agriculture

Review

Key Technologies of Plug Tray Seedling Transplanters in Protected Agriculture: A Review

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Abstract: The process of plug tray seedling transplanting is a crucial step in protected agriculture production. Due to issues such as high labor intensity, poor consistency of work quality, and low efficiency, the application of automated transplanting machines has provided a solution to these issues. For the diversity of transplanting operations, various mechanical structures and technological applications have been developed for automated transplanting equipment. Therefore, this paper provides systematic research of current studies on the key transplanter technologies. Firstly, through an analysis of the types of transplanting operations, the technical requirements of automated transplanting equipment for different operation types are elucidated. Subsequently, the key technologies applied in transplanting machines are discussed from the perspectives of substrate physical characteristics, end effectors, integration of multiple end effectors, vision systems, and transplanting path planning. Moreover, an analysis is conducted on the advantages, disadvantages, and application scenarios of different research methods for each key technology. Lastly, the existing problems and technical difficulties of the transplanting machine are summarized, and future research directions are discussed. This analysis provides a valuable reference for further research and development in the field of transplanting machines for plug tray seedlings.

Keywords: transplanter; plug tray seedlings; protected agriculture; end effector; vision system

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1. Introduction

Vegetables are an indispensable component of the human diet, as they provide essential nutrition, such as fiber, vitamins, antioxidants, and minerals [1]. The increasing global population has resulted in a surge in demand for vegetables [2]. Protected agriculture, including indoor, greenhouse, and artificial light plant factory cultivation [3–5], offers a viable solution to meet this demand [6]. Protected agriculture employs techniques that control climatic factors, such as light, carbon dioxide content, temperature, and humidity, to create favorable conditions for plants [7,8]. This method provides high yield, good quality, continuous production, efficient resource utilization, and minimal impact on environmental changes [9–11], making it an excellent option for vegetable crop production [12].

Plug tray seedling technology is widely utilized in protected agriculture due to its high germination rate, neat growth, seed-saving benefits, and suitability for mechanized operation [13]. After a period of growth in a plug tray, the seedlings must be picked, replanted, transplanted, and sorted to foster optimal growth conditions [14]. Plug tray seedling transplanters are machines used for transplanting seedlings from the high-density plug tray to the low-density plug tray or flower pot. A complete set of transplanting equipment typically requires functions such as inferior seedling position recognition, tray conveying, tray hole positioning, substrate gripping, and seedling planting. Additionally, since the target of transplanting machine operations is the substrate with seedlings, it is necessary to ensure that the transplanting gripper does not cause any damage to the seedlings during the transplanting process. Therefore, the design of transplanting machines is more complex compared to commonly used industrial automation equipment.

The research on transplanting equipment for vegetable production in protected agriculture started earlier in the 1980s and 1990s. In America, L.J. Kutz et al. [15] designed a nursery plant transplanter based on Puma560 industrial robot; K.C.TING et al. [16,17] developed a transplanter based on the SCARA robot. In the Czech Republic, HůLa et al. [18] conducted a comparative study on the transplanting effects of three different types of ABB robots. These early studies verified the feasibility of using industrial robots for tray seedling transplanting operations, but they did not conduct practical application research. In Korea, K.H.Ryu et al. [19] developed a transplanter with a CCD vision system, and Kang et al. [20] developed a transplanter with multiple claws based on the Cartesian coordinate manipulator. These transplanting machines have greatly improved the transplanting efficiency and success rate, and they basically met the requirements of practical applications. In Japan, Onosaka et al. [21] invented a transplanter composed of devices for transporting, grasping, selecting, planting, and seedling tray cleaning. Researchers in Japan have conducted extensive research on transplanting machines for field use [22,23] and have also developed transplanting machines for hydroponic cultivation [24,25], but there have been few studies on transplanting machines for plug tray seedlings in protected agriculture. After years of development, Europe has seen the emergence of mature commercial transplanting machines, especially in The Netherlands. The Dutch company Viscon [26] has extensive experience in facility horticulture and has produced a series of transplanters, such as Pic-O-Mat Blueline equipped with multiple patented end effectors, and the transplanting efficiency could reach 35,000 plants per hour. Viscon also has advanced vision systems, whereby crops can be effectively and reliably graded by detecting the volume, height, color, flower quantity, and other characteristics of a plant using a high-resolution camera. The transplanter produced by the TTA Company [27] in The Netherlands is widely used for transplanting vegetables, flowers, and other crops in facility horticulture, such as the PackPlanter Wireless series transplanter for transplanting, the FlexSorter series transplanters for grading, and the MidiPot and MidiCurve for potted flower transplanting. Other facility agricultural suppliers in The Netherlands, such as the Flier Systems Company [28], the ISO Group Company [29], the CODEMA Company [30], have also developed efficient transplanting equipment, which is widely used in practical production. Other companies, such as Urbanati [31] and TEA Project srl [32] in Italy, AgriNomix [33] and Bouldin & Lawson [34] in America, and Transplant System [35] in New Zealand, have all developed commercial transplanters for plug tray seedlings in protected agriculture. Although these commercial transplanting machines have matured in terms of functionality and design, they are designed for planting patterns and standards in a large-scale protected agriculture environment, especially in developed countries. However, there are differences in the production scale, planting mode, planting density, hardware configuration, and other aspects of protected agriculture in different countries. Transplanters have limitations in intelligence, applicability, and universality [36]. In addition, these complete sets of transplanting machines also face problems, such as high prices, high maintenance costs, and long maintenance cycles, which are still difficult for small and medium-sized facility vegetable production enterprises to accept. Therefore, Chinese researchers have developed many plug tray seedling transplanters suitable for their own planting patterns [13,37–41]. In addition to China, research on transplanting machines for potted seedlings in other developing countries has mainly focused on the application of transplanting machines in the field [42–46].

It is evident that the current commercial transplanting machines lack suitable applicability within the facility agricultural environment of developing countries. Transplanters incorporate multiple technologies, including mechanical, electrical, electronic, computer, machine vision, and intelligent sensing. Precisely due to the fact that transplanting machines are electromechanical integration devices encompassing multiple disciplinary technologies, there is a pressing need to scrutinize the pivotal technologies employed in existing transplanting machines, enhance their structural integrity, optimize their functionalities, and mitigate costs. These endeavors aim to render the machines adaptable to a broader spectrum of planting conditions, thereby facilitating their widespread implementation. Several scholars have reviewed some aspects of the key technologies for transplanting machines, but their research content is not comprehensive enough. The differences between the recently published reviews of technologies in plug tray seedling transplanters and this paper were compared and shown in Table 1.

Table 1. Comparison of the current review paper with previous reviews.

References	Content								
	Transplanting Types	Research Status	Substrate Physical Properties	End Effector	Multiple End Effector Integration	Overall Structure	Vision System	Path Planning	Research Direction
[47]		√		√			√	√	√
[48]				√					√
[36]	√	√		√	√		√	√	√
[49]				√					√
[50]				√	√				√
ours	√	√	√	√	√	√	√	√	√

The rest of this paper is organized as follows. In Section 2, we analyze the different types of transplanting operations. In the Section 3, we summarize the key technologies in the design of plug tray seedling transplanters. Finally, we discuss the current problems in the design of plug tray seedling transplanters. The paper is concluded with a conclusion and the future research direction for plug tray seedling transplanters.

2. Overview of Transplanting Operation

Automated transplanting operations can be categorized into several types based on their specific seedling purposes. These include widening-spacing transplanting, replacing bad seedling transplanting, grading transplanting, and tray-to-pot transplanting. As a result, the structural principles of the transplanter vary depending on the type of transplanting operation. In the following paragraphs, we will provide an overview of each type of transplanting operation.

2.1. Types of Transplanting Operation

To maximize planting space, seedlings are typically planted in high-density plug trays with small hole spacing. However, as the plants grow, the crowded environment becomes unsuitable for further plant development. To address this issue, seedlings must be transplanted into larger trays with wider hole spacing, which improves their growth space, light utilization, and ventilation. This process is known as widening-spacing transplanting, as shown in Figure 1a. Several transplanters are available for this kind of operation, including the Pack Planter series from the TTA company in The Netherlands and the RW series from the Urbinati company in Italy.

Substandard seed quality, inaccurate seeding in plug trays, suboptimal temperature and humidity conditions, inadequate nutrition, as well as plant diseases and pests, collectively contribute to a suboptimal germination rate (ranging from 80% to 95%) for seedlings cultivated in plug trays [51]. This results in poor-quality seedlings or empty holes. To mitigate the risks associated with disease and pest outbreaks and enhance the utilization rate of plug trays, it is imperative to implement procedures for the identification and removal of unhealthy seedlings or empty holes, followed by the subsequent replanting with vigorous and disease-free seedlings. This type of operation is referred to as replacing bad seedling transplanting, as shown in Figure 1b. The Fix-O-Mat TIFS-IV from the Viscon company and the CombiFix series from the TTA company are both examples of this type of transplanter.

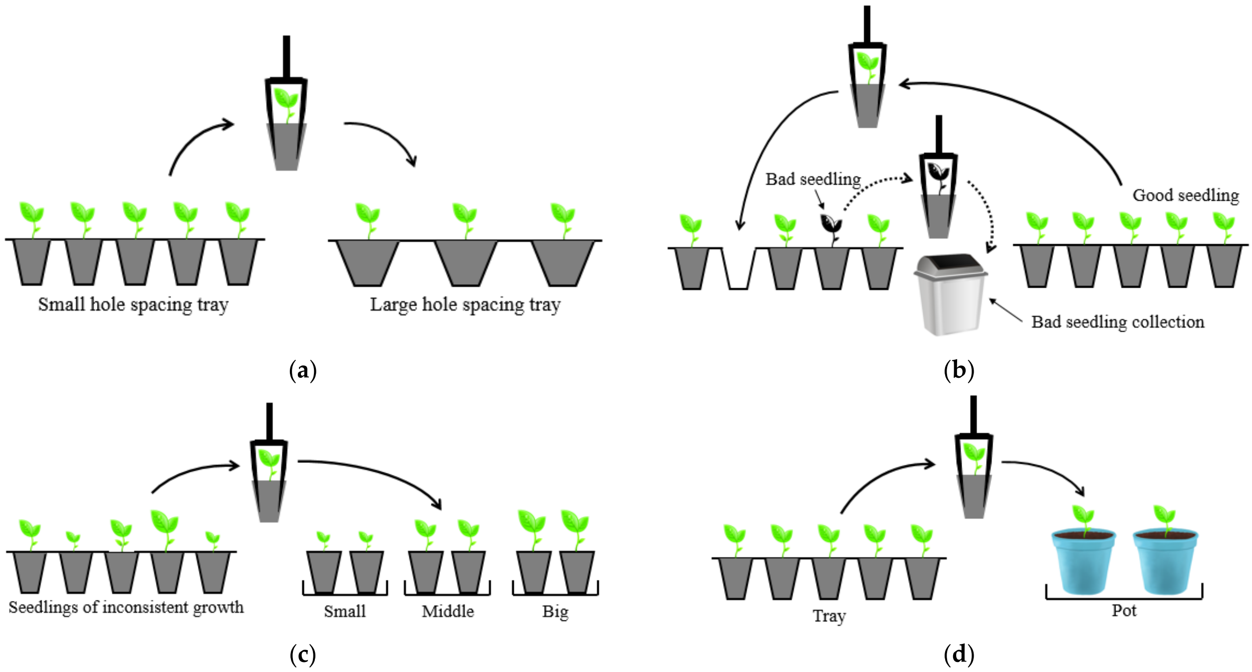

Figure 1. Types of transplanting: (**a**) widening-spacing transplanting, (**b**) replacement transplanting, (**c**) grading transplanting, (**d**) tray-to-pot transplanting.

The process of grading transplanting, as shown in Figure 1c, involves categorizing and grouping seedlings based on factors such as leaf size, leaf count, or plant height. This is typically performed to ensure that seedlings with similar characteristics are transplanted together, improving their uniformity and making them easier to manage. Grading can also be performed for marketing purposes, as seedlings with similar characteristics are often more attractive to buyers. The Select-O-Mat Phoenix from Viscon and the FlexSorter series from TTA are examples of grading transplanters.

Tray-to-pot transplanting is usually used for flower transplanting, where one or several flower seedlings from a plug tray are transplanted into a flower pot, as shown in Figure 1d. The Pic-O-Mat series from Viscon and the MidiCurve from TTA are examples of this type.

Some transplanting operations require a combination of the techniques mentioned above to meet specific process requirements. For example, TTA's FlexPlanter series can perform both widening-spacing and replacement transplanting, while Young Plant Sorter from Fliersystems can accomplish both grading and widening-spacing transplanting. The SPH-Sorter from Fliersystems can conduct replacement, widening-spacing, and grading transplanting.

2.2. Technical Requirements for Transplanting Operations

The structure and control methods of transplanters are determined by the types of transplanting operations performed. Therefore, the technical requirements of different types of transplanters vary accordingly.

The objective of widening-spacing transplanting is to augment the inter-plant spacing, necessitating the utilization of transplanter equipment equipped with multiple end effectors capable of adjusting the spacing between seedlings. When all seedlings in a tray are of good quality, the multiple end effectors can be lifted and gripped simultaneously, making the structural design and control methods of the end effectors and transplanting manipulators relatively simple. However, when the tray contains poor-quality seedlings or empty holes, the end effectors must independently lift and switch the grippers, making the overall structure and control of the transplanter more complex.

For replacement transplanting, the positions of poor-quality seedlings or empty holes in the tray are unknown, and thus, the end effectors must have the ability to stretch and grip independently. Modern commercial transplanting machines usually use a parallel structure with multiple end effectors to increase work efficiency.

Grading transplanting requires a more precise visual system and an end effector capable of independent driving. The tray-to-pot transplanting principle is similar to widening-spacing transplanting, and the technical requirements are also similar. Table 2 summarizes the technical requirements of transplanters for different types of transplanting operations.

Table 2. Technical requirements of transplanters for different operation types.

Types	Change Spacing for End Effectors	Independent Control for End Effectors	Visual System
Widening-spacing transplanting	Yes	Needed or not	No
Replacement transplanting	Needed or not	Yes	Yes
Grading transplanting	Needed or not	Yes	Yes
Tray-to-pot transplanting	Yes	Needed or not	No

3. Key Technologies of Transplanting Machines

A plug tray seedling transplanter system consists of various components, including the end effectors, transplanting manipulator, conveying and positioning mechanism, visual system, and control system. The research of a tray seedling transplanting machine involves several stages. The first stage involves studying the physical properties of the seedling substrate to design and test the end effector. Next, the transplanting manipulator is designed according to the specific agronomic requirements. Finally, the entire machine is optimized to achieve all the necessary functions required for the transplanting operation. The system composition diagram of plug tray seedling transplanting machines for protected agriculture is depicted in Figure 2.

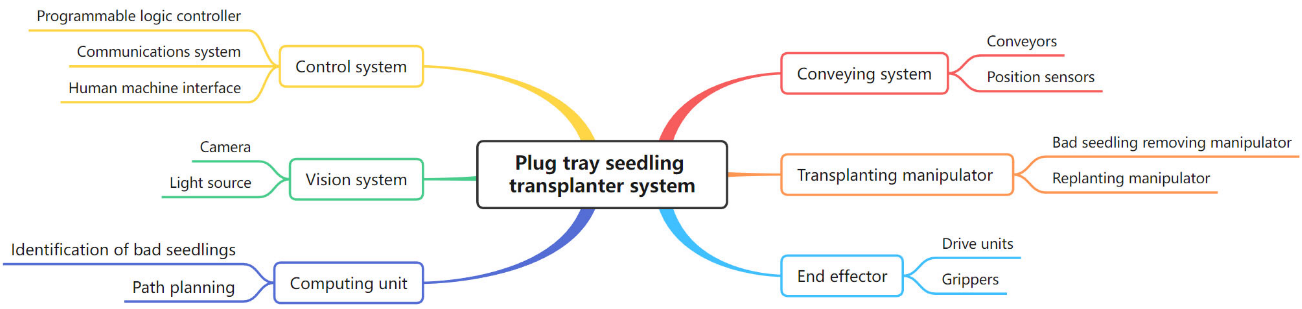

Figure 2. System composition diagram of plug tray seedling transplanter.

3.1. Physical Properties of Substrate

The physical properties of the plug tray seedling substrate are crucial in determining the success rate of the end effector's grasp. To optimize the design of the end effector, researchers have investigated this issue using methods such as force measurement platforms, simulation technology, and image technology. Their findings provide a theoretical foundation for the development of end effectors. A comparison of research methods for the physical properties of the substrate is shown in Table 3.

Table 3. Comparison of physical characteristics research methods.

Methods	Instruments/Tools	Purpose	Characteristics	Reference
Force measuring platform	Dynamometer	Measure the pulling force, penetration resistance, and clamping force of the gripper.	Cheap measurement platform needs to be designed, and the measurement data need to be recorded manually.	[52–54]
	Universal testing machine	Measure the tensile and compressive strength of the substrate, the pulling force, penetration resistance.	Simple operation, automatic recording of test data, moderate cost.	[55–57]
	Texture analyzer	Measure the matrix compression and creep test, the pulling force, penetration resistance.	Simple operation, high accuracy, automatic recording of test data, high cost.	[58–61]
	Direct shear apparatus	Measure the shear strength and shear stress of the substrate.	The test operation is complex, the test data are automatically recorded, high cost.	[62]
Simulation technology	FEM	Analyze the stress of the substrate and the gripper, simulate the damage of the substrate under different physical characteristic parameters.	Suitable for analyzing a substrate, which is easy to lose.	[63]
	DEM	Analyze the scattering of the substrate during the grasping process under different physical characteristic parameters.	Suitable for loose substrate.	[14,57]
Image technology	CT	Study the relationship between root density distribution, root micro-displacement, and the substrate crack expansion.	The equipment parameters need to be adjusted to obtain the three-dimensional image of root distribution.	[38,64,65]
	SEM	Study the substrate damage mechanism at the microscopic level of the internal composition and structure of the substrate.	Obtaining the internal section image of the substrate.	[66]

3.1.1. Force Measuring Platform

The force measuring platform can directly measure the force when the gripper acts on the substrate. Various instruments, such as force gauges, universal testing machines, texture analyzers, and direct shear instruments, are used to measure the tensile, compressive, or shear strength of substrates or seedlings, providing important data for optimizing the end effectors.

The dynamometer is commonly used for measuring various mechanical properties, including the penetration resistance of soil [53], the clamping force of the gripper [52], and the pulling force of the seedling [54]. The universal testing machine is often utilized for determining the substrate cohesion and tray adhesion [57], compression [55], tension [56], bending, and puncture. The texture analyzer is used to measure the compression [58–60], tearing, and surface puncture tests [61] of the samples. Additionally, the direct shear apparatus, is employed for measuring the shear strength of the substrate. By measuring the shear stress and shear displacement of the substrate, the cohesive force and internal friction angle of the substrate can be calculated [62].

3.1.2. Simulation Technology

Simulation technology can simulate the grasping process of seeding. By utilizing the finite element method (FEM) or discrete element method (DEM) simulation, researchers can simulate the grabbing process of substrate blocks by grippers, allowing for the calculation of the forces, deformation, and movement of both the gripper and substrate.

Several software, which can perform finite element analysis, such as Solidworks [63], Abaqus and Ansys [67]. These software can simulate the mechanical response of the needle force on the seedling substrate block. Discrete element analysis usually uses the EDEM software. Through EDEM simulation, the effect of grasping different viscous matrices can be compared [14,57]. By utilizing the EDEM–RecurDyn coupling simulation [62], the force exerted on the gripper can be assessed while concurrently analyzing the effect of the clamping force on substrate particles.

3.1.3. Image Technology

Image technology can directly observe the internal structure of the substrate and study the mechanism of substrate damage at the microscopic level. The commonly used techniques include CT and electron microscopy.

The utilization of CT technology [38,64,65] to scan the root system of seedlings enables the generation of a three-dimensional reconstruction of the root system, allowing for observation of the growth and distribution of the root system. Additionally, the impact of diverse composite substrates on seedling growth quality and substrate strength can be investigated by using electron microscopy (SEM) images [66], providing a theoretical basis for exploring the mechanism of substrate damage.

3.2. End Effector

The end effector is the component, which directly contacts the substrate block in the tray. Its function is to grasp the seedlings from a tray and plant them in another tray or pot. Its structure directly affects the operation quality and efficiency of the transplanter. According to the movement form of the gripper, the end effector mainly includes three types: the plug-in and clamping type, oblique insertion type, and deformed sliding needle type. The gripper can be shaped like a shovel or needle; the number of gripper fingers is usually two to four shovels or needles; and the driving methods include cylinder, electric push rod, motor, and electromagnetic [49]. A summary comparison of the end effector structures is shown in Table 4.

The plug-in and clamping type end effector performs insertion and gripping actions during the operation and is widely used in transplanters. In order to achieve the action of inserting and grasping, the plug-in and clamping end effectors are usually controlled by two sets of drives: one for insertion and retraction of the needle, the other for opening and closing of the needle [68]. Some researchers have also designed a linkage mechanical structure with a return spring using a single cylinder to achieve the insertion and clamping actions of the end effector [69,70]. There are also some plug-in and clamping type end effectors, which are limited to gripping actions only and need external manipulation to complete the insertion process [38,71].

The oblique plug-in type end effector refers to a gripper, which is inserted into the substrate at an oblique angle along the hole. Due to the oblique arrangement of the needle, the drive mechanism needs to convert the vertical linear motion of the drive components into linear motion with a certain tilt angle. The oblique insertion mechanism can be a guiding groove mechanism [57,72] or a connecting rod mechanism [53]. The driving unit can be a cylinder [14,54,57] or an electric push rod [53].

Both of these methods will increase the size of the end effector and make it inconvenient to integrate multiple end effectors; however, the structure is reliable and operates stably.

The deformation sliding needle type end effector usually uses the flexible seedling needle and the arc-shaped guide tube to realize the inclined insertion of the seedling needle [73–76]. This structure is compact, but due to the friction between the flexible needle and the guide tube during the operation, the wear of the needle and the tube may occur during long-term use, and poor lubrication may cause the needles to jam, affecting the operating stability.

Table 4. Structure comparison of end effectors.

Structural Style	Drive	Gripper Shape	Finger/Shovel Quantity	Principle Characteristics	Reference
Plug-in clamping type	Single cylinder	Aciculiform	4	Insert and clamp the substrate continuously within one push stroke of the cylinder.	[69]
	Single cylinder	Aciculiform	4	The cylinder piston rod retracts during the process of gripper insertion into the substrate to achieve the grasping action.	[38]
	Single cylinder	Aciculiform	4	The crank slider mechanism is used to drive the gripper, and the end effector can realize two working modes of oblique insertion and clamping.	[70]
	Double cylinder and air sac	Aciculiform	4	Two cylinders with a certain angle are used to drive gripper insertion into the substrate obliquely. The airbag between the two cylinders and the tightening spring are used to realize the clamping and opening of the gripper.	[68]
Oblique plug-in type	Single cylinder	Spade shape	4	The finger shovel is driven by the air cylinder and inserted along the four walls of the hole to reduce the damage to the seedling mound. By adding blocks, the substrate on the shovel is removed during the shovel recovery.	[57]
	Single cylinder	Aciculiform	4	Using a single cylinder and the guide groove mechanism to realize oblique insertion action of the gripper.	[54]
	Linear effector	Aciculiform	4	Using electric push rod and the connecting rod mechanism to drive gripper insertion into the substrate.	[53]
	Single cylinder	Spade shape	4	Using one cylinder completes the extension and retraction action of four groups of seedling spades.	[72]
Deformation sliding needle type	Double cylinder	Aciculiform	4	The large cylinder drives the small cylinder and the needle fixing plate to move downward together. Then, the small cylinder pushes the needle fixing plate to move downward to realize the clamping action.	[73]
	Single cylinder	Aciculiform	4	The single cylinder pushes four flexible needles through four oblique guide tubes to grasp the seedling substrate.	[77]
	Servo motor	Aciculiform	4	When picking up seedlings, the four sliding needles extend out of the guide tube and are inserted obliquely into the hole to hold the seedling substrate.	[76]
	Single cylinder	Aciculiform	4	With the pushing force of the seedling claw control cylinder, the gripping action is achieved by the deformation of the seedling needles.	[75]

3.3. Integration for Multiple End Effectors

In order to improve the efficiency of transplanters, multiple end effectors are usually integrated to realize the grasping of multiple plants or entire rows of seedlings with just a single movement of the manipulator. According to different structures, the integration methods can be divided into the expanding and contracting board type, parallelogram mechanism, rope connection type, cam type, independent control type, etc.

The expanding and contracting board type is simple in structure and control; according to actual needs, the board can be arranged horizontally [78] or vertically [79], but this structure is heavy, which limits the action speed of the system [80]. The parallelogram mechanism type is a lightweight spacing adjustable mechanism for integrating multiple end effectors [81]. This mechanism is capable of achieving precise separation of all end effectors with minimal stroke [37].

In cases where the closing and opening distances between the multiple end effectors are fixed, a simpler method is to use a soft belt [77] or steel wire [82] to connect adjacent end effectors. As the soft belt or steel wire rope are flexible bodies with certain elasticity, they can play a buffering role in the process of distance change. Tong [77] used a cylinder to make the grippers expand and close. However, these methods are limited to a single specification of the tray; the length of the soft belt or steel wire must be readjusted if the tray specification changes. The cylindrical cam [83] mechanism can also be used for adjusting the distance for multiple end effectors, but this kind of structure requires high machining and installation accuracy.

The above mechanisms are simple in structure and easy to control, but they can only realize the equidistant expansion and closing of multiple end effectors, and most of these can only be suitable for one kind of tray. If those kinds of mechanisms need to be applied to other hole spacings, the spacing between end effectors needs to be readjusted manually. In order to improve the versatility of the transplanter, many transplanter manufacturers have designed independent servo-driven end effectors, which can realize the adjustment of any distance between the end effectors.

The FlexPlanter and PackPlanter series transplanters produced by the TTA company employ independently controlled electric motors to drive the end effectors, which mesh with laterally arranged racks to achieve translational motion. The RW series transplanter produced by Urbinati also uses an independent motor to drive the end effector, only changing the transmission mechanism from gear rack to synchronous wheel and synchronous belt transmission. Feng et al. [40,84] have also developed a transplanter integrated with an end effector driven independently by synchronous wheel and synchronous belt.

3.4. Transplanting Manipulator

The function of a transplanting manipulator is to drive the end effector to move back and forth between the supply and target tray. There are four types of commonly used transplanting manipulators, including serial industrial robots, four-axis SCARA robots, parallel robots, and Cartesian coordinate manipulators. Table 5 summarizes the unique characteristics of transplanters with different structures.

Table 5. Comparison of transplanting manipulators.

Transplanting Manipulator	Structural Complexity	Bearable Load	DOF	Efficiency	Cost	Dimensions	Scalability
Serial Robot	Simple	High Load	5–6	High	Expensive	Middle	Best
Four-Axis SCARA Robot	Simple	Middle Load	4	Middle	Middle	Small	Good
Parallel Robot	Simple	Low Load	2–3	Low	Low	Small	Good
Cartesian Coordinate Manipulator	Complicated	High Load	2–3	High	High	Big	Bad

3.4.1. Series Industrial Manipulators

The earliest research on transplanters was generally based on industrial robotic arms [85], such as the Puma560 industrial robot [15] and the ABB robot [18]. These initial studies demonstrated the feasibility of using industrial robots for tray seedling transplanting operations, but they did not conduct practical application research. However, in recent years, there have been increased applications of industrial robot transplanters in vegetable production practice. For example, the Danish BEKIDAN company designed a flower grading transplanting system based on the DENSO six-axis industrial robot. Additionally, the Dutch horticultural production solution provider CODEMA company developed a transplant robot workstation using the KUKA robot, and the FANUC robot, equipped with a multiple end effectors' manipulator. Serial industrial robots provide a simple and space-efficient option for factory layout and installation, but they are more expensive.

3.4.2. SCARA Manipulator

The SCARA manipulator has become a popular choice for transplanting operations due to its compact structure, high speed, and high loads. Several researchers and companies have developed transplanting solutions using SCARA robots. Appropriate loads for SCARA robotic arms can be selected according to the requirements of transplanting operations, and they can be equipped with single [16,17], or multiple end effectors. However, SCARA robots typically have only four degrees of freedom, which limits their range of motion. To increase the motion range of the SCARA robot in transplantation operations, it is possible to install the robot on a linear module [86].

3.4.3. Parallel Manipulator

Parallel manipulators are known for their high rigidity and high speed. By using a two-degree-of-freedom parallel manipulator in combination with a conveyor, transplantation operations can be realized [87,88]. However, three-degree-of-freedom parallel manipulators are more commonly used [89]. The Italian Otechmek company, and Canadian CMP Automation Company [90], have both developed transplanting machines based on parallel manipulators. Due to the low load-bearing capacity of parallel manipulators, they are usually equipped with only a single end effector, which limits the efficiency of the entire transplantation operation.

3.4.4. Cartesian Coordinate Manipulator

The Cartesian coordinate manipulators have a simple and intuitive coordinate system, which makes them easy to program and operate. They are rigid and stable, which makes them suitable for heavy loads and high-speed operations. Therefore, this structure is often preferred in transplanters for vegetable seedlings. In Cartesian coordinate manipulators, there are two types of configurations available: two degrees of freedom and three degrees of freedom. In early research, the two-degree-of-freedom Cartesian coordinate manipulator was commonly used [19,20] due to its low cost and simple structure. However, the transplanters based on a three-degree-of-freedom Cartesian coordinate manipulator have a large workspace [40,91], as they can move in all three axes (x, y, z).

Due to the high load-bearing capacity of transplanters based on Cartesian coordinate manipulators, these machines are typically equipped with multiple end effectors to enhance operational efficiency. In this type of transplanter structure, there are various installation forms of end effectors according to the actual operational requirements, such as fixed installation and adjustable spacing installation. With fixed installation, multiple end effectors are closely adjacent to each other, and the spacing between them cannot be adjusted. The position of the end effectors must be adjusted by the translational axis of the Cartesian coordinate manipulator, which drives all the end effectors to move as a whole. Examples of such fixed installation end effectors include combifix II from the TTA company (TTA, Bleskensgraaf, The Netherlands) and Vision Planter from the ISO Group company (ISO-Horti Innovators, Gameren, The Netherlands). For the adjustable spacing installation, independent servo motors are typically used to drive the end effectors, such as the Pic-O-Mat Blueline, from the Viscon company (Viscon Group, Gravendeel, The Netherlands), and TEA 600N, from the Hamilton Design & TEA Project Company (Hamilton Design USA, Burton, OH, USA). When the end effectors can be driven independently, numerous cables or air pipes usually need to be arranged, such as the SPH-Transplanter, from the Flier Systems Company (Flier Systems, Barendrecht, The Netherlands), and the PlugPlanter S Model, from the Bouldin & Lawson company (Bouldin and Lawson, LLC, McMinnville, TN, USA). However, too many cables and organs can easily become entangled, leading to failures. In order to solve this problem, wireless end effectors have been developed, such as the PackPlanter Wireless transplanter, and the RW64 greenhouse transplanter, from the Italian Urbinati Company (Urbinati S.r.l., San Mauro Pascoli, Italy).

It can be observed that horticultural equipment manufacturing and solution providers around the world rely on their industrial base, and advanced technologies, such as machine vision, servo drive, and human machine interface (HMI), have developed various forms and functions of transplanters based on rectangular coordinate manipulators, which are widely used in facility horticulture. However, this large-scale transplanting equipment requires specialized hole trays, top seedling devices, etc., and its high cost hinders its promotion and application in small-scale facility agricultural environments. We summarize the key performance parameters of the commercial transplanters from various countries, as shown in Table 6.

Table 6. Commercial transplanters and technical parameters.

Country /Manufacturer	Model	Number of Grippers	Wired/Wireless	Independent Drive	Independent Clamp	Efficiency (Plants/Hour)	Applicable Plug Tray	Vision System	Air Consumption (L/min)	Power (kw)	Weight (kg)
The Netherlands/Viscon	Pic-O-Mat Blueline	4–8	Wired	Y	Y	10,000	Max size 600 × 400	N	--	--	--
	Pic-O-Mat Greenline	4–14	Wired	Y	Y	21,000	Max size 600 × 400	N	--	--	--
	Pic-O-Mat Redline	8–24	Wired	Y	Y	35,000	Max size 600 × 400	N	--	--	--
	Pic-O-Mat PC11	2–4	Wired	Y	Y	6000	4 plants per pot	N	--	--	--
	Pic-O-Mat PFS-8	8	Wired	Y	Y	10,000	4 plants per pot	N	--	--	--
	Pic-O-Mat VMP	6–12	Wired	Y	Y	12,000	4 plants per pot	N	--	--	--
	Fix-O-Mat TIFS-IV	12	Wired	Y	Y	12,000	--	Y	--	--	--
	Select-O-Mat Phoenix	12	Wired	Y	Y	8000	--	Y	--	--	--
The Netherlands/TTA	FlexPlanter	Multiple	Wired	Y	Y	3000–30,000	Plug size 9–30 mm	Y	60	5	2000
	FlexPlanter XF	Multiple	Wired	Y	Y	10,000–30,000	Plug size 9–30 mm	Y	15	--	4500
	PackPlanter wireless	Multiple	Wireless	Y	N	10,000–60,000	Plug size 9–30 mm	N	20	2.5	800
	PackPlanter	Multiple	Wireless	N	N	10,000–50,000	Plug size 9–30 mm	N	20	2	550
	PackPlanter S	Multiple	Wireless	Y	N	10,000–20,000	Plug size 9–30 mm	N	20	2	450
	MidiFlat	Multiple	Wireless	Y	N	4000–40,000	Plug size 9–60 mm	N	17	3	700
	MidiVision	Multiple	Wireless	Y	Y	5000–40,000	Plug size 9–60 mm	Y	17	3.5	800
	FlexSorter	Multiple	Wired	Y	Y	3000–12,000	Plug size 9–60 mm	Y	60	5	2000
	FlexSorter XF	Multiple	Wired	Y	Y	10,000–30,000	--	Y	16	--	4500
	MaxSorter	Multiple	Wired	Y	Y	6000–12,000	--	Y	35	--	3800
	Combifix II	Multiple	Wired	N	Y	12,000–20,000	Plug size 9–30 mm	Y	535	5	2250
The Netherlands/Flier Systems	SPH-Transplanter	Multiple	Wired	Y	Y	--	--	Y	--	--	--
	Young Plant Sorter	Multiple	Wired	N	Y	8000	--	Y	--	--	--
	Plug Fixer	5	Wired	N	Y	11,000	--	Y	--	--	--
The Netherlands/ISO Group	Vision Planter	Multiple	Wired	N	Y	--	--	Y	--	--	--
	Plug Planting Machine	Multiple	Wired	N	Y	--	--	N	--	--	--
Great Britain/TEA	TEA 600N	12	Wired	Y	Y	18,000	Plug size 30–50 mm	N	70	1	600
	TEA 1500N	12	Wired	Y	Y	12,000–14,400	Max size 600 × 400	N	80	1	700
	TEA 2000N	16	Wired	Y	Y	16,000	Max size 600 × 400	N	80	1	750
	TEA 1500J	2–12	Wired	Y	Y	12,000–14,400	Max size 600 × 400	N	80	1	650
	TEA 2000J	16	Wired	Y	Y	16,000	Max size 600 × 400	N	80	1	700
Italy/Urbinati	RW32	40	Wireless	Y	N	40,000	--	--	80	4	960
	RW64	80	Wireless	Y	N	56,000	--	--	80	5	1300
USA/Bouldin & Lawson	PlugPlanter S Model	16–32	Wired	Y	N	16,400–32,500	--	--	--	--	--

3.5. Growth Status Identification for Seedlings

Among the four types of transplanting operations, the widening-spacing, as shown in Figure 1b, and grading transplanting, as shown in Figure 1c, both require identification of the growth status of seedlings. The system for recognizing healthy seedlings is summarized in Table 7.

Leaf area is one of the most suitable characteristics of seedlings used in evaluating quality. Researchers have studied the use of machine vision technology in the measurement of the leaf area [92]. Generally, the leaf images are obtained by a monocular CCD camera, and the leaf area is obtained using a threshold segmentation method [92–94]. Leaf color, leaf number, and plant height [95] can also serve as parameters for evaluating the growth of plug tray seedlings. The plant height data can be obtained using a line laser [94,95] or depth camera [96,97].

The feature extraction of seedling characteristics in the above methods is based on traditional machine vision morphological methods. Such methods are greatly affected by image background, lighting, and shadow of occlusion, and the stability of recognition performance is not ideal [98,99]. With the development of computer power and deep neural networks, the image recognition technology based on convolutional neural networks [100,101] has been increasingly applied in the identification of healthy seedlings for transplanting machines.

By using binocular vision [102] or depth cameras [97,103,104] to obtain point clouds of seedlings, three-dimensional reconstruction techniques can be employed to obtain the three-dimensional model of the seedlings. This method can provide more growth information, thereby improving the accuracy of identification and grading for plug tray seedlings.

Table 7. Vision identification systems.

Reference	Method	Camera Model	Resolution	Light Source	Collected Information	Algorithm	Performance
[94]	Monocular CCD camera, line laser	--	--	650 nm wavelength red light source line laser	Leaf area and plant height	Thresholding and linear structured light 3D location algorithm	Plant height accuracy is 5 mm.
[92]	Monocular CCD camera	PU LNIX TMC-7DSP	640 × 480	6 fluorescent lamps (380–780 nm), 40 W	Leaf area	Improved watershed algorithm and threshold segmentation	The recognition accuracy is 98%, and the average recognition time of a disc of seedlings is 4.396 s.
[95]	Monocular CCD camera, line laser	PULNiX TM-7CN	768 × 484	770–790 nm laser, 2 quartz halogen light sources, 300 W	Leaf area and plant height	Template matching and line structured light 3D positioning algorithm	The accuracy of hole identification is 95%.
[93]	Monocular camera	Pulnix TM-745	--	2 tungsten filament lamps, 120 W	Leaf area	Otus adaptive threshold segmentation	--
[19]	Monocular CCD camera	CCD	--	--	Leaf area	Threshold segmentation	--
[105,106]	Monocular camera	JoinHope Image OK-AC1300	--	Four F40BX/480 fluorescent lamps, 36 W	Side view of seedlings at 0 and 90 positions (upright degree and plant height)	Threshold segmentation	Each image processing algorithm takes 0.35 s on average.
[102]	3D stereo positioning with binocular vision	DaHeng Image DH-GV400UC	752 × 480	--	Top view of hole seedling	SIFT feature matching algorithm	The three-dimensional reconstruction image of the original acupoint plate is obtained.
[107]	Monocular camera	Epson Inc. GT800	512 × 512	--	Seedling hole area and total area	Three-layer neural network algorithm	--
[108]	Monocular camera	JHSM300E	3 megapixel	--	Top view of hole seedling	Threshold segmentation	The accuracy of hole identification is 100%.
[97]	Depth camera	Intel RealSense SR300 depth sensor	640 × 480	--	Seedling depth image	Point cloud clustering algorithm	The identification accuracy is 96.59% for 105-hole disc of seedlings with 10 days growth time.
[109]	Monocular CCD camera	PU LNIX TMC-7DSP	640 × 480	Six F40BX/480 fluorescent lamps, 36 W	Leaf area and blade circumference	Improved watershed algorithm and threshold segmentation	The identification accuracy of inferior seedlings is above 98%.
[96]	Depth camera	Realsense D415	1280 × 720	30 mm × 90 mm kM-BRD7530 LED	Seedlings' height and edge points	ExG algorithm	Image processing average time is 0.753 s.
[110]	Monocular CCD camera	DaHeng MER-131-75GC	1280 × 1024	Lemons OPT-L133037-W	Plug seedlings, plug bodies, and stem leaves	Threshold segmentation, morphological processing	--

3.6. Path Planning Methods

The transplanting operation of plug tray seedlings requires the manipulator to move back and forth between the supply tray and the target tray. The length of the manipulator's moving path is different with different moving strategies, which affects the operation efficiency of the transplanter.

In the path planning methods of the transplanter, the simplest kind is the fixed order method, such as the far-to-near, near-to-far, or snake-like trajectory [111], where the sequence of seedling selection is fixed, and real-time calculation of the path is not required, but the path distance is generally longer, and the efficiency is lower. Other methods are based on common optimization algorithms, such as the ant colony algorithm [112], genetic algorithm [113], greedy algorithm, etc. Some scholars have also combined and improved several algorithms [114] for trajectory planning. The trajectory planning methods based on optimization algorithms can optimize the path distances, but they take a longer time. Therefore, it is recommended to use optimization algorithms for transplanter trajectory planning after comparison with the fixed order methods.

Overall, the path planning strategy for vegetable seedling transplanting should consider the tray layout, space availability, and operation efficiency. By carefully planning the manipulator's track, the transplanter can improve the efficiency of the transplanting operation and reduce energy costs.

4. Discussion

4.1. Summary of Current Problems

By comparing the research status of plug tray seedling transplanters in different countries and regions, significant disparities in the technological level and application of transplanting machines can be observed. The significant gaps between developed and developing countries can be attributed to several factors, such as economic resources, infrastructure and agricultural development, technological knowledge level, policy and government support. Based on the above reasons, there are differences in the production scale, planting mode, planting density, hardware configuration, and other aspects of protected agriculture in different countries and regions. Transplanters have limitations in intelligence, applicability, and universality. In order to promote better application of transplanters in various protected agricultural conditions, the following problems need to be resolved in future research:

- Limited standardization and compatibility. In protected agriculture, variations exist in the dimensions of seedbeds, planting densities, and tray specifications utilized by different regions and growers. Furthermore, there is a wide range of seedling substrate compositions and proportions employed. Manual seeding predominates, leading to inconsistencies in seedling position. Additionally, the timing of transplanting operations is not standardized. All these differences in the production modes of vegetables have led to the poor practicability of transplanters. Therefore, it is necessary to standardize the production mode by unifying the supporting planting equipment and planting agronomy, combining agronomy with equipment, so as to reduce the complexity of transplanting equipment development.
- Insufficient intelligence and automation. The existing transplanting machines have made some progress in terms of intelligence, but there is still room for improvement. Some aspects include sensing and perception, decision making and control, adaptability, learning, and human–machine interaction. With the development of artificial intelligence technology, we can develop a plant growth status recognition system based on deep learning and three-dimensional reconstruction technology, conduct research on motion control algorithms of multiple grippers to improve the transplanting efficiency, and use the internet of things (IoT) technology to develop remote monitoring functions for transplanters.
- Limited adaptability to diverse agricultural environments. Transplanting machines often face challenges in adapting to the wide range of agricultural environments

found in different regions and countries. Variations in climate, soil conditions, crop varieties, and planting practices necessitate flexible and adaptable machines. Currently, there is a lack of transplanting machines, which can easily accommodate these variations, resulting in suboptimal performance and reduced efficiency. Future research should focus on developing transplanting machines, which can be easily customized and configured to suit different agricultural environments, ensuring optimal transplanting outcomes.

- Cost effectiveness and affordability. The high cost of transplanting machines is a significant barrier to their widespread adoption, particularly in developing countries and small-scale farming operations. The extensive equipment sets and specialized components required for transplanting machines contribute to their high procurement and maintenance costs. To encourage broader adoption, research efforts should concentrate on developing cost-effective solutions, including the use of affordable materials, streamlined designs, and modular components. By reducing the overall cost of transplanting machines, their accessibility and affordability can be enhanced, facilitating their integration into diverse agricultural systems.

4.2. Research Focus and Development Trend

Considering the aforementioned issues associated with transplanters in protected agriculture, the following research directions are recommended to be prioritized for further investigation:

- Integration of advanced sensing technologies. One of the prominent trends in transplanting machine research is the integration of advanced sensing technologies. This includes the incorporation of diverse sensors, such as cameras, 3D scanners, lidar, thermal imagers, and hyperspectral sensors. These sensors enable precise and comprehensive data acquisition, facilitating a deeper understanding of both the crop and the surrounding environment. By integrating data from multiple sensors, transplanting machines can enhance their perception capabilities, enabling real-time monitoring and analysis of crucial parameters, such as soil moisture, plant health, and environmental conditions.
- Development of intelligent decision-making algorithms. Another key focus in transplanting machine research is the development of intelligent decision-making algorithms. Machine-learning techniques, such as deep learning, can be applied to analyze the collected data and extract meaningful insights. These algorithms enable transplanting machines to make informed decisions based on real-time information, optimizing transplanting strategies and enhancing overall efficiency. Additionally, the integration of artificial intelligence and machine vision technologies allows for automated detection and classification of seedlings, improving the accuracy and precision of transplanting operations.
- Advancements in robotics and automation. The advancement of robotics and automation technologies plays a significant role in the evolution of transplanting machines. Researchers are exploring the development of robotic systems with improved dexterity, allowing for more precise and efficient handling of seedlings. Automation features, such as autonomous navigation, adaptive grasping, and coordinated multi-robot systems, are being investigated to enhance the performance and productivity of transplanting machines. These advancements aim to reduce the reliance on human labor, increase operational efficiency, and minimize human errors.
- Compact and lightweight technology for transplanting machines. The development of compact and lightweight technology for transplanting machines offers a promising solution to address the challenges related to the adaptability and cost effectiveness of large-scale equipment. By adopting smaller and more flexible transplanter systems, greater versatility can be achieved, allowing for tailored configurations and programming specific to different crop types and environmental conditions. The utilization of finite element analysis techniques enables the optimization of structural design for

transplanting machine components, while incorporating lightweight materials in the manufacturing process enhances overall performance. Furthermore, the downsizing of equipment also contributes to cost reduction. Integrating cost reduction into this discussion, the development of compact and lightweight transplanting machines not only enhances adaptability but also improves cost effectiveness, making them more accessible to a wider range of users.

5. Conclusions

This review highlights the existing gaps and challenges in the applicability of current transplanters to diverse protected agricultural environments. To address these issues, the development of compact general-purpose transplanters is recommended to promote their widespread adoption in various protected agricultural settings. However, the variations in planting modes and hardware configurations of plug seedlings present a significant challenge in achieving compact universal transplanters.

As agricultural labor declines and protected agriculture continues to advance, the mechanization and automation of protected agriculture production become inevitable. To overcome the associated difficulties and challenges, it is crucial to closely monitor technological advancements in the industry and develop unified standards for protected agriculture planting. A collaborative approach involving experts from diverse disciplines, particularly engineers and researchers specializing in protected agriculture planting, is essential. By fostering the synergistic integration of agricultural mechanization and agronomic principles, alongside the standardization of protected vegetable cultivation, the widespread adoption and utilization of automated plug tray seedling transplanting equipment can be effectively facilitated. This transformation holds the potential to enhance the applicability and efficacy of transplanting machines in protected agriculture, resulting in improved efficiency and cost reduction. It requires continuous research and development efforts to address the specific needs and challenges of different agricultural environments. Furthermore, interdisciplinary collaborations and knowledge exchange are vital for driving innovation and advancing the field of transplanting machine technology. By leveraging these strategies, the vision of efficient and sustainable protected agriculture can be realized, contributing to the growth and development of modern agricultural practices.

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