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Transplanting Machinery and Key Components: A Comprehensive Review

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Abstract— *As demand for agricultural products continues to grow, mechanized transplanting technologies and equipment are constantly evolving. Transplanting is one of the primary cultivation methods for crops such as grains, oilseeds, and vegetables, and it represents a critical technical step in crop production, playing a significant role in increasing crop yields. This paper outlines the current state of research on transplanters and their key components. It categorizes and summarizes the research and development of existing transplanters based on their driving modes, classifies transplanting mechanisms according to different seedling retrieval methods and analyzes their working principles, and analyzes and summarizes the existing issues with current transplanters and transplanting mechanisms. Based on these issues, the paper proposes recommendations for future development. High-efficiency, low-damage transplanting technology is key to increasing crop yields, and strengthening the integration of agricultural machinery and agronomy is an important method for reducing crop production costs. Intelligence, full automation, and green, low-carbon operations represent important future research directions for transplanters.*

Keywords— Transplanting machine, transplanting mechanism, intelligent, fully automated, eco-friendly and low-carbo.

I. INTRODUCTION

Crops come in diverse varieties, and their cultivation methods are equally varied. Transplanting is one such method, primarily suited for crops like rice, corn, peppers, tomatoes, cotton, and rapeseed [1]. Rice is a primary staple crop for humanity and ranks among the world's three most significant food crops, with global annual production reaching approximately 450 million tons [2-8]. Vegetables are indispensable in daily diets and constitute a vital component of food consumption. In recent years, the vegetable industry has experienced rapid growth, accompanied by a continuous expansion of vegetable cultivation areas worldwide [9]. The agricultural workforce is currently experiencing a pronounced aging trend, leading to a sharp decline in labor availability and creating a labor shortage in agriculture [10-11]. Faced with the contradiction between growing demand for agricultural products and the rapid depletion of agricultural resources and labor, as well as the challenge of meeting increasing demands for sustainable food production, it is imperative to enhance crop yields per unit area of farmland. Agricultural mechanization and automation play a crucial role in effectively reducing labor intensity and enhancing agricultural productivity [12-14]. To address this contradiction, the mechanization and automation of rice and vegetable transplanting are of significant importance, representing an inevitable trend that improves planting efficiency, reduces labor intensity, and increases crop yields [15]. To further boost agricultural output, research on seedling cultivation and transplanting techniques has been proposed, as this technology can extend the crop growth period [16]. Compared to traditional seedling cultivation methods, greenhouse seedling production offers several advantages, including higher seedling survival rates, stronger stress resistance, shorter cultivation cycles, and reduced pest and disease incidence [17-18]. The transplanting process involves removing seedlings from seedling trays and planting them in the field soil. Mechanized transplanting has become the mainstream method for large-scale vegetable and rice cultivation [19-20]. Transplanting is categorized into manual and mechanized methods. Manual transplanting requires bending or squatting postures, involving monotonous and labor-intensive work. Mechanized transplanting can replace agricultural workers in performing repetitive tasks, reducing labor intensity [21-22]. Mechanized transplanting is further divided into semi-automatic and fully automatic systems [23]. Semi-automatic transplanters lack seedling tray conveyors, requiring manual intervention for seedling retrieval [24]. Compared to semi-automatic and manual methods, fully automatic transplanters operate without human interference. They achieve full automation throughout the entire process—from removing seedlings from trays to conveying and depositing them into planting holes—maintaining high-speed operation. Consequently, they impose stringent requirements on seedling quality [25-27].

Research on transplanters primarily encompasses studies on the main body of transplanters and transplanting mechanisms. Current transplanters primarily include walk-behind transplanters, ride-on transplanters, and unmanned transplanters. Walk-behind and ride-on transplanters are more commonly used in field transplanting operations, while unmanned transplanters are mostly in the experimental stage. Compared to ride-on transplanters, unmanned transplanters utilize autonomous navigation systems and automated control technologies to enable self-propulsion. Navigation systems currently used in agriculture mainly include satellite navigation systems and machine vision systems [28]. The transplanting device is a critical component of transplanters [29-30], responsible for seedling retrieval, transport, and planting. Numerous device types exist, primarily categorized by retrieval method into gripper-type, push-out-type, pneumatic-type, insertion-type, and combination-type. By drive method, they are primarily categorized into mechanical, pneumatic, and mechatronic types. Among mechanical transplanting devices, common designs include planetary gear systems, multi-link mechanisms, and cam-link mechanisms [31].

This paper provides a review of research on crop transplanters. The research framework is illustrated in Figure 1. Specifically, the study systematically summarizes the current research progress and status of various types of transplanters, analyzes the working principles, technologies employed, and operational performance of different types of transplanters, and summarizes various types of transplanting devices, describing their structural composition, working principles, and seedling transplanting performance. Building on this foundation, the paper analyzes the existing issues in the research on transplanters and transplanting devices and discusses the future development prospects of transplanters. It aims to provide a reference for research on crop transplanters and their key components, as well as offer suggestions for the future development direction of transplanters.

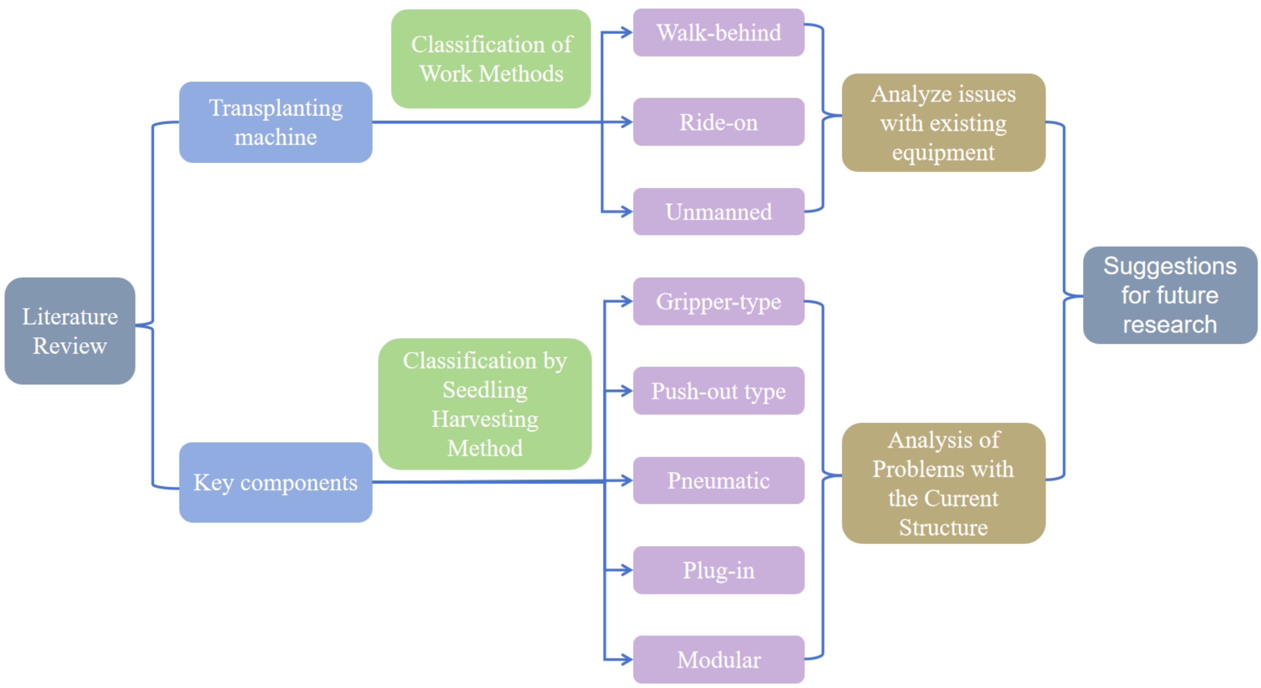


FIGURE 1: Structure of this article

II. CURRENT RESEARCH STATUS OF TRANSPLANTING MACHINES

The transplanting machine is a complex mechanical system primarily comprising drive and control units, chassis, and transplanting working units [32]. Research on transplanters has progressed from walk-behind models to rider-type machines and unmanned transplanters, progressively reducing labor intensity while continuously enhancing operational efficiency to achieve comprehensive automation in seedling transplantation. Currently, widely adopted are high-speed rider-type transplanters, which require an operator to control the machine's movement [33]. Unmanned transplanters, fully autonomous mobile field transplanters, remain largely experimental but have seen partial adoption in agricultural production [34]. Meanwhile, walk-behind transplanters remain prevalent for small-plot transplanting or for replanting seedlings in previously transplanted fields.

2.1 Research on Walk-Behind Transplanters

Research on walk-behind transplanters has enabled the transition from manual to mechanized transplanting, reducing labor intensity and improving operational efficiency. These transplanters feature simple structures and flexible operation, making them suitable for small plots in various terrains. However, despite these advantages, labor intensity remains high during large-scale transplanting, and their efficiency is lower than that of self-propelled transplanters, which limits their suitability for large-scale production.

Currently, numerous simple walk-behind transplanters based on lever mechanisms have been developed. While these designs are low-cost, they require substantial manual effort. As shown in Table 1, which compares four representative simple walk-behind transplanter designs, a common characteristic is that their operation relies entirely on human labor without any auxiliary power source.

TABLE 1
POLE-BASED MANUAL WALKING TRANSPLANTER WITHOUT ADDITIONAL POWER

Machine Type	Developer/ Organization	Features	Machine Images
4-row manual rice transplanter	Bangladesh Rice Research Institute [35]	This transplanting machine features a pull-back design, allowing adjustment of plant spacing during transplanting, with an operational efficiency of 0.033 hectares per hour.	
Artificial Rice Transplanter Based on a Four-Bar Mechanism	Vibhakar C. et al[36].	This compact machine is designed to meet the operational needs of small-scale farmers.	
Reconfigurable Four-Bar Linkage Transplanter	Felezi M.E. et al[37].	Adjustable planting row spacing and planting depth	
Manual Two-Row Vegetable Transplanter	Thorat P. V. et al[38].	Four seedlings can be planted at once, achieving an operational efficiency of 463 plants per hour.	

The use of external power significantly reduces manual labor intensity, as the transplanting operations of such machines no longer rely on human strength, thereby greatly enhancing transplanting efficiency. Yuan Xinbin et al. innovatively designed a lever-based ejection-type ordered transplanting machine [39], as shown in Figure 2(a). This machine features an innovative gear-driven automatic tray feeding mechanism. Operated by an operator walking alongside to control its movement, it achieves the required plant spacing for seedling transplantation. Yanmar Agricultural Machinery developed the Yanmar AP4 hand-guided step-type transplanting machine [40], as shown in Figure 2(b). This machine is manually guided and driven, employing a crank-rocker transplanting mechanism. It features four working rows with four adjustable planting row spacings. Both the longitudinal seedling feed rate and planting depth are adjustable. Its relatively simple mechanism makes it suitable for small field operations.

(a) (b)

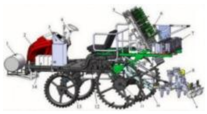
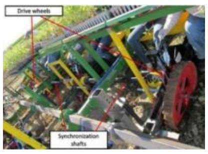
FIGURE 2: (a) Ejector ordered transplanter [39]; (b) Yanmar AP4 walk-behind stepper transplanter [40]

2.2 Research on Ride-on High-Speed Transplanter

Currently, ride-on high-speed transplanters are widely used for transplanting operations. These machines feature high automation levels and enable large-scale transplanting. They require manual operation for transplanting seedlings. Some models incorporate automated navigation technology, which substantially reduces operator workload [41]. By adopting a human-machine collaboration model and high-speed operation, these machines significantly enhance the efficiency and quality of large-scale transplanting. The shift to seated operation for transplanters greatly reduces operator fatigue, enabling extended working hours during transplanting operations.

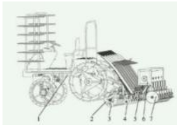
In the development of ride-on transplanters, various methods have been employed to continuously enhance the efficiency and quality of crop transplanting. Progress has been made from manual seedling feeding and transplanting to mechanized automatic seedling delivery and transplanting, progressively reducing the labor intensity of transplanting operations. As shown in Table 2, four representative ride-on transplanters are presented, all of which effectively meet the agronomic requirements for crop transplanting.

TABLE 2
RIDE-ON HIGH-SPEED TRANSPLANTER

Machine Type	Developer / Organization	Features	Operational Performance	Machine Images
Semi-Automatic Seedling Transplanter for Vegetables[42].	Xin Jin et al.	Manual operation is required to complete seedling removal and feeding.	Two rows can operate simultaneously; transplanting frequency reaches 50-70 plants per minute; seedling upright rate is 93% to 91.1%; planting depth compliance rate is 96% to 92%.	
PF2R Automatic Transplanter[43].	Yanmar Company.	Adjustable planting spacing and planting depth	Capable of transplanting two rows simultaneously, with a transplanting efficiency of 2.55 mu per hour, and featuring automatic seedling delivery.	
Ride-on Fully Automatic Vegetable Seedling Transplanter[44].	Han Luhua et al.	Capable of automatically conveying seedling trays, it fully utilizes integrated electromechani-cal, pneumatic, and hydraulic system engineering to achieve automated seedling transplanting.	Capable of simultaneous operation on two rows; transplanting frequency reaches 40-60 plants per minute; both seedling retrieval success rate and planting qualification rate exceed 90%.	 1. Air compressor; 2. Engine; 3. Control system; 4. Operating system; 5. Feeding mechanism; 6. Pick-up mechanism; 7. Rotary discharge mechanism; 8. Planting mechanism; 9. Soil covering ring; 10. Hydraulic lifting mechanism; 11. Driving wheel; 12. Frame; 13. Driven wheel; 14. Battery.
Three-Row Precision Synchronous Transplanter[45].	Manuel Perez-Ruiz et al.	Enables precise control of three rows working in sync during seedling transplanting operations, ensuring transplanted seedlings are aligned in a grid-like rectangular pattern.	Three rows transplanted simultaneously, with the machine traveling at 1.6 km/h and a row spacing of 380 mm.	

Some developed ride-on transplanters incorporate additional functions tailored for transplanting operations beyond their core transplanting capability. This enables them to perform other planting tasks concurrently while completing crop transplantation. Multifunctional transplanters reduce the number of machines entering the field, minimize soil disturbance, save planting time, and improve transplanting quality. However, their complex machinery structure and the need for coordinated interaction among multiple components present significant technical challenges in both development and operation. Table 3 lists three representative multifunctional transplanters.

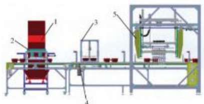
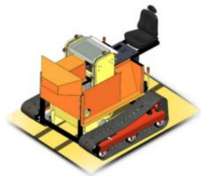
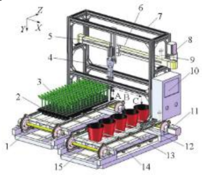
TABLE 3
RIDE-ON MULTI-FUNCTION TRANSPLANTER

Machine Type	Developer	Additional features	Advantages	Operational Performance	Machine Images
2ZY-6 Rapeseed Mat Seedling Transplanter [46].	Wu Jun et al.	Cutting slits, transplanting, and covering with soil while firming down	Improve the efficiency and quality of crop transplanting	In rice stubble fields: The machine's travel speed must be within 1.15 m/s; planting pass rate reached 85.66%. In dry fields: The machine's travel speed must be between 0.8 and 1.2 m/s; planting pass rate reached 87.01%.	 1. Rice transplanter chassis; 2. Power cutting disc; 3. Forming roller; 4. Dryland profiling device; 5. Transplanting device; 6. Counterweight box; 7. Soil covering and suppression mechanism.
Automatic Tray Seedling Transplanter [47].	Han Changjie et al.	The transplanting condition monitoring system has been added, enabling real-time observation of transplanting conditions[48].	Adjust transplanting operations in a timely manner according to transplanting conditions to ensure the quality of transplanting operations.	Transplanting machine operating speed: 1.4–1.7 km/h; Planting frequency: 123 plants/min; Transplanting success rate: 97.07%; Lodging rate: only 1.67%.	
Multi-Function Vegetable Seedling Transplanter [49].	Shao Yuanyuan et al.	Laying drip irrigation tape and covering with plastic film, transplanting seedlings, applying fertilizer, covering with soil, and watering	Effectively reduce the number of times machinery enters the field and minimize repeated soil compaction damage.	Transplanting frequency: 57–88 plants per minute; Average seedling survival rate: 96.4%–98.6%; Qualified planting depth rate: 97.2%–99.0%.	

2.3 Research on Unmanned Transplanting Machines

Due to high labor costs and labor shortages, unmanned transplanters have gradually become a popular research direction for transplanters [50]. The fundamental technologies of unmanned transplanters encompass robotic arm technology, visual recognition systems, autonomous navigation systems, path tracking control technology, and automated control systems [51]. Compared to high-speed rider-type transplanters, unmanned transplanters operate via automated control and can autonomously navigate along pre-planned paths [52]. Eliminating the need for manual operation significantly reduces labor requirements while enhancing transplanting efficiency and quality. Table 4 details three existing unmanned transplanting machines, providing comprehensive specifications for each.

TABLE 4
UNMANNED TRANSPLANTER

Machine Type	Developer	Function	Operational Performance	Machine Images
High-Efficiency Fully Automatic Pot Seedling Transplanter for Greenhouses[53].	Hu Jianping et al.	Features automatic backfilling, hole digging, positioning conveyance, and rapid, smooth planting capabilities.	Movement error ranges from 0.15 to 1.22 mm; Transplanting frequency: 120 plants per minute; Transplanting pass rate reaches 90.23%.	 1. Soil loader; 2. Soil filling device; 3. Hole punching device; 4. Conveying device; 5. Transplanting device;
Electric Self-Propelled Dual-Row Transplanter [54].	Ning Mengjiao et al.	Capable of performing integrated operations including furrow opening, seedling retrieval, soil covering, and plastic mulching.	Machine travel speed: 0.14 km/h; Transplanting success rate: 88%; Seedling survival rate: 86%.	
Lightweight Automatic Transplanter for Greenhouse Seedling Trays[55].	Han Luhua et al.	Capable of performing automated seedling feeding, delivery, and transplanting operations.	For 128-cell and 72-cell seedling trays, transplanting efficiency reached 1,221 plants per hour and 1,025 plants per hour respectively; transplant success rate achieved 90.70% in both cases; seedling pot breakage rate remained below 5%.	 1. Source plate conveying mechanism; 2. Hole disc; 3. Plug seedling tray; 4. Seedling terminal effector; 5. Rodless cylinder; 6. Linear module; 7. Frame; 8, 11. Motor; 9. Photoelectric switch; 10. Control system; 12. Flower pot; 13. Conveyor chain; 14. Beam rod; 15. Target disc conveyor mechanism.

2.4 Comparison of Different Types of Transplanters

Based on the operator's working methods, existing transplanters are categorized into the three types above, each with distinct advantages and disadvantages. A comparative analysis is presented in Table 5.

TABLE 5
COMPARISON OF TRANSPLANTER TYPES

Type	Applicable scenarios	efficiency	peculiarity	How it works	Labor intensity
Walk-behind transplanter	small fields, hilly mountains and seedling replenishment operations	Low	Low cost, simple structure, light and flexible	Walk with the randomizer	Big
Ride-on transplanter	Large-scale plains and large-scale operations	High	High degree of automation, easy operation, balance cost and efficiency, currently widely used	Operate in the cockpit	Small
No one transplanter	Greenhouse planting	Higher	Achieve full automation, high operation accuracy, good quality and high degree of intelligence	The transplanter can be remotely controlled	Basically none

III. CURRENT RESEARCH STATUS OF TRANSPLANTING DEVICES

The transplanting mechanism is a critical component of transplanting machines [56]. Its design must ensure high operational efficiency, minimal seedling damage, and prevent seedling displacement [57]. Addressing these design requirements, current research on transplanting mechanisms encompasses multiple types [58]. Classified by seedling retrieval methods, they primarily include gripping-type [59-60], insertion-type [61], ejection-type [62-63], pneumatic [64], and combined types [65].

3.1 Pinch-Type Transplanting Mechanism

The gripping seedling retrieval method involves directly grasping the seedling stem, seedling pot, or entire seedling with an end-effector to perform seedling retrieval, transport, and planting operations. By designing appropriate motion trajectories, gripper-type transplanting mechanisms can minimize damage to seedlings while enhancing transplanting efficiency. This method imposes higher requirements on seedlings, necessitating thicker stems, and carries a higher risk of stem damage. Based on mechanical structure, these mechanisms can be further categorized into rod-driven transplanting mechanisms and gear-driven transplanting mechanisms.

3.1.1 Transplanting Mechanism of the Rod Mechanism

Research on transplanting mechanisms based on rod mechanisms is extensive, encompassing types such as connecting rod slide mechanisms, multi-link mechanisms, crank-connecting rod mechanisms, and crank-rocker mechanisms. While these mechanisms offer advantages like low cost and simple structure, their transmission stability is poor, making them unsuitable for high-speed transplanting. Vivek P et al. developed a pneumatic automatic vegetable seedling transplanting mechanism [66].

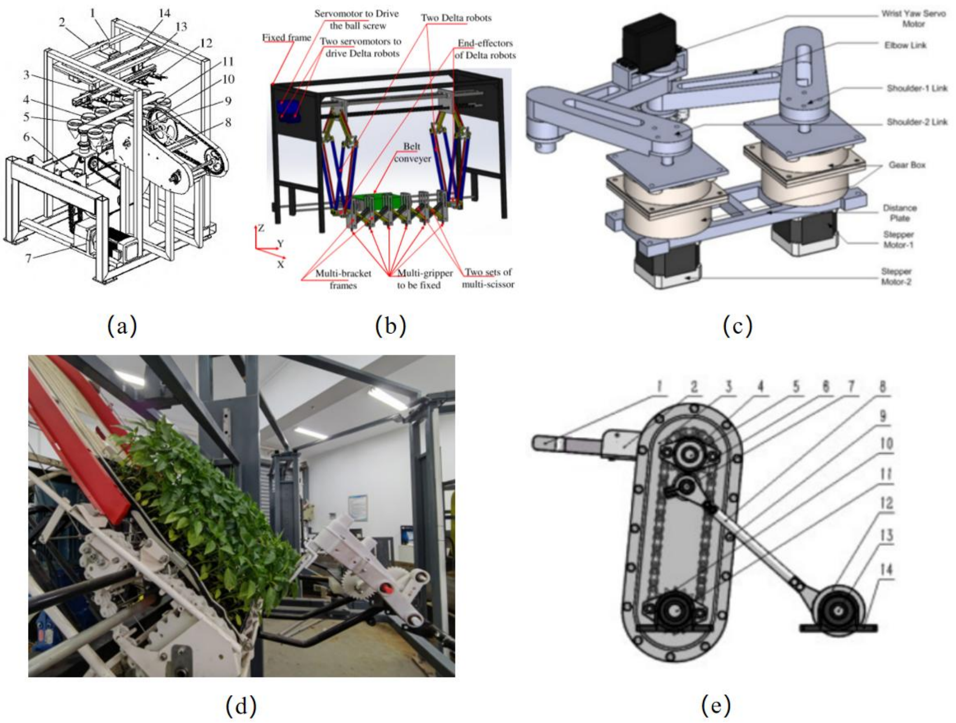


FIGURE 3: Transplanting Mechanism Based on a Rod Mechanism. (a) The whole row of stem seedling picking devices [67]; (b) Three-degree-of-freedom multi-grip potting and transplanting mechanism [68]; (c) 2-degree-of-freedom parallel transplanting mechanism [70]; (d) Clamping stem-type picking and planting integrated automatic transplanting mechanism [71]; (e) Crank Rocker Stem Gripper Potting Device [72]

This mechanism adjusts the opening size of the seedling gripper according to stem thickness, reducing seedling damage. Set at a transplanting speed of 20-25 plants per minute, it achieved an average transplanting success rate of 89.59%. Wang et al. designed a pneumatic stem-gripping automatic seedling picker [67], as shown in Figure 3(a). At a transplanting speed of 75 plants per minute, this mechanism achieved a 97.36% seedling pickup success rate with a substrate breakage rate of 5.07%, meeting transplanting requirements. Assal, S. F. et al. proposed a partially decoupled 3-degree-of-freedom (DOF) multi-claw pot seedling transplanting mechanism for open agricultural fields [68-69], as shown in Figure 3(b). It can remove seedlings from seedling trays and plant them individually, verifying its safety in terms of force and deformation. K. Rahul et al. designed a 2-DOF parallel transplanting mechanism [70], as shown in Figure 3(c). Employing mechatronic integration, this mechanism achieves automation with a simplified structure, utilizing microcontrollers and sensors to enable precise grasping and placement of seedlings. Hu et al. designed a stem-gripping integrated harvesting and transplanting mechanism [71], as shown in Figure 3(d). This mechanism achieved a seedling retrieval success rate of 91.1%, a transplanting success rate of 78.5%, and an uprightness qualification rate of 94.9%. Cai et al. proposed a novel crank-rocker stem-gripping pot seedling transplanting device [72], as shown in Figure 3(e). This mechanism features a simple structure. At a transplanting speed of 50 transplants per minute, the missed transplant rate and seedling damage rate were 2.14% and 3.57%, respectively, essentially meeting transplanting requirements.

3.1.2 Gear Mechanism Transfer Device

The transplanting mechanism with a gear system utilizes gear transmission to plan the motion trajectory of the end effector, incorporating components such as circular gears, elliptical gears, and non-circular gears. This type of transplanting mechanism can rotate to perform transplanting operations, offering high transplanting efficiency, smooth operation, and high transmission precision. However, its structure is relatively complex, gear manufacturing costs are high, and its design requires optimization of structural parameters to meet transplanting requirements, presenting significant design challenges. Xin et al. proposed an elliptical gear-based double-crank five-bar transplanting mechanism [73], as shown in Figure 4(a). This mechanism sequentially performs seedling pickup, seedling delivery, and planting actions, forming a figure-eight trajectory. It features a simple structure and low cost, achieving a 98% seedling pickup success rate at 100 rpm. The team also developed a non-circular gear-linkage combination transplanting mechanism [74], as shown in Figure 4(b), enabling coordinated execution of four processes: seedling pickup, seedling delivery, film perforation and hole digging, and planting. Bench tests yielded a 94% seedling pickup success rate and 92% transplanting success rate, meeting the requirements for mechanized integrated rice seedling tray film transplanting. Ye et al. designed a planetary gear-based tray seedling transplanting mechanism utilizing incomplete eccentric circular gears and non-circular gear transmission [75], as shown in Figure 4(c). This mechanism can perform two operations per rotation cycle, achieving a transplanting efficiency of 200 seedlings per minute.

(a) (b) (c)

FIGURE 4: Gear-driven transplanting mechanism. (a) Elliptical Gear-Double Crank Five-Bar Transplanting Mechanisms [73]; (b) Non-circular gear-linkage combination transplanting mechanism [74]; (c) Planetary wheel system hole tray seedling transplanting mechanism [75]

3.2 Plug-in Transplanting Mechanism

The insert-type transplanting mechanism directly inserts the seedling-picking needle or end-effector gripper into the seedling pot. Through mechanical transmission, it performs insertion and withdrawal actions, transplanting seedlings along a predetermined trajectory. Based on mechanical structure, it is primarily divided into slide-type and gear-type transplanting mechanisms. This type of transplanting mechanism features a simple structure and high operational efficiency, making it a widely adopted seedling retrieval method. However, it can cause damage to the seedling roots, necessitating the cultivation of high-quality seedling substrates during the nursery stage.

3.2.1 Transfer Mechanism for Slide Structures

The slide-guided insertion transplanting mechanism constrains the movement trajectory of the planting arm or end effector via a slide, coordinating with the transplanting mechanism to complete transplanting operations. This type of mechanism offers high seedling retrieval stability and minimal damage to seedlings. However, its transplanting efficiency is low, necessitating auxiliary control systems or multiple seedling retrieval mechanisms to enhance efficiency. Choi et al. from South Korea developed a five-bar slider transplanting mechanism [76], as shown in Figure 5(a). Its structure is simple and exhibits high seedling pickup success rates, but its pickup efficiency is low, reaching only 30 plants/(min·row). Yue et al. designed a fully pneumatic reciprocating seedling pickup device [77], as shown in Figure 5(b), achieving transplanting frequencies of 120 plants/min and 144 plants/min. Its average seedling pickup success rate reached 97.9%, with a planting success rate of 95.3%. The team also developed a dual-row seedling picker and its control system [78], as shown in Figure 5(c). This device achieves a picking efficiency of 180 plants/min with a transplant success rate of 97.3%, significantly enhancing transplant efficiency. Its flexible pneumatic end-effector design effectively reduces damage to seedling roots. Han's team proposed a novel pre-bending transplanting method, employing a mechanism combination innovation approach to design a side-entry horizontal-transplanting manipulator [79], as shown in Figure 5(d). This device effectively retrieves seedlings with minimal damage, achieving an automatic transplanting success rate of 97.57%. A simplified automatic transplanting device was also designed [80], as shown in Figure 5(e), featuring a straightforward structure that achieves efficient, low-consumption seedling transplantation at a rate of 15 plants/min/grip with a 95.47% success rate. Shi et al. designed an eight-row duckbill-type planting mechanism driven by an electric motor and pneumatic cylinder [81], as shown in Figure 5(f). This mechanism achieved a qualified transplanting rate of 96.62% and a transplanting efficiency of 7,135 plants per hour, meeting the agronomic requirements for dense planting with small plant spacing and row spacing.

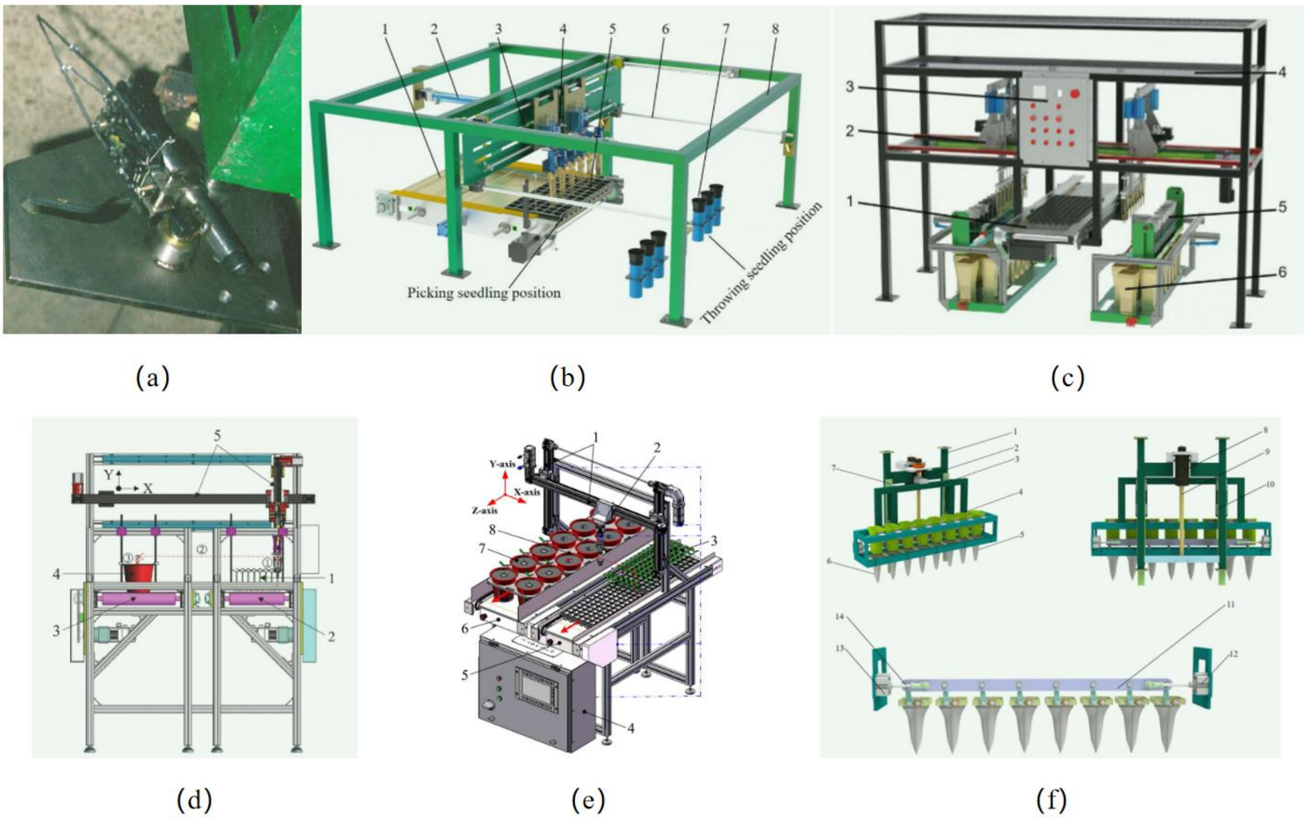


FIGURE 5: Insertion Transplanting Mechanism with Slide Structure. (a) Five-link chute transplanting mechanism [76]; (b) Reciprocating seedling picker with full pneumatic drive [77]; (c) Double-row seedling pick-up device [78]; (d) New pre-bent seedling transplanting robot [79]; (e) Simplified greenhouse transplanting robot cell [80]; (f) Eight rows of duckbill planting mechanism [81]

3.2.2 Gear-Based Transfer Mechanism

The gear-driven insertion transplanting mechanism is similar to the gripping transplanting mechanism described in Section 3.1.2. Both share the same advantages and disadvantages, providing stable transmission while posing significant challenges in planning the end-effector's motion trajectory. These challenges include strong coupling and numerous parameters in the mechanism's optimization. ISLAM et al. proposed a novel long-needle multi-gripping automatic transplanting mechanism [82], as shown in Figure 6(a). This mechanism is suitable for small transplanters, employing a gear-driven crank-slider system to achieve a linear seedling retrieval trajectory. Zhou et al. developed a fully automatic rotary transplanting mechanism for vegetable seedling pots [83], as shown in Figure 6(b). This mechanism performs a series of operations including seedling picking, transportation, plastic film penetration, shaping, and planting, achieving a seedling picking success rate of 92.4% [84]. Sun et al. proposed a transplanting mechanism featuring a two-planetary-frame symmetrical structure driven by a cam-epicyclic gear combination mechanism [85], as shown in Figure 6(c). This mechanism utilizes the combination to generate variable-speed oscillation, forming a pointed-nose seedling-picking trajectory. The transplanting mechanism operates at 60 r/min with a seedling-picking success rate of 93%. Xu et al. designed a variable-speed well-type hole-forming transplanting mechanism for hilly terrain transplanters [86], as shown in Figure 6(d). This mechanism employs a parallel four-bar linkage based on non-circular gears. The interaction patterns between the hole-forming mechanism and soil were analyzed to optimize the mechanism's parameters. Yu et al. proposed a hybrid six-bar single-degree-of-freedom integrated seedling-picking and planting mechanism constrained by non-circular gears [87], as shown in Figure 6(e). This mechanism achieves an "eagle-beak-shaped" static trajectory for seedling retrieval and an "approximate straight-line" dynamic trajectory for planting. At rotational speeds of 25–45 r/min, it achieves a 96.1% seedling retrieval success rate and a 91.4% planting success rate.

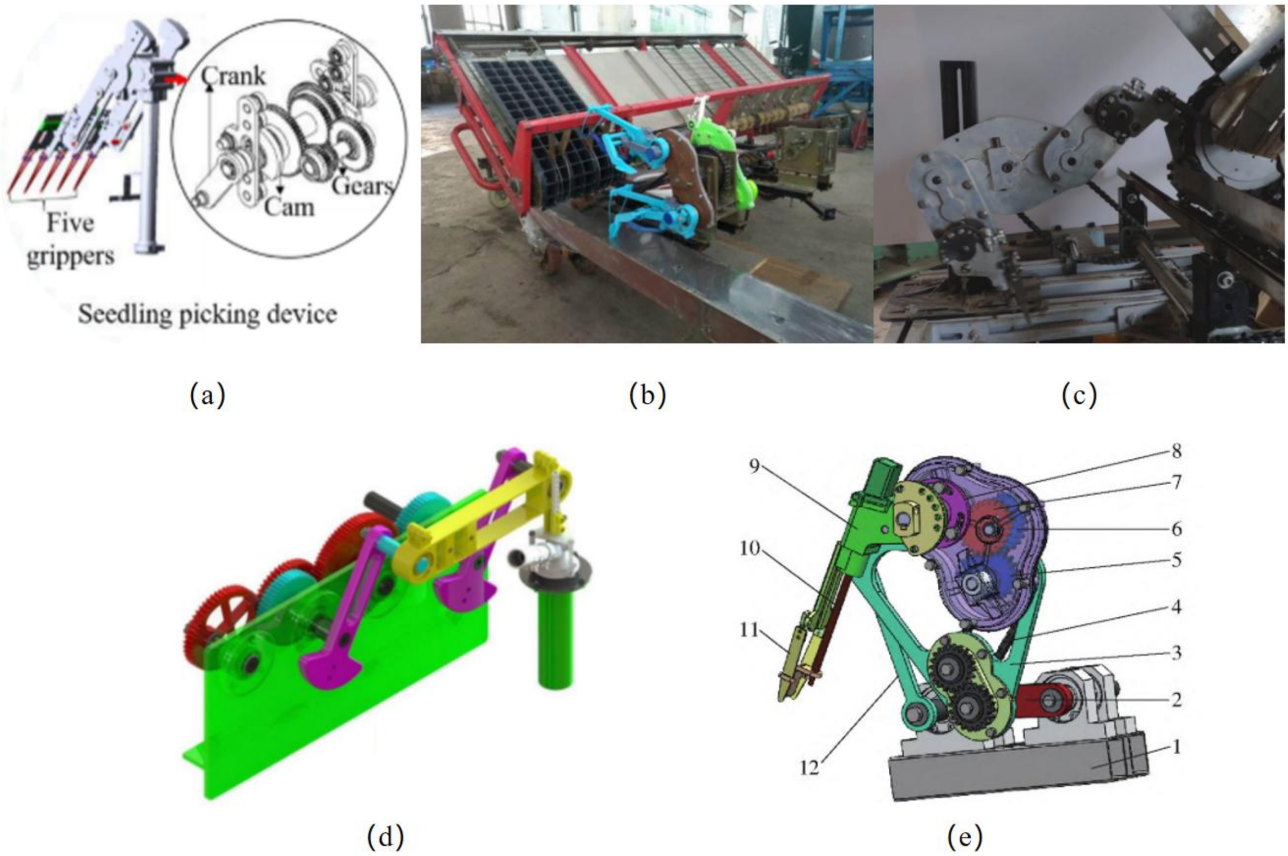


FIGURE 6: Insert-type transplanting mechanism with gear structure. (a) Long-needle multi-clamp automatic transplanting mechanism [82]; (b) Fully automatic rotary transplanting mechanism for vegetable potting plants [83]; (c) Plant-integrated transplanting mechanism [85]; (d) Variable speed well cellar type hole forming transplanting unit [86]; (e) Integral transplanting mechanism for picking and planting [87]

3.3 Ejector-Type Transplanting Mechanism

The push-out seedling removal method employs a push rod that passes through the drainage holes at the bottom of the seedling tray to eject the seedlings. These seedlings are then collected by a conveyor belt or a dedicated seedling removal mechanism. This mechanism features a simple structure and results in low seedling damage rates. However, it requires precise alignment of the drainage holes at the tray bottom, with equal center-to-center distances between adjacent holes [88-89].

SUGGS et al. developed a transplanting mechanism that uses a push rod to eject seedlings and employs a needle-type picker for seedling retrieval, achieving a picking efficiency of 180 plants per minute. However, this method results in partial loss of root soil during seedling extraction [90]. Zhang et al. proposed a rotary-type ordered seedling-throwing device based on a push-rod ejection mechanism [91]. This device uses a push rod to dislodge seedlings from trays, which then fall into the field via guide tubes under gravity to complete transplanting. Wang et al. designed a pneumatic downward-pressure high-speed seedling picker [92], as shown in Figure 7. They developed a high-speed seedling picking sequence and control system, achieving a picking frequency of 120 plants/min with a 100% success rate. The substrate breakage rate was 22.46%, and the stem and leaf damage rate was 3.54%.

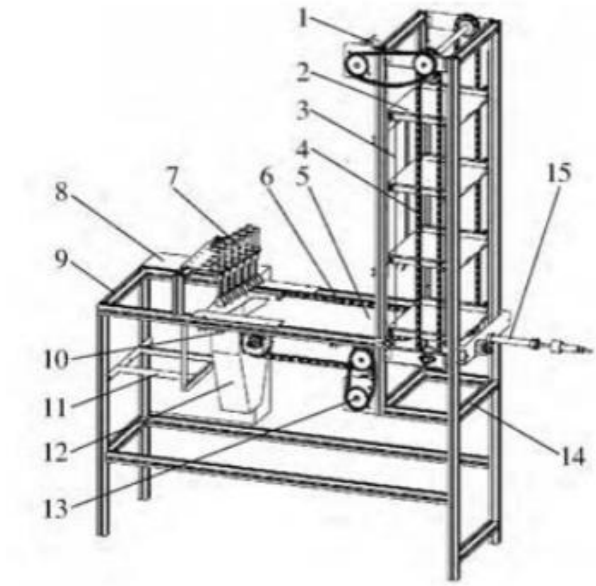


FIGURE 7: Pneumatic downward pressure type high-speed seedling extraction device [92]

Wen et al. designed an insert-and-eject seedling removal device [93], as shown in Figure 8. This device employs a combined mechanical-electrical-pneumatic drive system to achieve automated transplanting operations. When tested with 30-day-old seedlings, it achieved a removal rate of 120 plants per minute, a success rate of 97.22%, and a seedling damage rate of 1.39%.

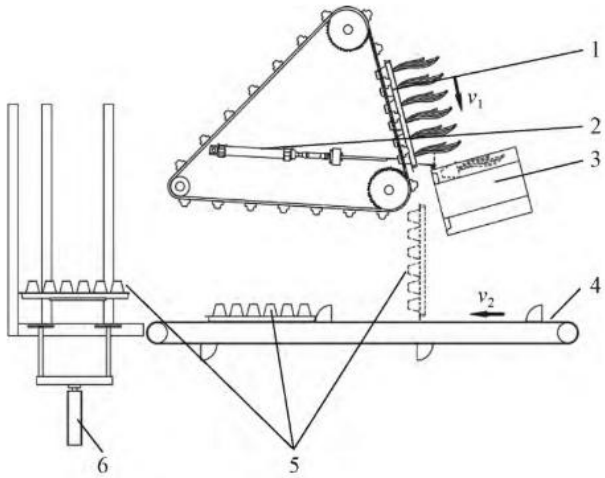


FIGURE 8: Ejector type seedling extraction device [93]

3.4 Pneumatic Transplanting Mechanism

The core of pneumatic transplanting mechanisms lies in utilizing airflow dynamics to extract seedlings from seedling trays, minimizing mechanical contact damage to young plants. However, this type of mechanism consumes relatively high energy and demands precise control over airflow intensity. It primarily employs compressed air to create pressure differentials for seedling handling, and can be categorized into two methods: suction-type and blowing-type seedling extraction.

Bao et al. developed an air-suction transplanting mechanism that utilizes a negative-pressure fan and microcontroller to coordinate control of air pressure within the seedling tube, enabling seedling retrieval and placement through air suction [94].

Luo et al. developed a pneumatic seedling removal device [95-96], which employs a jet airflow generated by an air compressor directed at the bottom of the seedling tray to blow seedlings out into a seedling guide tube, thereby completing the removal process. Yuan et al. designed a composite air-blowing and vibration seedling removal mechanism for vegetable transplanting [97], where a vibration device reduces friction between some seedling pots and the tray, followed by an air-blowing device that blows the seedlings into the guide tube to complete removal. Mao et al. developed an automatic row-based seedling removal device that uses air force to eject seedlings from trays [98]. As shown in Figure 9, it integrates mechatronics with a pneumatic system to achieve automated, high-speed seedling removal and ejection while minimizing damage to seedlings. Tests demonstrated that this device achieves a seedling removal success rate exceeding 95%, with removal efficiency meeting transplanting requirements.

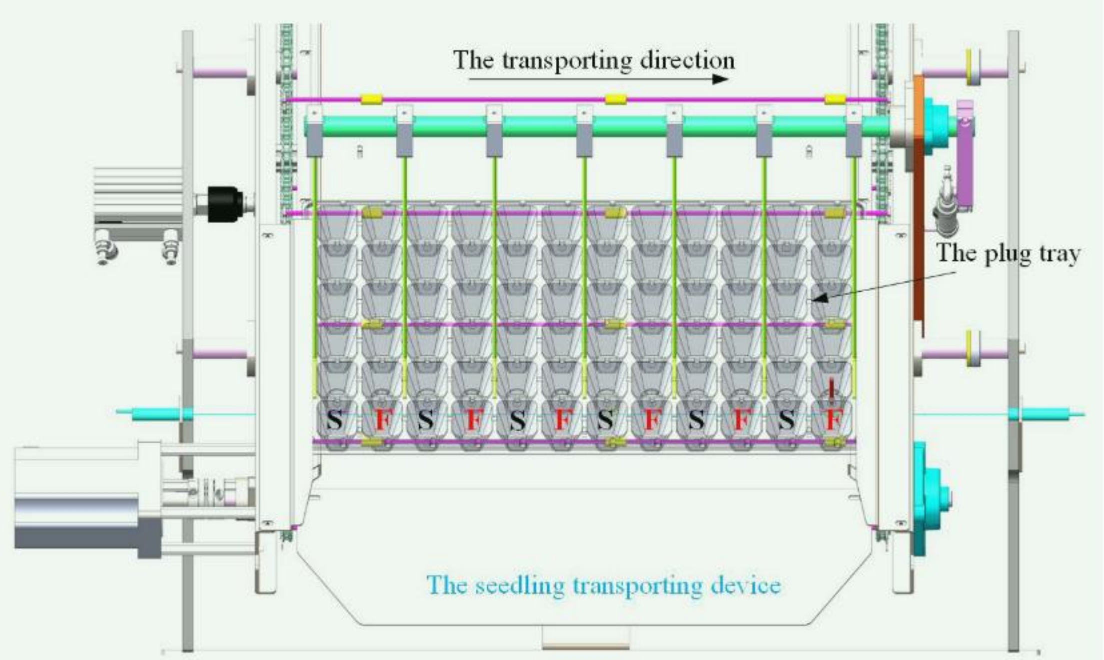


FIGURE 9: Air-blown whole-row automatic seedling pick-up device [98]

3.5 Combination Transplanting Mechanism

A combined transplanting mechanism integrates two or more seedling-picking methods, leveraging the advantages of each to achieve efficient, low-damage seedling retrieval. However, this mechanism features a complex structure and higher production costs.

Han et al. designed and manufactured a novel seedling-picking device [99], as shown in Figure 10. This device integrates mechanical, electrical, and pneumatic technologies to achieve efficient seedling transplantation while minimizing damage to the roots.

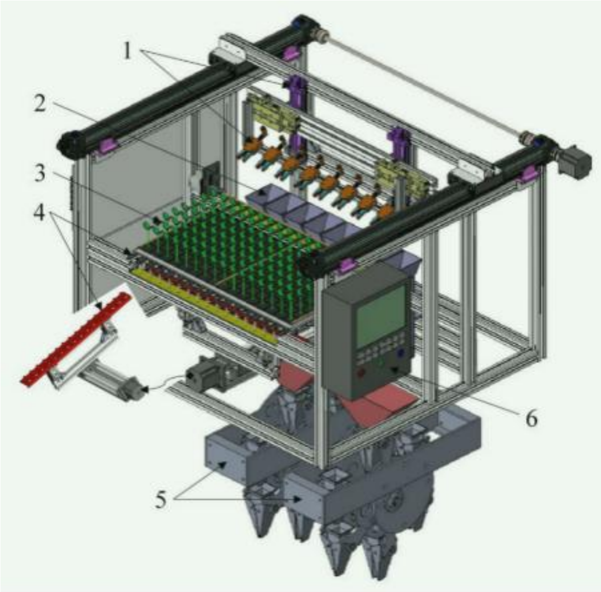
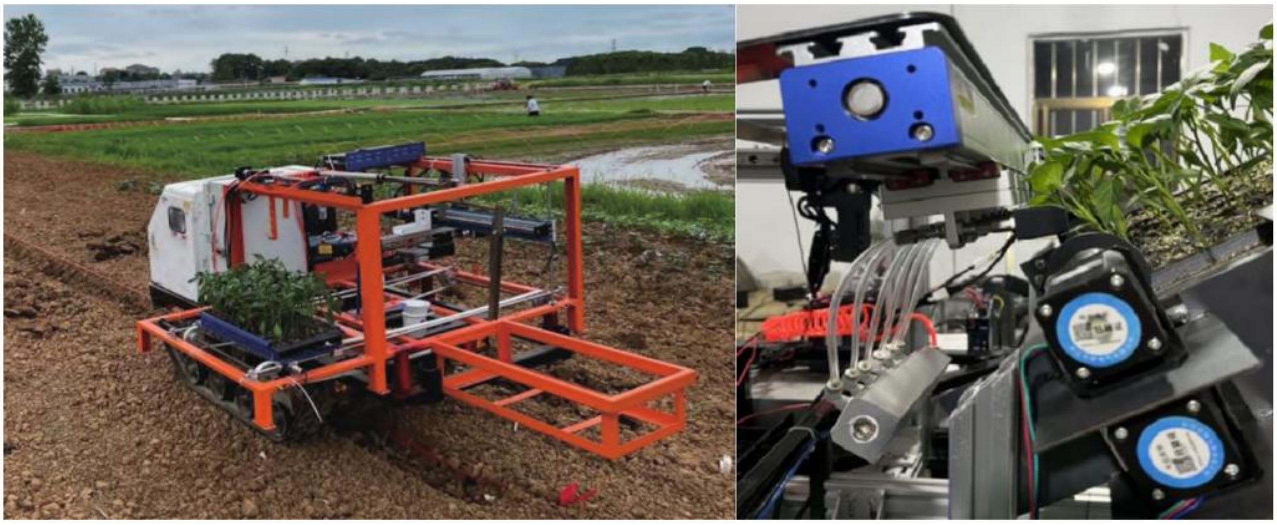


FIGURE 10: New high efficiency transplanting and picking up device [99]

The push-and-grip seedling removal device is currently one of the most extensively researched modular seedling removal systems. Zhang developed a push-pot-grip-stem transplanting mechanism [100], as shown in Figure 11(a). This mechanism combines a push-pot unit with a grip-stem seedling removal and placement unit to achieve both functions. Field trials demonstrated an average seedling removal success rate of 93.05% with a qualified plant spacing rate of 88.17%. Ni et al. designed a similar push-and-grip transplanting mechanism [101], incorporating a PLC-based control system that utilizes pneumatic cylinders and hydraulic motors to execute transplanting operations. Song et al. developed a crank-rocker-type seedling-picking mechanism based on the push-and-grip method. Its gripping force is powered by a return spring, enabling precise control over gripping intensity. However, due to the significant inertial forces of the linkage mechanism, this design exhibits relatively low transplanting efficiency [102]. Zhou et al. developed an automated seedling pickup and placement mechanism integrating electric and pneumatic systems [103], as shown in Figure 11(b). This system employs an electromagnetic ejector pin mechanism coordinated with pneumatic flexible grippers to perform ejection and grasping actions. At a transplanting speed of 72 plants per minute, it achieved a transplant success rate of 91.69%.



(a) (b)

FIGURE 11: Ejector-gripper type seedling removal device. (a) Top Pot - Stem Clamping Transplanting Mechanisms [100]; (b) Automatic transplanting machine with electrical combination [103]

3.6 Comparative Analysis of Transplanting Mechanisms

Transplanting mechanisms are classified into five types based on different seedling retrieval methods: gripping, insertion, pneumatic, ejection, and combination. Each type possesses distinct advantages, disadvantages, and implementation forms, as shown in Table 6.

TABLE 6
COMPARISON OF TRANSPLANTING MECHANISMS FOR DIFFERENT SEEDLING REMOVAL METHODS

Type of transplanting mechanism	Forms of realization	Vantage	Damage to seedlings	Economic evaluation
Clamping type	Seedlings are picked up by clamping the stalks or pots with the seedling clamps.	Capable of adapting to seedlings of different sizes and forms; relatively simple structure, suitable for high-speed operation.	Easily injures young stems.	High requirements for seedling growth conditions, requiring sturdy stems and a long seedling cultivation period.
Inserted type	Insert the needle into the pot and remove the seedling.	It causes little damage to seedlings and can be adapted to a wide range of substrate types.	Easily causes seedling substrate to break apart, damaging seedling root systems.	High requirements for seedling substrate and seedling cultivation techniques.
Pneumatic type	Sucking or blowing seedlings out of seedling trays using air currents.	No contact seedling extraction, no mechanical damage, multiple seedlings can be operated at the same time.	Easily lost seedlings, damaged seedling substrate.	High energy consumption, high costs, highly susceptible to environmental influences, and stringent requirements for controlling air pressure.
Ejector type	Ejecting seedlings from the bottom of the seedling tray using an ejector bar.	No contact with seedling stems and leaves, minimal damage, precise seedling extraction, high stability.	Low damage rate to seedlings, mainly damaging the roots of seedlings.	Requires special seedling trays, which are costly, not very versatile, and have a complex structure.
Combinatorial type	Utilizes two or more structures that work in conjunction with each other to complete the seedling extraction.	More adaptable, with higher seedling extraction efficiency and success rate, able to cope with complex seedling conditions.	Low seedling damage rate.	Complex structure, high cost, difficult to control, requires simultaneous coordination of multiple components.

IV. CURRENT ISSUES

4.1 Problems with Existing Transplanters

1) **Limited functionality:** Existing transplanters have limited functionality, with most capable only of transplanting crops. Crop cultivation involves multiple planting processes, each essential for high yields. For instance, field operations often require additional tasks like mulching, irrigation, and fertilization. This necessitates specialized machinery entering the field to perform these functions, thereby reducing the need for multiple machine purchases. However, frequent entry of agricultural equipment into fields can lead to soil compaction and crop damage.

2) **Insufficient intelligence:** Existing transplanters lack sufficient intelligence. Although research on unmanned transplanters exists, most remain in the experimental stage or are limited to greenhouse use, unable to operate in the complex field environment. Most ride-on transplanters still require manual assistance for seedling feeding during transplanting, limiting transplanting efficiency. This approach is prone to missed plants and cannot dynamically adjust planting parameters such as spacing and depth. It also fails to provide timely evaluation and feedback on transplanting quality. Overall transplanting operations thus require significant labor costs.

3) **Limited versatility:** Existing transplanters have limited versatility, with each model capable of transplanting only one specific crop. Different farmland environments require distinct transplanters for operation. High-speed transplanters designed for large-scale operations prove ineffective in mountainous terrain, hilly landscapes, and small plots. Employing multiple transplanters increases costs. Furthermore, most transplanter designs cater to single crop types, necessitating equipment changes when transplanting different crops—further elevating agricultural production expenses.

4) **Environmental concerns:** Existing transplanters are predominantly powered by diesel or gasoline engines. This drive method causes environmental pollution, which is inconsistent with the future trend of green and low-carbon agriculture. Additionally, such transplanters generate significant noise. Research on electric transplanters remains limited, and they are primarily suited for greenhouse transplanting. Their batteries have limited endurance, preventing continuous operation over large areas, and they often suffer from insufficient power.

4.2 Problems with Existing Transplanting Mechanisms

1) **Seedling damage:** Existing transplanting mechanisms pose issues of seedling damage. Different seedling retrieval methods cause varying forms of damage due to their distinct operating principles: gripping methods may damage seedling stems, while insertion, pneumatic, and ejection methods may compromise seedling pots. Such damage can lead to slow post-transplant development, reduced seedling survival rates, and ultimately lower crop yields.

2) **Instability and complexity:** Existing transplanting mechanisms suffer from instability and complexity. The cam-rod mechanism generates significant vibration during transplanting, leading to unstable operation and reduced precision in seedling pickup and placement. This results in issues such as missed transplants or inconsistent planting depths. While planetary gear mechanisms offer stable transmission, their complex structure incurs higher production costs and requires advanced machining techniques. Maintenance of these mechanisms also incurs substantial expenses. Additionally, some transplanting mechanisms require specialized seedling trays incompatible with standardized trays, further increasing production costs.

3) **Limited crop adaptability:** Existing transplanting mechanisms have certain limitations. Most are designed for a single crop type, requiring the use of corresponding mechanisms for different crops. This leads to increased production costs for agricultural crops.

4) **Poor integration with agronomy:** The current transplanting mechanisms are poorly integrated with existing seedling cultivation techniques. Existing seedling cultivation practices lack standardization, and the seedling trays used for growing seedlings vary significantly. This necessitates designing transplanting mechanisms tailored to different tray types, which in turn increases agricultural production costs.

V. OUTLOOK FOR FUTURE DEVELOPMENT

5.1 Development Recommendations for Transplanters

1) **Multifunctional design:** Given the diversity of crops and the complex, variable conditions of farmland, developing multifunctional transplanters is key to reducing costs in future agricultural production. Research focuses on integrating functions such as mulching, transplanting, watering, and fertilizing into a single machine. This enables the completion of basic crop planting processes with a single pass through the field, eliminating the need to purchase multiple machines and minimizing soil disturbance caused by repeated passes.

2) **Universal design:** Enhance the universal design of transplanters to enable a single machine to perform transplanting operations for multiple crops through simple adjustments, thereby further reducing agricultural production costs.

3) **Intelligent research:** Enhance intelligent research on transplanting machines by integrating autonomous driving technology. Utilize vision and image processing technologies to monitor transplanting operation quality in real time and adjust operations accordingly, thereby preventing issues such as missed plants.

4) **Integrated control system:** The integrated control system dynamically adjusts transplanting operations in real time based on field conditions, ensuring consistent plant spacing and planting depth. This enables the transplanting mechanism to dynamically modify seedling pickup trajectories and instantly adjust seedling orientation, guaranteeing upright growth post-transplanting. The result is highly efficient, low-loss transplanting operations that can be performed unmanned, further reducing labor requirements.

5) **Electric transplanters:** Strengthen research on electric transplanters to align with the future green and low-carbon development trends in agriculture. Given that electric transplanters require prolonged operation under harsh environmental conditions, frequent recharging can impair operational efficiency, while battery replacement increases operational costs. Therefore, extending battery runtime and optimizing battery lifespan will be critical challenges to address in electric transplanter research.

5.2 Development Recommendations for Transplanting Mechanisms

1) **Damage reduction:** In current agricultural production, damage to seedlings caused by existing transplanting mechanisms remains a key factor limiting transplanting quality and efficiency. Future transplanting mechanism designs must enhance theoretical analysis. For gripper-type transplanters, optimize the gripping force of the seedling picker to prevent damage to seedlings. Design suitable insertion-type transplanting mechanisms to ensure complete seedling retrieval. Control the airflow volume in pneumatic transplanters to maintain seedling pot integrity while ensuring successful seedling extraction.

2) **Stability and lightweight design:** To enhance transplanting efficiency, conduct a structural dynamic analysis of the transplanting mechanism to ensure transmission stability during high-speed operation. Simplify the structural design of the transplanting mechanism to achieve lightweight construction.

3) **Multi-crop adaptability:** Designed for transplanting multiple types of crops, this system breaks the limitations of transplanting machinery by enabling a single unit to handle transplanting operations for various agricultural crops, thereby reducing agricultural production costs.

4) **Integration with agronomy:** Strengthen the integration of agricultural machinery and agronomy practices. Standardize seedling cultivation and transplanting procedures by adopting uniform seedling trays. Design transplanting mechanisms specifically for these standardized trays to better align research with seedling cultivation and transplanting techniques. This approach will standardize trays compatible with transplanting equipment and reduce production costs for seedling trays.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper

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