar models were produced by Picador (France), Pearson (UK), and others.

Fig. 8. Futura series transplanters[39]

Vivek Periasamy [40] developed a specialized seedling extraction mechanism that utilizes a cylinder to push seedlings from their trays. A conveyor belt subsequently transported the pushed seedlings to the area beneath a robotic arm, which was responsible for the extraction and placement of the seedlings. The entire system was controlled by a PLC, achieving a maximum seedling extraction success rate of 93.45%. Feng Shijie [41] designed a lifting device adapted to movable seedling trays, as shown in **Fig. 9**. The lifting mechanism underneath jacked up the tray under PLC control to separate the seedlings and the tray when the seedling tray reached a fixed position. This device had a low rate of substrate loss, but it is difficult to popularize because it is used only for homemade movable seedling trays.

Ma Guoxin [42] proposed a method for seedling extraction that utilized an airflow ejection-wrapped clamping technique. In this method, air was directed upward through the drainage holes of the seedling tray to eject the seedlings, which were subsequently enveloped by a corresponding end effector to complete the extraction process. However, because of the small diameter of the nozzle and its operation below the drain, it is prone to being clogged by the soil in the cavity tray. Han Lühua [43] constructed an air-blown potting release device for the bottom of vegetable hole tray seedlings, which overcame the adhesion between the seedlings and the inner wall of the hole tray through the high-pressure airflow generated by air jet from the bottom drainage port of the hole tray. This device realized non-mechanical contact relaxation and facilitated the subsequent transplanting of the seedlings by easy manual pulling or mechanical reliable clamping, but it could cause root damage.

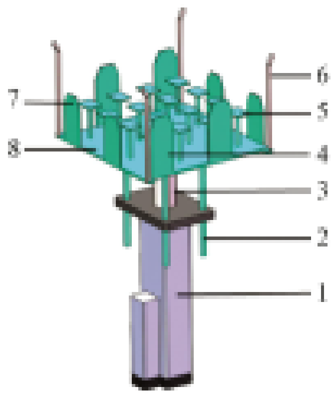

Fig. 9. Structure composition of opening and lifting mechanism[41]
1. electric cylinder 2. guiding rod 3. push rod 4. long push plate 5. lifting platform 6. half Y-shaped positioning bar 7. short push plate 8. bottom plate

This seedling picking technique is characterized by its ability to minimize substrate damage while achieving a high success rate in seedling extraction. However, the force applied during the pushing process needs to be regulated meticulously to avoid the risk of the push rod penetrating the pot, which could compromise the integrity of the root system. Furthermore, the operation of push-type seedling picking devices necessitates a high level of coordination among its various components, accompanied by stringent control requirements for positioning maneuvers. The push rod is often used in conjunction with a clamp-type seedling picking device, which increases the complexity of the device. During the extraction process, as the push rod displaces the seedling, the robotic arm grasps the seedling, thereby facilitating the completion of the extraction procedure.

4. Straight-falling Type

In contrast to the conventional method of upward seedling extraction, the straight-falling seedling picking technique employs a downward approach, with the seedlings being removed vertically from a hole tray, allowing them to fall directly into a seedling feeding apparatus or planting mechanism. Straight-falling seedling extraction can be categorized into several types, including negative pressure, air blowing, and mechanical downward pressure systems.

The US Company Renaldo developed a fully automated vegetable transplanting machine in 2013, which utilized air-based root trays specifically designed for seedlings cultivated in specially designed conical hard composite trays. This machine employed a negative pressure mechanism to extract seedlings from the top and transport them through a conveyor system to the planting device. However, this system had several drawbacks, including the high cost of the seedling trays, complex construction, the potential for substrate disintegration during the extraction process, and suitability for only small seedlings. Wang Chao [44] analyzed a pneumatic downward-pressing seedling picking device and designed the seedling ejector as a U-shaped structure to reduce the damage to the leaves of the potting seedlings. When the seedling extraction speed was 120 plants per minute, the success rate of seedling extraction could reach 100%, but the potting body had a high breakage rate. In addition, this device needed to be used in conjunction with the bottomless hole tray. Yuan Ting [45] proposed an air-blowing and vibration composite seedling extraction mechanism, as shown in Fig. 10. This device applied vibration and blowing force to the upper surface of the mantle to counteract the adhesion force between the mantle and the inner wall of the burrow tray. This device had high efficiency but was affected by environmental factors.

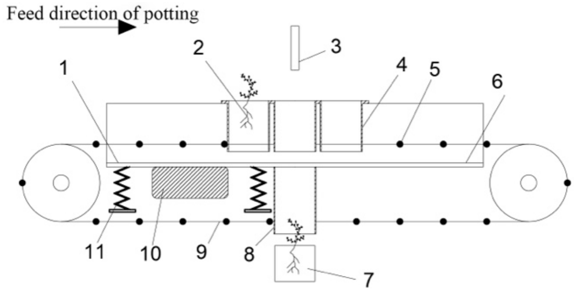

Fig. 10. Principle of seedling unloading[45]
1. vibration plate 2. potting seedlings to be taken 3. blowing tube 4. toggle 5. hole seedling tray 6. bottom plate 7. non-woven cloth wrapped potting seedlings 8. seedling guide tube 9. chain with toggle 10. vibrator 11. spring

The straight-falling type seedling picking device exhibits great flexibility and facilitates the automation and systematic collection of seedlings, allowing seedlings to be picked and cast simultaneously. However, its applicability is limited, as it is primarily suited for specific non-standard seedling trays or specialty crops.

A comparative analysis of various seedling picking devices showed that the clamping-type seedling picking device has a simple structure and demonstrates strong adaptability to different seedling forms. In contrast, the pushing-type seedling picking device has a compact design, high extraction efficiency, and low seedling damage rate. The straight-falling-type seedling picking device enables contactless extraction, thereby reducing the likelihood of seedling injury, and it can simultaneously perform extraction and planting, thus enhancing transplanting efficiency. However, it is compatible with specific seedling trays only, making it particularly suitable for the transplantation of small-scale seedlings. The advantages and disadvantages of various seedling picking devices are shown in Table 1.

Table 1. Advantages and disadvantages of different seedling picking devices

Seedling picking device		Advantages	Disadvantage
Clamping type	Insertion clamping	Adaptation to diverse seedling potting methods with a straightforward design	Potting seedlings may stick to the needle and damage the substrate
	Direct clamping	High transplanting efficiency with low substrate damage	High requirements for component positioning accuracy
Pushing type	Minimized substrate damage coupled with a high success rate in		Complex structure and

	seedling extraction	control system
Straight-falling type	Effective targeting, elevated seedling extraction efficiency, and minimal seedling injury rates	Utilized for specialized seedling trays and particular crops that exhibit limited practicality

5. Pot Seedling Identification Technology

Seedling supply is an important part of the automatic transplanting machine, but plugs with no seedlings or weak seedlings in factory nurseries account for approximately 5%-10% of all plugs. These problems will lead to reduced production, thus affecting the quality of transplanting machine work. Therefore, classification needs to be performed according to the growth of plug seedlings. Manual classification is a difficult and expensive process that relies heavily on manual labor. Computer vision is regarded as one of the most effective solutions to achieve automatic classification. The seedling picking device combined with pot seedling detection technology can significantly improve the quality of seedling picking, thereby improving the success rate of transplanting.

Scholars used computer vision to extract features such as seedling color, morphology, or physical size, and these features have been used to replenish and screen seedlings on the basis of the recognition results. Tong Junhua [46] used the binarization and watershed algorithm to segment the collected tray seedling images according to the shape of the tray and then located the seedlings by using the center of gravity method to obtain the number and area of the seedlings. The quality of the seedlings was determined, and the accuracy rate reached 98%. Jin Xing [47] designed a low-damage seedling picking device consisting of a semantic segmentation algorithm and a seedling picking point estimation algorithm. Locating the seedling leaves and calculating the optimal seedling extraction angle of the mechanical claw enabled the mechanical claw to avoid the seedling leaves during the seedling extraction process, thus reducing damage to the seedling leaves. As verified by the seedling extraction test, the injury rate was 4.16%, indicating a 15.28% reduction in the seedling damage rate compared with the common seedling extraction method. Jin Xin [48] proposed a low-damage transplanting method for leafy vegetable seedlings on the basis of machine vision and image processing. Image processing was performed on the side image of the seedlings to obtain the height and extreme edge points of the seedlings. Then, the pixel coordinates in the RGB image were obtained, and the depth image was aligned with the RGB image to obtain the depth information of the corresponding extreme point. According to the coordination information, path planning of the end effector was conducted to realize low-damage transplantation of the seedlings.

With the rise of computer vision technology and artificial intelligence, image processing technology has been widely used in agricultural production due to its low cost and easy implementation. Deep learning technology based on convolution neural network architecture can automatically learn features from large-scale labeled image datasets and has good recognition accuracy and speed. With the continuous development of convolution neural networks, single-stage detectors such as single-shot multi-box detector [49] and you only look once (YOLO) [50] and two-stage detectors such as RCNN [51] and faster RCNN [52] have also been widely used in agricultural detection. Zhenbo Li [53] used the improved faster RCNN to detect the growth status of hydroponics lettuce seedlings, and the average accuracy was 86.2%. Li Tao [54] used EfficientNetv2 lightweight network as the feature extraction network of YOLOv5, used the CARAFE up sampling module and EMA attention mechanism to classify tomato plug seedlings, and selected the Plant Village public dataset as the auxiliary domain. Through pre-training, the transfer of model weight was realized, and the recognition effect was improved, with an average accuracy of 95.6%.

Usually, most scholars employed the visual system to detect plug seedlings from top to bottom, as shown in **Fig. 11**. However, this detection method is only effective in the case of light mutual occlusion of leaves. A large error occurs when the leaves are dense and the occlusion is serious. At the same time, the method has poor adaptability in the case of leaf tilt and different shapes. To solve the above problems, scholars proposed to use the side view to distinguish the characteristic information of adjacent plug seedlings, as shown in **Fig. 12**. This method can detect the uprightness, height, width, and stem diameter of plug seedlings and classify plug seedlings by these parameters. Wu Jianmin [55] detected the seedling stem below the leaf and adjusted the position of the photoelectric sensor according to the height of the pot seedling to avoid the influence of the pot seedling branches and leaves on the photoelectric sensor. Yang Yi [56] collected the image of the stem of the fiber spot area under the leaves of white palm seedlings by using a micro camera and optical fiber in a dark room and used the visual algorithm to extract the stem image and the stem projection area. The unqualified seedlings were determined by comparing the extracted stem projection area of the white palm seedlings to be tested with the critical value of the stem quality classification of the white palm seedlings, and the hole location information of the unqualified seedlings was obtained.

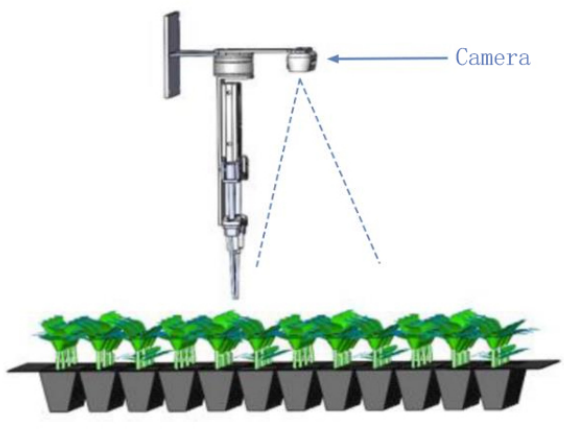

Fig. 11. Top-view perspective[47]

However, in addition to the lack of seedlings and weak seedlings generated during the cultivation of plug seedlings, the parts of the transplanter can cause problems such as stem fracture and matrix block crushing as the transplanter operates. The above two methods cannot effectively detect defects. Shenyi Zhao [57] proposed a new side-view detection method. The pot seedlings were taken out of the seedling tray, and the camera detected the pot seedlings that were still in the hand. The leaves of the adjacent seedlings were not shaded at this time, as shown in Fig. 13. RGB-D cameras could capture images of multiple seedlings at the same time and obtain pixel information, such as leaves, stems, and lumps, for each seedling. This method not only detected the absence of seedlings and the presence of weak seedlings but could also feedback key seedling damage information.

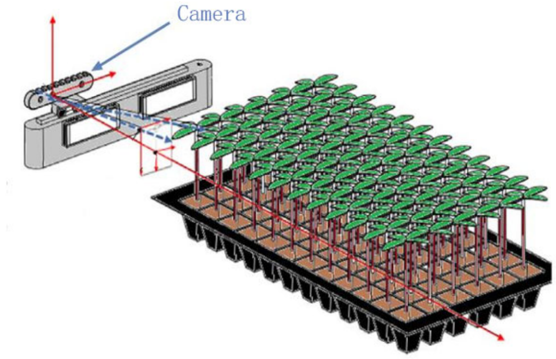

Fig. 12. Side-view perspective[48]

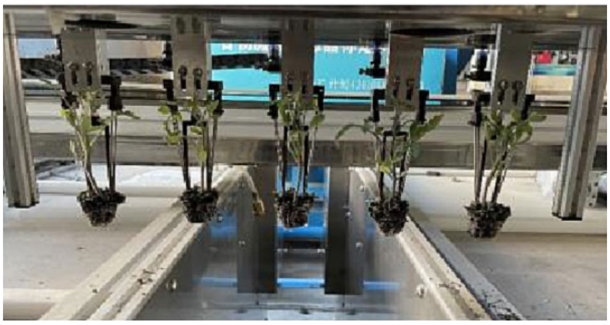

Fig. 13. New side-view detection method[57]

6. Discussion

The current state of transplanting mechanization is characterized by significant imbalances and inadequacies, influenced by a multitude of factors. Notably, the research and development (R&D) of seedling picking devices exhibits numerous shortcomings and deficiencies. Furthermore, a disparity exists between supply and demand, as evidenced by the issues of inadequate machinery and the lack of suitable equipment for practical use. Additionally, mismatches exist between certain vegetable varieties, cultivation practices, and the equipment utilized, and alignment between planting methods and mechanized transplanting processes is lacking.

6.1 Summary of Current Problems

Notable differences in the level and application of automated seedling picking technologies can be observed by comparing the current status of research on automated seedling picking devices in different countries and regions. The significant gap between developed and developing countries can be attributed to a number of factors, such as economic resources, infrastructure and agricultural development, level of technological knowledge, policies, and government support. For these reasons, the scale of vegetable production, cropping patterns, planting densities, and hardware configurations vary in different countries and regions. Future research should focus on addressing the following key issues to enhance the effective implementation of automated seedling picking devices in diverse conditions:

(1) Standards for the production of seedling trays have yet to be fully established. While the number of cavities in the trays has been standardized, the materials used for the pots, the dimensions and depth of the cavities, and the size of the drainage holes lack uniformity. The variety of seedling trays is extensive, with pots made from diverse materials, including soft trays produced from polystyrene and polyvinyl chloride or paper pots made from specialized seedling paper. The aforementioned challenges have hindered the implementation of factory nurseries and significantly constrained the advancement of automated seedling picking devices. Furthermore, certain transplanting machinery, both domestically and internationally, necessitates the use of specific hole trays. For instance, soft cross-bottom hole trays are required for Yoma vegetable transplanting machines, while foam hole trays are essential for Ferrari transplanting machines. This dependency on particular tray types is a primary factor that contributes to the limited versatility of automatic seedling picking devices.

(2) Climatic environments vary greatly in different parts of the globe, which also leads to large differences in vegetable varieties, nursery methods, and transplanting agronomy, restricting the R&D and popularization of automatic seedling picking devices. The seedling picking devices developed by universities and scientific research units have only been tested in the laboratory, lacking field test verification, and their actual seedling picking effect is unknown, resulting in the lack of highly stable, automatic transplanting equipment in the market.

(3) In recent years, the number of research and patents on fully automatic transplanting machine and automatic seedling picking devices has increased with the comprehensive development of mechanized planting. However, the improvement of their seedling picking efficiency is not high. With the increase in seedling picking speed, the success rate of seedling picking decreases drastically, thus having difficulty meeting the requirements for high-speed transplanting machines. In addition, developments in automatic seedling picking equipment are limited to mechanical structure and path optimization, ignoring research in the intelligence aspect, thereby seriously restricting the development of automatic transplanting technology.

(4) The capacity for technological innovation within enterprises is currently limited, and the combination of production, learning, research, and promotion is unable to keep up with the demand, resulting in a low conversion rate of R&D and achievements. The development cycle for automated seedling picking devices is prolonged and entails high investment costs, thus diminishing corporate enthusiasm to pursue fully automated seedling picking technology. Furthermore, the profitability of the vegetable cultivation sector is gradually declining, and substantial initial investments are required for the introduction of automated transplanting equipment, necessitating ongoing maintenance and repair in the future. In addition, the vegetable farming labor force is aging, with a large number of part-time farmers whose education level is relatively low and therefore have difficulty applying new technologies. These factors lead to greater challenges in promoting vegetable transplanting and automated seedling picking technology.

6.2 Future Development Trend

The following development recommendations are proposed to address the challenges associated with automatic seedling picking devices and thus ensure that automatic transplanting machine seedling picking devices can be launched in the market as soon as possible to liberate the labor force, improve the production efficiency, and reduce production costs:

(1) Standards for the production of seedling trays have yet to be fully established. While the number of cavities in the trays has been standardized, the materials used for the pots, the dimensions and depth of the cavities, and the size of the drainage holes lack uniformity. The variety of seedling trays is extensive, with pots made from diverse materials, including soft trays produced from polystyrene and polyvinyl chloride or paper pots made from specialized seedling paper. The aforementioned challenges have hindered the implementation of factory nurseries and significantly constrained the advancement of automated seedling picking devices. Furthermore, certain transplanting machinery, both domestically and internationally, necessitates the use of specific hole trays. For instance, soft cross-bottom hole trays are required for Yoma vegetable transplanting machines, while foam hole trays are essential for Ferrari transplanting machines. This dependency on particular tray types is a primary factor that contributes to the limited versatility of automatic seedling picking devices.

(2) Establishment of uniform standards for potting and seedling production. An efficient mechanized production system should be built synergistically, and the development of uniform standards for selection and breeding must be accelerated. Potting inconsistency is the main reason for the poor versatility of automatic seedling picking devices, and the creation of uniform standards for potting materials, potting cavity size, depth, and bottom hole size can promote the development of automatic transplanting machines, which is conducive to promoting the mechanization of vegetable planting.

(3) Development of high-speed seedling picking devices. At present, the success rate of seedling picking devices developed by various research teams or companies can generally reach more than 90%, but the seedling picking speed is low and cannot meet the requirements of high-speed transplanters. A challenge related to the use of automated seedling picking devices is how to achieve high speed and low damage. Improving the seedling picking rate and reducing the seedling damage rate will be the future development direction of automated seedling picking devices.

(4) Improving the intelligence of seedling picking devices. The integration of technologies such as sensors, computer vision, artificial intelligence, and deep learning into seedling extraction devices can enhance the automation level and intelligence. These technologies can detect the growth condition of potting seedlings, eliminate weak and diseased seedlings, and compensate for the lack of seedlings. Furthermore, the application of intelligent algorithms to control the seedling picking device can improve the precision of seedling extraction while minimizing damage to young plants. The performance reliability of agricultural robots can be significantly improved by incorporating advanced algorithms into existing models, ensuring that transplanting machines operate with high precision, efficiency, and quality during the transplanting process.

7. Conclusions

This study summarizes the gaps and challenges faced by automatic seedling picking devices. High-speed, low-loss universal seedling picking devices should be developed to reduce the damage of pot seedlings on the basis of ensuring the success rate of seedling picking, thus solving the above problems. The devices' high-speed operation will ensure a significant increase in transplanting efficiency, while their low loss characteristics can effectively protect seedlings and reduce mechanical damage during transplanting. With the lack of field operation data monitoring of the seedling picking devices, research on seedling picking devices should be combined with agronomy, informatization, and intelligent technology in future research to realize seamless integration with the agricultural production system, thus providing a reference for the R&D of next-generation automatic transplanting machines.

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