Development and field testing of biodegradable seedling plug-tray cutting mechanism for automated vegetable transplanter

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Abstract

Transplanting seedlings from plug trays into the field can cause transplant shock and lower the seedling survival rate. In order to avoid the need for a complicated clamping mechanism, this study developed a biodegradable seedling plug-tray cutting mechanism (SPCM) that separates seedlings with plug cells from plug trays. In order to cut and separate the plug cell from the plug tray and enable the seedling to fall into the transplanting hopper, the three sub-mechanisms that make up the SPCM align the plug cell at the point of seedling discharge. Approximately 82% of the plug cell was separated by the SPCM before being delivered to the planting unit. Additionally, using pepper and cabbage seedlings, the SPCM-equipped transplanter achieved a 74% transplanting performance, with an average field efficiency of 68%, a field capacity of 0.032-0.035 ha h^{-1}, and a labor requirement that was 73% lower than that of manual seedling transplanting. The majority of pepper seedlings (85%) were transplanted with a planting angle of less than 10°, and 7% of cabbage seedlings were inclined with a planting depth of 48 mm for pepper and 53 mm for cabbage. These transplanting results were considered satisfactory. In conclusion, the SPCM represents a step toward effective and sustainable vegetable seedling transplanting. Enhancing productivity, precision in planting, and sustainability offer stimulating prospects for additional study and advancement in the area.

Introduction

Vegetable seedling transplanting can be accomplished either manually, relying on human labor, or through machines (Kumar and Raheman, 2011). Manual vegetable transplantation with human labor is a drudgery task that requires high labor intensity (up to 180 man-hours per hectare) and has low efficiency and high costs (Iqbal *et al.*, 2021), prompting the development of transplanting machines. The vegetable transplanters are of two types, *i.e.*, semi-automatic and fully automatic. The semi-automatic type transplanting machinery requires additional human intervention to place the seedling into the planting device and thus has low field efficiency (Javidan and Mohammadzamani, 2019), while the fully automatic type transplanters are capable of selecting and delivering individual seedlings to the planting device using a suitable metering mechanism (Wen *et al.*, 2021). While seedling feeding and metering are mechanized in fully automatic transplanters, they are performed manually in semi-automatic ones, thus requiring more labor and relying on the efficiency of human workers. Therefore, adopting a fully automatic transplanting method can significantly enhance work efficiency and lower labor requirements and production costs (Kumar and

Raheman, 2011). This shift towards the fully automatic transplanting machine is an unavoidable trend in the evolution and advancement of modern vegetable transplanters.

There have been several transplanting machines developed and available in the market that uses different picking, metering and planting mechanisms for the transplanting of vegetable seedlings in the field (Gutiérrez *et al.*, 2009; Kumar and Raheman, 2012; Liu *et al.*, 2022). However, the fully automatic transplanting mechanism requires the seedlings to be prepared with special care, ensuring that all the seedlings and potting materials are uniform (Kumar and Raheman, 2011). This uniformity can be achieved by using plug trays to grow seedlings in a controlled environment (Basak *et al.*, 2019; Jang *et al.*, 2018). Preparing seedlings in plug trays has several advantages over traditional soil-based preparation methods. This approach simplifies the transplanting process, shortens the seedling growth period, and reduces preparation costs. Additionally, it allows for control of the growth rate by adjusting the growth medium, nutrient and water supply (Choi *et al.*, 2019). Therefore, most automated transplanting devices have been developed to pick up individual seedlings from plug trays, especially ones made of plastics (Han *et al.*, 2019; Jorg *et al.*, 2021).

The extraction of seedlings from plastic plug trays is a delicate process, as improper handling can decrease seedling survival rates. Common errors in handling include the detachment of the seedling shoot from the roots, breaking of the root bulb, and damaging the seedling stem. Thus, the mechanism for picking up seedlings has received significant attention from researchers and equipment manufacturers. Choi *et al*. (2002) developed and evaluated a sliding-type seedling pick-up prototype device in the laboratory, which extracted the seedlings from 200 cell plug trays and got a 97% success rate in extracting 23-day-old seedlings at the frequency of 30 plants per minute. A programmable logic controller type automatic delivery mechanism for potted-seedling was introduced, which claimed to pick up seedlings from the pot with precise, high speed, and non-damaging (Yang *et al.*, 2013). Ni *et al*. (2015) further explored the plug pick-up mechanism, introducing a pneumatic-driven end-effector with a shovel-shaped needle for gripping tomato seedling plugs. Bingliang *et al*. (2019) used simulation software to introduce counterweight in rotary-type seedling pick-up mechanisms operated by the planetary and elliptical gear to improve the working stability, which reduced the working force required by around 10% for each axis. Researchers in China employed air blowing cum vibration type seedling unloading mechanism in a domestic vegetable transplanter, which appealed to have a promising success rate of 92% and damage rate limited to 3% (Yuan *et al.*, 2019). Despite the enormous use and development of gripper-type pick-up devices, they were still claimed to have a complex structure with bulky volume in design. Therefore, Tian *et al*. (2022) enhanced the gripper design using discrete element modeling based on the elastoplastic contact model by optimizing the diameter of the needle, insertion depth, and grabbing speed and reported a 7% higher integrity rate compared to the existing system. Several researchers reported using similar gripper-type devices to pick up seedlings from the plastic plug trays while developing semi-automatic and fully automated vegetable transplanters (AVT) (Han *et al.*, 2019). In 2021, Shao *et al.* (2021) developed a multi-adaptive feeding device for vegetable seedling transplanter, with rows of end effectors used for picking seedlings from plug cells and dropping them into chain cups in groups. The developed prototype was tested with cucumber, pepper, and tomato seedlings at three different feeding frequencies and yielded a success rate between 73% and 88%.

In recent years, there has been a shift towards using biodegradable products to replace plastic products to reduce environmental pollution (Chen *et al.*, 2019). The development of biodegradable film technology introduces biodegradable plug trays that are replacing the traditional plastic plug trays (Fuentes *et al.*, 2021; Paudel *et al.*, 2022; Zhang *et al.*, 2019). Using biodegradable plug trays over plastic plug trays completely eliminated the step of removing the seedling from the trays during transplanting (Kumar and Raheman, 2011), and reported to shows fertilizing effect on the plant after degradation (Fuentes *et al.*, 2021). However, most of the AVT machines are designed to use plastic plug trays equipped with a seedling pick-up mechanism that separates seedling and soil media from the plug trays and transplants it into the soil, which may result in transplanting shock to the seedlings (Muriuki *et al.*, 2014). Furthermore, there have been very few studies on the application of biodegradable plug trays. There was no known study on an AVT that uses seedlings grown in biodegradable plug trays and transplanted on the field. Existing seedling pick-up mechanisms are not suitable for biodegradable plug trays due to their lower strength compared to plastic trays (Evans and Hensley, 2004; Evans and Karcher, 2004), which further decreases with the introduction of moisture (Zhang *et al.*, 2019). Hence, there is a need to develop alternative mechanisms to incorporate eco-friendly biodegradable plug trays in AVT.

Therefore, this study aimed to design a plug-tray cutting and metering device for germinated vegetable seedlings grown in biodegradable plug trays. The effectiveness of the developed mechanism was assessed by replacing the existing pick-up mechanism of a commercial transplanter and evaluating its performance in a real-world agricultural field setting.

Materials and Methods

Biodegradable plug trays

The biodegradable plug trays were prepared by mixing recycled newspaper and cardboard waste in a ratio of 80% and 20% by dry mass, respectively. During the pulp preparation process, wet strength and surface sizing agent were added at a 5% concentration each by mass. This was done to ensure that the strength of the plug trays was not significantly reduced when exposed to moisture, as previous research had indicated that the strength of plug trays, and bio-containers can decrease significantly upon moisture exposure (Zhang *et al.*, 2019). These additives resulted in different physical and mechanical properties compared to plug trays without them. Moreover, the addition of these agents did not have a harmful effect on the germination and growth of seedlings in the trays. Detailed compositions of the plug trays and their properties in different lab tests have been reported by Paudel *et al.*, (2022). Each plug tray contains a total of 96 plug cells arranged in a rectangular cone structure with 12 rows and 8 columns (Figure 1a). The average opening size of each plug was 30×30 mm with a tapered base of 20×20 mm, resulting in a plug volume of 27 ml. The average weight of an empty plug tray at laboratory-condition was 204±15 g.

Properties of seedlings in the plug trays

Germination of pepper (*Capsicum annuum* Linnaeus) and cabbage (*Brassica rapa*, subspecies *pekinensis*) seedlings was carried out using biodegradable plug trays in a controlled environment for seven days, maintaining a temperature of 25°C and a photoperiod 18 hours with light in the wavelength range of 440 nm to 680 nm. After germination, the seedlings were transferred to a greenhouse for further development (Figure 1b). The growing process occurred between June and July 2022 at the polyethylene-covered unheated greenhouse at Gyeongsang National University. The seeds were purchased from a local market, soaked in water for 24 hours to promote sprouting, and then placed in a germination medium of bioplus compost. The compost was composed of 9% zeolite, 11% perlite, 11% peat moss, and 69% cocopeat by volume and was selected based on its previous successful performance in seedling preparation experiments. Prior to placing the sprouted seeds, the moisture content of the soil medium was adjusted to approximately 65% (dry basis). Over the next 33 days, the seedlings were irrigated twice a day through an overhead sprinkler system, with each irrigation lasting 5 minutes, followed by 3 days of hardening after 33 days to enhance the strength of the plug trays (Figure 1c, d). At the end of the hardening stage, the moisture content of the individual plug medium was approximately 15% (dry basis). The properties of the seedlings, plug cells, and growing medium at the time of transplanting are presented in Table 1.

Conceptual working of the fully automated vegetable transplanter

Most commercially available AVTs are designed to pick up individual seedlings from plastic plug trays. However, when using biodegradable plug trays, pre-separated plug cells, or paper pot seedlings must be manually fed into the pick-up or metering mechanism. This increases human intervention in the machine, and the machine's efficiency relies on the human operator's ability to properly place the seedlings into the planting mechanisms (Jo *et al.*, 2018). To address this issue, this study implemented a seedling plug-tray cutting mechanism (SPCM) as an alternative to the existing seedling pick-up mechanism.

The SPCM operates on a simple principle of separating a plug cell with seedlings from a plug tray one at a time. This unit involves placing a plug tray with seedlings into a holding rail. Within the holding rail, the flight mechanism propels the plug trays in the forward direction to the appropriate position. Additionally, with a helical groove shaft arrangement, the holding rail can move laterally to align an individual plug cell with the seedling discharge point. Once the plug cell is aligned, cutting blades descend from top to bottom, detaching the plug cell with the seedling from the tray. The separated plug cell at the seedling discharge point then falls through a seedling drop tube and is received by the hopper of the transplanting unit. After detachment, the cutting blade returns to its initial position, and the holding rail moves laterally by the width of a plug cell, aligning the next plug cell at the seedling discharge point. This process continues until the edge of the holding rail reaches the seedling discharge point, completing the detachment of a row of plug cells. To advance to the next row, a link mechanism operates, moving the plug tray forward by the width of a plug cell. This aligns a new row of plug cells at the seedling discharge point. The cutting mechanism then repeats the process in reverse direction. The conceptual design of the SPCM, along with the working principle of the AVT, is depicted in Figure 2. This fully automated mechanism effectively separates seedling plug cells from the tray at the seedling discharge point and delivers them to the transplanter hopper without any human intervention.

Development of the seedling plug-tray cutting mechanism

For an AVT to function correctly, the forward speed, seedling cutting, dropping, and transplanting mechanisms must be synchronized properly (Kumar and Raheman, 2008). In this case, the SPCM was intended to be incorporated into a commercial vegetable transplanter (Kubota Korea, SKP-100W-KR), replacing its

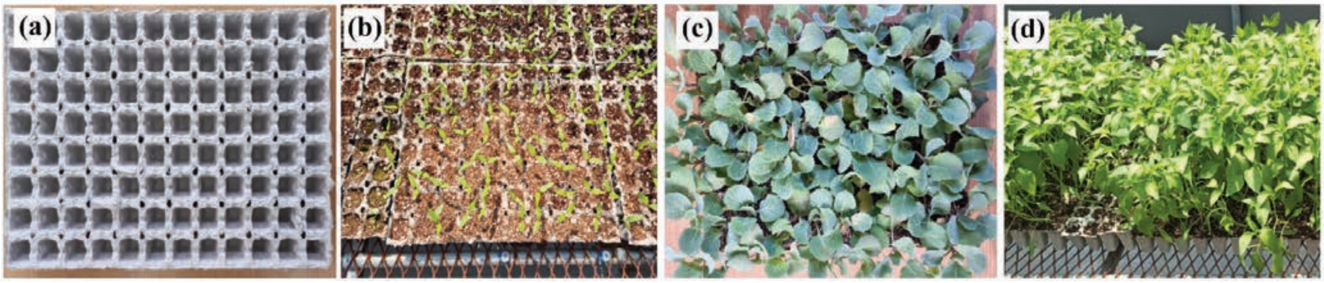

Figure 1. Paper-based biodegradable plug trays for growing seedlings; **a**) an empty plug tray; **b**) seeding germination in plug trays; **c**) cabbage seedlings; **d**) pepper seedlings.

Table 1. Properties of pepper and cabbage seedlings along with the biodegradable plug cell after hardening stage.

Particulars	Pepper (mean ± SD)	Cabbage (mean ± SD)
Seedling shoot height, mm	190.0±7.0	67.3±4.0
Seedling fresh weight, g	1.99±0.06	1.04±0.08
Seedling dry weight, g	0.25±0.02	0.28±0.04
Weight of plug cell with seedling and growth medium, g	16.4±1.1	14.5±1.0
Plug-cell spacing in plug trays, mm	36.0±2.0	36.0±2.0
Moisture content of individual plugs with medium and seedlings (dry basis), %	15.0±0.8	15.0±1

SD, standard deviation.

existing seedling pickup mechanism. So, while designing the SPCM, the space and power availability within the existing transplanter were considered. Furthermore, the designed SPCM had to be synchronized with the prevailing transplanter mechanism, so no changes were required in other components of the AVT. The design of the SPCM was divided into three sub-mechanisms, described in the concurrent sections, to help understand the design.

Lateral movement of trays

The purpose of lateral movement mechanisms in AVT was to efficiently relocate seedlings within a plug tray, ensuring precise alignment of each plug cell at the seedling discharge point. The SPCM's lateral movement mechanism effectively maintained the seedlings' upright position and prevented any damage throughout the process. This was achieved through the utilization of multiple components, including a double helical grooved shaft, sliding shafts, linear bearings, a linear guide slider, and a base plate equipped with holding rails (Figure 3). During operation, the lateral movement mechanism continuously propelled the tray in a lateral direction (11), advancing towards the end before reversing its direction. The precise control over this movement was facilitated by the implementation of the double helical grooved shaft.

The double helical grooved shaft (2) had a diameter of 30 mm and featured a square grooved cut of 5×5 mm. It consisted of 8 revolutions, measuring 288 mm in height, with a pitch of 36 mm that matched the spacing of the seedling's plug cell in plug trays. The sliding shafts (3), spaced 470 mm apart, were 20 mm in diameter and had a length of 717 mm. They were held in place by SK20 shaft holders (1). Smooth movement of the base plate (5) was ensured by the implementation of linear bearings (4). The base plate, measuring 537×369 mm, was connected to the linear bearings and featured a linear guide slider (9) with a driving pin (10) mounted on the double helical grooved shaft. The holding rail (6) of the base plate consisted of 9 rails, spaced 36 mm apart, with a length of 598 mm. The front section of the holding rail had a 51 mm cantilever for the cutting mechanisms to operate, while the

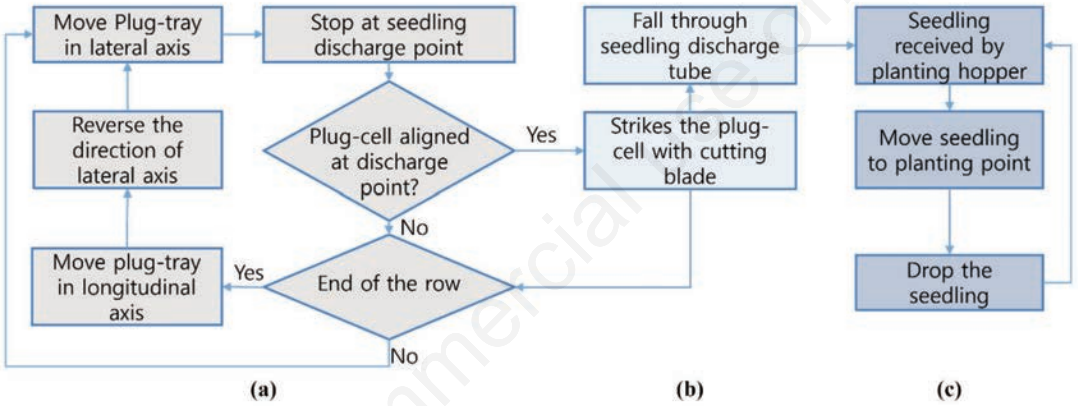

Figure 2. Working principle of the automated transplanting machine. **a**) Plug-cell separation unit; **b**) seedling supply unit; **c**) planting unit.

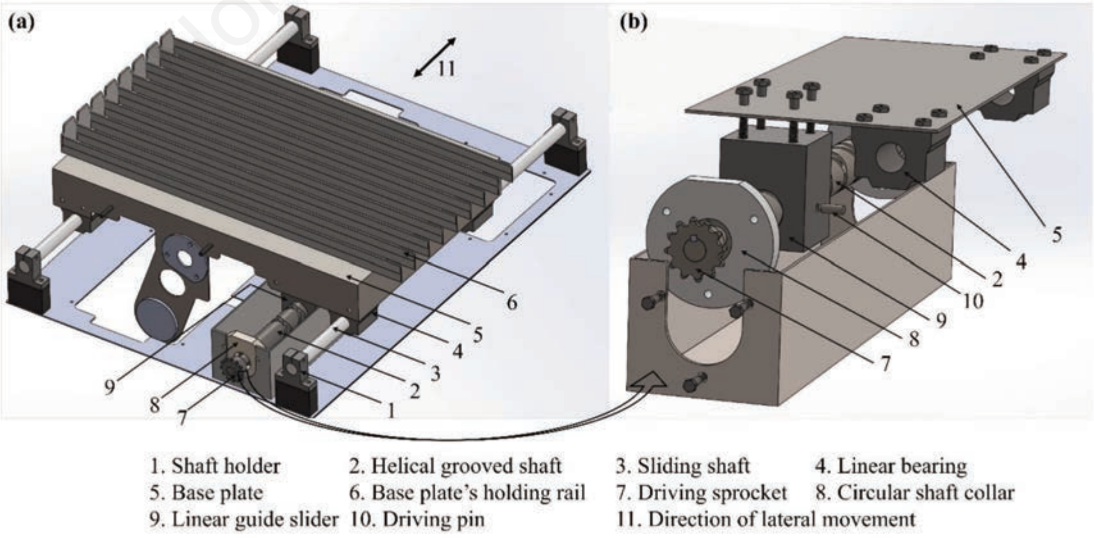

Figure 3. Detailed design and assembly of the component used for (**a**) lateral movement mechanisms of the seedling plug-tray cutting mechanism with (**b**) a closer view of its helical grooved slider assembly system.

rear section had a 10 mm cantilever for easy tray placement. With a height of 31.5 mm, the holding rail can accommodate the plug trays. Additionally, the base plate included other components for various mechanisms in the AVT, which are discussed in the subsequent sections. Circular shaft collars (8) equipped with deep groove ball bearings held the double helical grooved shaft in place. One end of the shaft was connected to a sprocket (7) chain assembly, which powered the rotation of the shaft. The shaft would rotate for one revolution, pause for the cutting mechanisms to operate, then rotate for another revolution and follow a similar pattern. A semi-cog gear assembly controlled this alternating rotation and the rest of the grooved shaft. In each revolution of the grooved shaft, the linear guide slider would move 36 mm, corresponding to the pitch of the helical groove. This movement, in turn, propelled the base plate at the same distance. The smooth motion of the base plate was facilitated by four linear bearings mounted on each corner of the base plate, sliding along 20 mm shafts. In each revolution of the grooved shaft, the linear guide slider would move 36 mm, corresponding to the pitch of the helical groove. This movement, in turn, propelled the base plate at the same distance. The smooth motion of the base plate was facilitated by four linear bearings mounted on each corner of the base plate, sliding along 20 mm shafts. The grooved shaft was designed with a double helix groove that formed an infinite grooved double helix, with the endpoint on each edge connected without any dead points. When the linear slider mounted on the groove of the shaft reached the edge, its direction would be reversed, allowing the linear motion to continue until the grooved shaft rotated again.

Longitudinal movement

The goal of the longitudinal movement mechanisms in the SPCM was to move the plug tray, positioned on the holding rail of the base plate, in the longitudinal (forward) direction (31). This motion occurred when the lateral movement mechanisms reached the edge of the row, just before changing direction. This mechanism aimed to align the subsequent row of the plug tray and seedlings with the seedling discharge point once the cutting process for the preceding row was finished. The longitudinal movement mechanism utilized several components to achieve its functionality, as illustrated in Figure 4. These components included a movable base plate (12) with an additional driving disc (18), shafts (19, 22), gears (17, 21, 23, 24), links (13, 14, 15, 20), a rod (28), and plates with vertical spikes (flight) (27). Together, these components facilitated the forward movement of the plug tray.

Power was transferred to the mechanism through the driving shaft (26), which was attached beneath the base plate and spanned its entire width. The driving shaft (26) continuously received power through chain sprocket mechanisms. Within its span, two wedge-shaped cams (25) engaged with one of six cylindrical spikes located along the circumference of the driving disc (18) when the movable base plate reached each edge. This engagement caused the rotation of the shaft (19). The rotational power from shaft (19) was then conveyed to the output shaft (22) through a series of auxiliary gears (21, 23, and 24), with gear (17) acting as driving gear. The gear ratios were adjusted to ensure that the output shaft (22) completed one full rotation when the wedge cam (25) engaged with the driving disc (18). This rotational power was subsequently transferred from the shaft (22) to the quaternary link (20) via an eccentric link driving disc (29). The eccentric movement of link (20) within the link mechanisms (12, 13, 14, 15, 20, and 27) shown in Figure 4 resulted in the forward motion of the tray spikes (27), pushing the plug tray forward and distributing the force evenly through rod (28). Once the tray spikes (27) moved forward, they descended beneath the base plate and returned to their original position without disturbing the plug tray. This cyclical process repeated when the base plate reached the opposite end of the row, with another wedge cam, similar to (25), engaging with one of the six cylindrical spikes located along the circumference of the next driving disc, similar to (18), to rotate the shaft (19) and continue the process.

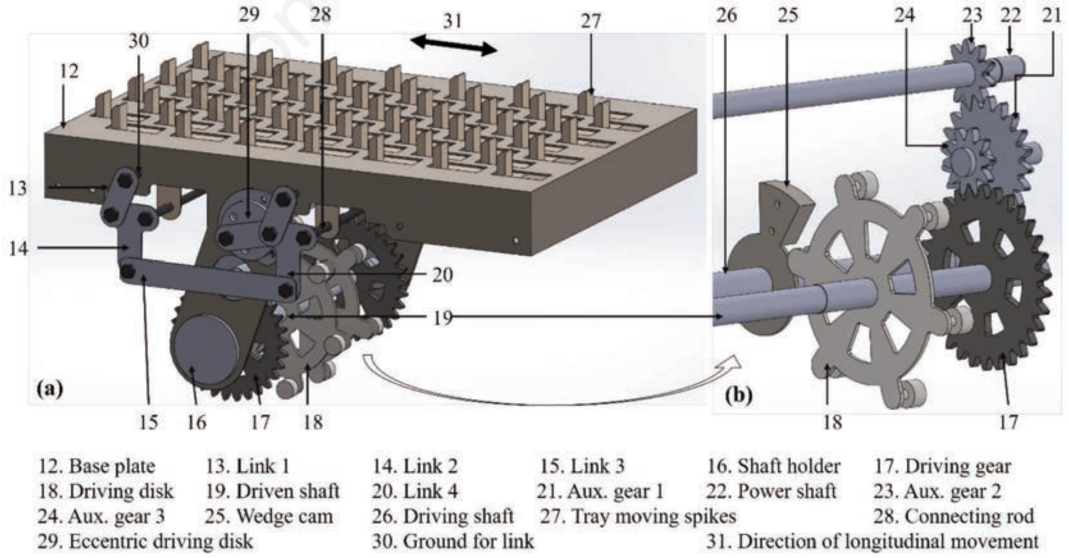

Figure 4. Detailed design and assembly of the component used for (**a**) longitudinal movement mechanisms of the seedling plug-tray cutting mechanism with (**b**) a closer view of its gear system.

Cutting mechanism

The cutting mechanism played a critical role in the SPCM by separating individual plug cells from the plug trays at the seedling discharge point. Figure 5 illustrates the components involved in this mechanism. The cutting blade, a crucial part of the mechanism, comprised a stationary blade (32) and a rotary blade (33). The blade assembly executed vertical strikes from top to bottom, effectively separating the plug cells positioned on the front cantilever section of the holding rail of the base plate. The stationary blade was fixed to the body of the linear slider (34), enabling its vertical motion along the sliding shaft (35). A metal plate ensure synchronized movement between the linear sliders.

The rotary blade (33) was mounted on a shaft (38) that passed through the linear slider and pendants (36) and featured an L-shaped cam (40) at the end. The pendant followed the path of the chain (37), connected to the sprockets (44 and 45). This setup ensured that the blade connected to the pendant and linear slider moved downward during the cutting stroke, retracted from the holding rail, ascended along the chain, and returned to the holding rail. The L-shaped cam (40) had the function of rotating the shaft (38) of the rotary blade by 90 degrees in a clockwise direction. At the beginning of the downward stroke, the edge of the metal box (39) struck the L-shaped cam, causing it to rotate 90 degrees, aligning both faces in a parallel manner. When the cutting stroke finished, another face of the L-shaped cam rotated the shaft counterclockwise by 90 degrees. Throughout the blade's motion, the shaft and blade remained in the counterclockwise 90-degree position. During the cutting stroke, the stationary and rotary blades combined to form a rectangular U shape with outer dimensions of 35×45 mm. Power to operate the cutting mechanism was transmitted from the shaft with gear (41) to the shaft containing gear (42). Inside the gearbox (46), the power was further transmitted to the shaft containing the driving sprocket (44), which was connected to the sprocket (45) through a chain connection.

Combination of mechanisms and power transmission

The SPCM was developed to be integrated into a commercial vegetable transplanter (Kubota Korea, SKP-100W-KR) as a replacement for its existing seedling pickup mechanism. Thus, during the design phase of the SPCM, considerations were made for the available space and power within the existing transplanter. Figure 6a provides an overview of the fully assembled AVT, powered by a 3.1 kW engine (47). The engine distributes power to various components through belts, pulleys, gears, chains, and sprockets. In its assembled configuration, the SPCM receives power through the chain and sprocket arrangement from point (48). An independent power source (induction motor) was also used as a power source at point (48), connecting to shaft (49) for testing the SPCM mechanism independently (Figure 6b). From shaft (49), power was distributed to the cutting mechanisms through gear (50) and to the plug-tray moving mechanisms via chain sprocket mechanisms to shafts (51 and 2). The shaft (51) was equipped with a half-cog gear assembly containing 9 cogs that transmitted power to the driven gear containing 9 cogs but half the time during one rotation of the driving gear. This assembly resulted in periodic motion for lateral mechanisms through a grooved shaft (2) such that the cutting mechanisms struck the plug trays during the resting stage of lateral mechanisms. The sprocket mechanisms powered the shaft containing wedge shaped cam (14). At the end of the lateral movement, the wedge-shaped cam engages with one of the six cylindrical spikes located along the circumference of the driving disc. This engagement operates the longitudinal mechanisms responsible for moving the plate containing the spikes (27) in a longitudinal direction, thereby moving the plug trays.

Performance evaluation of seedling plug-tray cutting mechanism

To separate the plug cell from the plug trays effectively, without causing damage to the seedlings, it was essential to study and understand the operational parameters of the SPCM. This involved

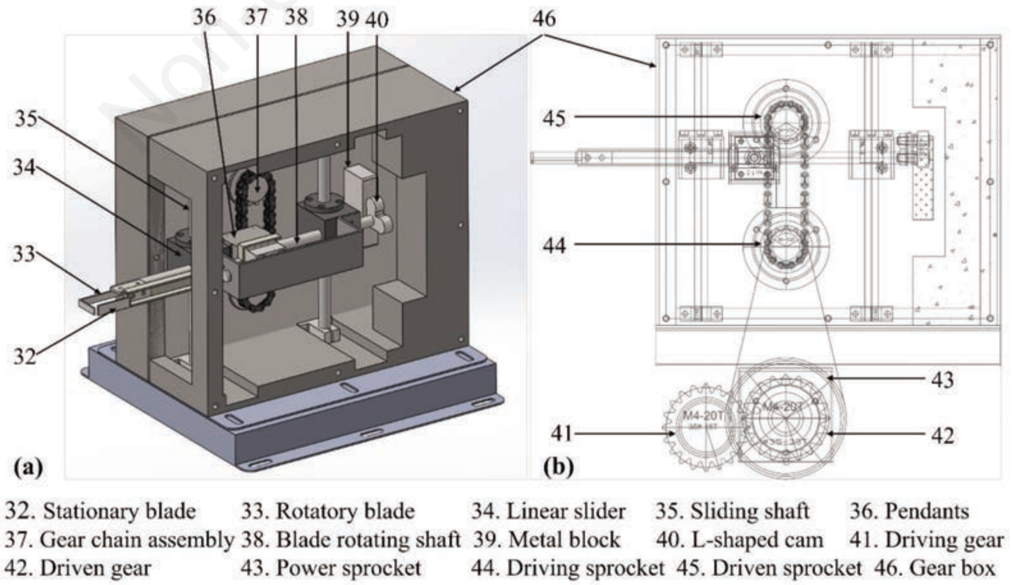

Figure 5. Cutting mechanism of the seedling plug-tray cutting mechanism; (**a**) assembly view of the cutting mechanisms and (**b**) detailed CAD design of the mechanisms.

analyzing the working speed of the various components, the characteristics of the seedlings being used, and their impact on the performance of the SPCM. To evaluate the performance and functionality of the SPCM, it was tested on a stationary bench using an induction motor as a power source before being integrated into the transplanter machine. The testing involved determining the cutting frequency, the rate of plug-cell damage during cutting, the frequency of missed or incomplete cutting, and the rate of stagnation at the seedling drop tube for paper-based biodegradable plug trays with pepper seedlings at various operation speeds. Two optimal speeds were identified for low and high-gear setups to achieve the maximum cutting and dropping rate with minimal missed cutting and stagnation in the drop tube.

Performance evaluation of automated transplanter

The performance of a newly developed SPCM was evaluated through its integration with an existing commercial transplanter (Kubota Korea, SKP-100W-KR) by replacing its seedling pick-up mechanisms to create an AVT (Figure 7a). The specifications of the AVT are shown in Table 2. The integration of the SPCM was designed such that the seedling drop tube of the existing transplanter aligned seamlessly with the drop tube of the SPCM mechanisms, thereby eliminating the need for any changes to the planting mechanisms. To evaluate the field performance of the 3.1 kW walk-behind AVT with integrated SPCM, pepper and cabbage seedlings grown in 8×12 cell, paper-based biodegradable plug trays were used. The machine was tested in a plot measuring 40×10 m, with three ridges prepared at heights of 15, 20, and 25 cm. The soil in the field was sandy loam, characterized by a wet bulk density of 1.42 g cm^{-3}, dry bulk density of 1.23 g cm^{-3}, pH of 6.53, and moisture content of 13.36% on a dry basis. During testing, the machine was operated at forward speeds of 0.72 and 0.83 km h^{-1}. The planting unit (hopper), soil covering device, and depth adjusting wheel were retained from the original transplanter.

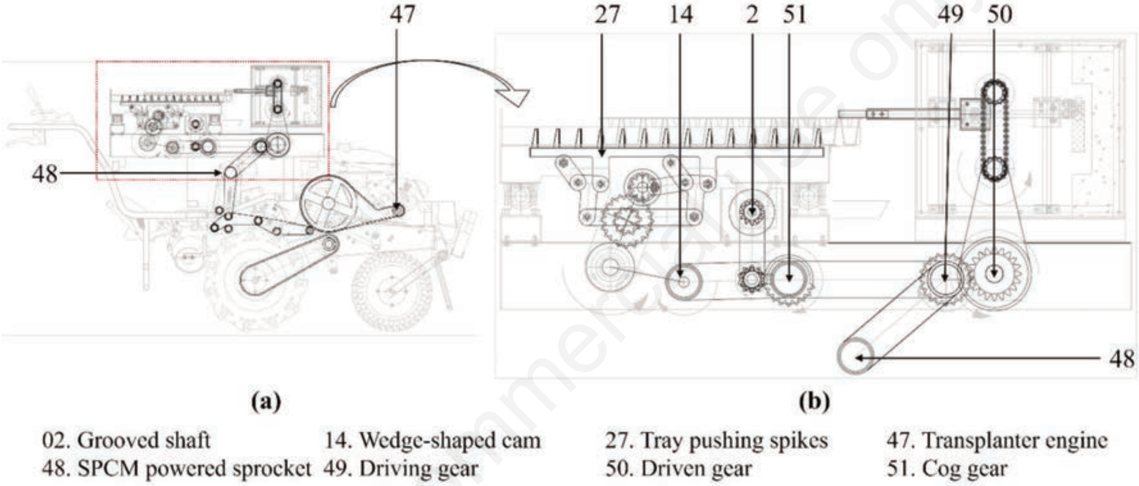

Figure 6. Side view of the assembly of the mechanisms showing the power distribution from the engine to all function parts in (**a**) entire transplanter and (**b**) focused on developed seedling plug-tray cutting mechanism parts.

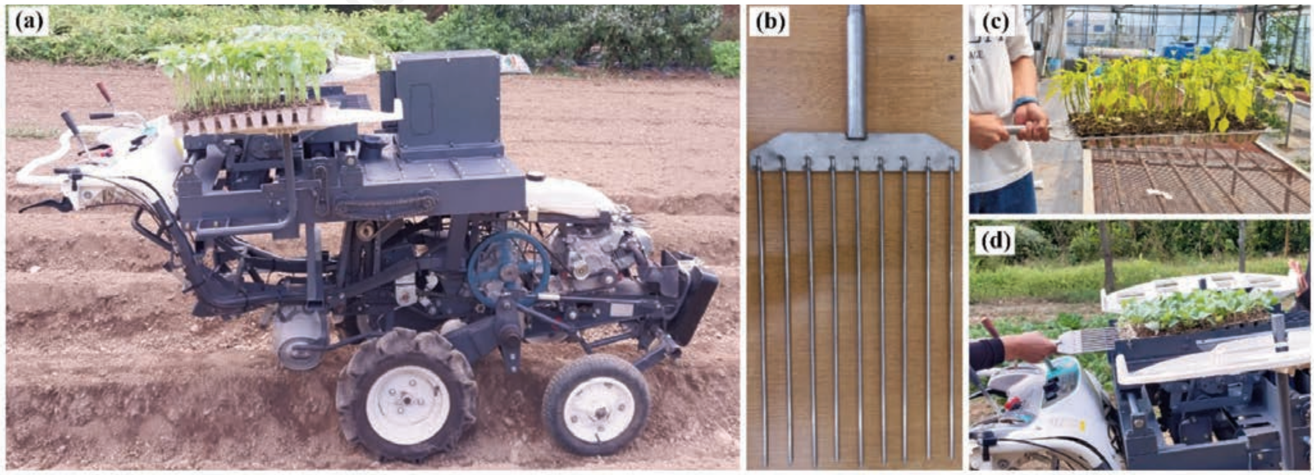

Figure 7. (**a**) Overall view of the fully automated vegetable transplanter with seedling plug-tray cutting mechanism in the field; (**b**) plug-trays carrying tool; (**c**) holding pepper seedling plug trays; (**d**) placing cabbage seedling plug trays to the holding rail of transplanter during a field test.

Before recording the AVT's performance, pre-experimental trials were conducted to ensure each component's functionality and verify proper uprightness, depth for the transplanted seedlings, and adequate soil coverage. A plug tray containing 96 seedlings was placed in the plug tray holding rails with the help of a plug-tray holding device (Figure 7b). The plug-tray holding device featured nine cylindrical finger rods mounted on a base handle, spaced 36 mm apart to match the width of the plug trays. When carrying the plug trays, the finger rods of the tool were inserted from below, distributing the force evenly and avoiding damage to both the seedlings and plug trays (Figure 7c, d). The AVT's plug-tray moving mechanism was operated such that the first plug cell of the plug trays aligned at the seedling discharge point. The AVT was then operated along the length of the field. For this study, a factorial experimental design approach was adopted, involving the operation of the AVT at two different speeds (high and low gear) and three ridge heights (15, 20, and 25 cm). During the AVT operation, the time required for tasks such as placing the seedlings in the holding rail, aligning the plug cell with the seedling discharge point, taking turns at the headland, adjusting the depth lever, and engaging/disengaging the clutch were recorded. Additionally, the time needed for transplanting the seedlings in the field was recorded. The field capacity of the AVT, fuel consumption rate, and wheel slip percentage were also determined. Upon completion of the transplanting process, measurements were taken in the field to assess the planting frequency, missing frequency, plant spacing, planting angle, and planting depth.

Data analysis

The data collected during the field test was documented using Microsoft Excel 2016. The Statistical Package for the Social Sciences v.26 by IBM Corporation in Armonk, New York, USA, was used for statistical analysis. Means obtained during the different tests were compared using analysis of variance (ANOVA). Statistical differences between treatments were determined using Tukey's honestly significant difference post hoc test at a significance level of $p \leq 0.05$.

Results and Discussion

Field performance

The developed automated vegetable seedling transplanting machine was of a single-row type, with an average planting rate of 30 plug cells per minute at a forward speed of 0.72 km h^{-1} (low speed), and 35 plug cells per minute at 0.83 km h^{-1} (high speed). The result for the plug-tray cutting and transplanting performance rate is summarised in Table 3. According to the result (Table 3), when testing the AVT with pepper and cabbage seedlings in plug trays, 80% and 83% of pepper seedling plug cells were successfully detached and dropped from the seedling discharge unit (SDU) at lower and higher speeds, respectively. The corresponding values for plug trays with cabbage seedlings were 84% and 81%, respectively. This shows that, on average, the developed AVT can deliver 82% of the plug cells to the planting unit, while the mechanisms appear to be inefficient for the 18% of seedlings remaining at the holding rail due to stagnation around the SDU or cutting errors. Out of the seedlings supplied to the planting unit through the SDU, the AVT's planting unit can successfully transplant approximately 91% of both pepper and cabbage seedlings in the field. However, around 9% of the seedlings were not transplanted, which was a mis-transplanting rate of an AVT. As a result, 73% of pepper seedlings and 75% of cabbage seedlings were successfully transplanted into the field, resulting in an overall 74% transplanting performance of the developed AVT. The transplanting performance

Table 2. Specification of the fully automated vegetable transplanter.

Parameters	Specification
Original model	SKP-100(W)-KR
Original manufacturer	Kubota
Engine type	Gasoline
Rated engine power, kW	3.1
Output power, kW	2.19
Rated engine speed, rpm	1600
Rated working speed, km/h	1.5
Working width, mm	650
Dimension after modification (l/b/h), mm	2150/1360/1370
Dimension of SPCM (l/b/h), mm	1300/720/440
Plant Spacing, mm	300-600
Number of rows	1

SPCM, seedling plug-tray cutting mechanism.

Table 3. Results of the field test showing the average performance of seedling plug-tray cutting mechanism and transplanter in separating plug cells from plug trays and transplanting them to the field. The data represent the number of plug cells containing seedlings.

Crop	Speed	Bund height (mm)	Total plug cell	Dropped from SDU	Cutting error and stagnation	Successful plantation	Unsuccessful plantation
Pepper	Low	150	96	76	20	67	9
		200	96	74	22	67	7
		250	96	79	17	73	6
	High	150	96	72	24	67	5
		200	96	83	13	74	9
		250	96	83	13	76	7
Cabbage	Low	150	96	82	14	76	6
		200	96	85	11	76	9
		250	96	76	20	69	7
	High	150	96	77	19	67	10
		200	96	77	19	71	6
		250	96	80	16	73	7

SDU, seedling discharge unit.

was low compared to the performance of automated transplanters with seedling pick-up mechanisms (Wen *et al.*, 2021), where 92% of seedlings were successfully transplanted into the field without injury. However, the performance was very similar to some automatic transplanters with pick-up mechanisms at their initial development stage, where 71% of potted tomato seedlings (Xin *et al.*, 2019) and 78% of vegetable seedlings (Jin *et al.*, 2018) were successfully transplanted into the field. Table 4 shows the quality of work achieved by the AVT. During field testing, normal plant spacing was set at 400 mm for lower gear riding speed (0.72 km h^{-1}) and 450 mm for higher gear riding speed (0.83 km h^{-1}). Results revealed that the average plant spacing for pepper seedlings was 391±27 mm at low speed and 429±15 mm at high speed. Similarly, the plant spacing for cabbage seedlings was 387±22 mm at low speed and 440±19 mm at high speed. Statistical analysis showed no significant difference in plant spacing between pepper and cabbage seedlings at the same forward speed despite differences in bund height. The two-way ANOVA indicated a significant interaction effect of speed and bund height on plant spacing for both pepper and cabbage seedlings ($p<0.05$) but no significant difference in plant spacing within the same forwarding speed ($p>0.05$). Planting depth for both pepper and cabbage seedlings increased with bund height, and the interaction effect of speed and bund height was significant ($p<0.05$). For the same bund height, the planting depth increased with increased speed. The average planting depth for pepper seedlings was 50 mm, 52 mm, and 59 mm at bund heights of 150 mm, 200 mm, and 250 mm, respectively. The corresponding planting depth for cabbage seedlings were 42 mm, 47 mm, and 54 mm, respectively. For pepper seedlings, the range of planting angle was 0° to 30°, with 85% inclined at less than 10°, 10% between 10° and 20°, and 5% above 20°. Measuring the angle of the cabbage seedlings was more difficult due to their smaller height, but upon visual inspection, 7% of the seedlings were found to have significant tilting (≈ >30°). Tilted planting was found to be low at a bund height of 200 mm due to sufficient planting depth and high at 150 mm due to shallower planting depth, as well as at 250 mm due to excessive soil covering for both pepper and cabbage seedlings. Iqbal *et al.* (2021) studied the transplanting performance of a 2.6 kW pepper transplanter and found that at a forward speed of 1.08 km h^{-1} (300 mm s^{-1}), the desired planting depth of 40 mm was achieved, and the planting angle was 0±3.26°. However, when the speed was increased or decreased by 0.18 km h^{-1} (50 mm s^{-1}), the range of planting angle was between -16.35° and 19.5°. In our study, most of the planting angles of pepper seedlings also fell within this range. Khadatkar and Mathur (2022) reported a coefficient of variation of 1.9% for plant spacing and 1.5% for planting depth when transplanting pepper seedlings at a 600 mm plant spacing and 45-50 mm planting depth. However, in this study, the coefficient of variation for plant spacing was found to be 6.9% at low speed, 3.4% at high speed for pepper seedlings, 5.7% at low speed, 4.45% at high speed for cabbage seedlings. For planting depth, the coefficient of variation was 14.7% at low speed, 14.9% at high speed for pepper seedlings, 16.0% at low speed, and 14.5% at high speed for cabbage seedlings. The coefficient of variation for planting depths was high for a particular speed due to different planting depth obtained at different bund heights.

Field capacity and labor requirement

Table 5 summarizes the overall performance metrics of the AVT. While testing it on a field with an average forward speed of 0.72 km h^{-1} at low gear and 0.83 km h^{-1} at high gear speed, the percentage of wheel slip varied from 2.8% to 3.4%. The average fuel

Table 4. Quality of work achieved from the automated vegetable transplanter for pepper and cabbage seedlings at different speed and bund height combinations. Data are presented as mean ± standard deviation, except for planting angle, which is presented as a range.

Particulars	Parameters					
Speed, km h^{-1}	0.72 (low gear)			0.83 (high gear)		
Bund height created, mm	150	200	250	150	200	250
Plant spacing (pepper), mm	383±13^a	393±16^a	392±43^a	431±13^b	427±8^b	430±20^b
Plant spacing (cabbage), mm	385±26^a	386±16^a	393±24^a	433±18^b	448±18^b	439±21^b
Planting depth (pepper), mm	52±6^{abc}	50±10^{bc}	57±4^{bc}	46±7^a	53±4^{abc}	61±4^c
Planting depth (cabbage), mm	42±7^a	44±4^{ab}	53±5^c	42±5^a	50±5^{bc}	55±4^c
Planting angle (pepper), x°	$0 \le x \le 20$	$0 \le x \le 9$	$0 \le x \le 16$	$0 \le x \le 21$	$0 \le x \le 10$	$0 \le x \le 30$

Different letter alongside the value represents a statistical difference in mean at $p<0.05$ based on Tukey's *post hoc* test.

Table 5. Summary of the field performance of the automated vegetable seedling transplanter for transplanting pepper and cabbage seedlings germinated and grown in paper-based biodegradable plug trays.

Particulars	Parameters	
Speed, km h^{-1}	0.72 (low gear)	0.83 (high gear)
Planting/cutting frequency, min^{-1}	30	35
Theoretical field capacity, ha h^{-1}	0.0468	0.0539
Actual field capacity, ha h^{-1}	0.0324	0.0358
Field efficiency, %	69.4	66.4
Average labor requirement, man-h ha^{-1}	61.5	55.8
Average missed planting rate for pepper, %	9.63	8.74
Average missed planting rate for cabbage, %	9.04	9.84

consumption was found to be 1.25 l h^{-1}. The field capacity at low gear speed was 0.032 ha h^{-1}, and at high gear speed was 0.035 ha h^{-1} with corresponding field efficiency of 69% and 66%. The field efficiency was reduced at a higher speed because the machine needed to be stopped frequently due to higher cutting and stagnation errors during transplanting. However, previous literature suggested that to improve the field efficiency, the operating speed of the transplanter must be high (*i.e.*, 2.0 km h^{-1} and beyond) (Khadatkar *et al.*, 2018). Kumar and Raheman, (2011) developed an AVT for paper pot seedlings and reported to have a field capacity of 0.026 ha h^{-1} and field efficiency of 31.88%, while in the case of walk-behind type self-propelled AVT with seedling pick-up mechanisms, Park *et al*. (2005) reported a field capacity of 0.045 ha h^{-1} when tested with Chinese cabbage seedlings. The field capacity of developed AVT was lower than that of Park *et al*. (2005) because of the frequent stagnation of seedlings around the seedling discharge point, which needed to be cleaned manually before further operations, and because of the single working row. Regarding the labor requirements, for the developed AVT, the labor requirement varied from 55.8 man-h ha^{-1} to 61.5 man-h ha^{-1}, depending on the forwarding speed. This includes the labor required to place the seedling on the holding rail of the AVT and operate it. The human power required for transplanting using AVT was low compared to the labor required for manual transplanting the paper pot (229 man-h ha^{-1}) and bare-root seedling (320 man-h ha^{-1}) (Kumar & Raheman, 2011). Thus, the developed SPCM incorporated AVT required 73% less labor than the labor required to manually transplant paper pot seedlings.

Challenges and prospects

The development of an AVT poses a substantial financial challenge and requires the highest levels of plant uniformity and quality (Parish, 2005). Additionally, creating a new mechanism for these AVTs presents several technical hurdles, such as integrating complex systems, cost considerations, and maintenance requirements (Khadatkar *et al.*, 2018). However, developing a new mechanism can offer significant benefits regarding efficiency, planting accuracy, and sustainability (Sharma and Khar, 2022). An advanced mechanism may also help to lower the cost of transplanters and present opportunities for further research and development in the field.

The SPCM-based AVT faces challenges in competing with traditional pick-up mechanism-based transplanters due to its low transplanting performance. This performance issue was caused by frequent cutting and stagnation errors, particularly in the last two rows of plug trays, which received limited normal support force during the cutting stroke. Furthermore, the current operating speed of the developed mechanism was comparatively low compared to other commercially available transplanters. Javidan and Mohammadzamani (2019) mentioned that the transplanter's performance at the speeds of 2 km h^{-1} and 1 km h^{-1} were statistically the same. However, the higher speed of the machine resulted in higher field capacity, thus selected as the optimized speed. Another challenge for the SPCM-based AVT was the use of biodegradable plug trays for seedling preparation. While plastic plug trays have been in use for a long time (Marr and Jirak, 1990), biodegradable plug trays are still a relatively new concept for many vegetable growers. Kumar and Raheman (2011) reported that the cost of manufacturing and operating a transplanter was higher than that of manual transplanting, but it reduced labor requirements by 55% and saved time by 72%. However, the current study did not examine the costs associated with developing the transplanter. Despite these challenges, there are several promising aspects to this study. The growing interest among farmers in biodegradable plug trays as a means to reduce plastic waste is likely to drive further research and development in the creation of biodegradable plug-tray-based AVT (Chen *et al.*, 2019; Filho *et al.*, 2021). Plants germinated and grown in biodegradable plug trays had a high survival rate and offered nutritional benefits (Khan *et al.*, 2000). The transplanting performance and operating speed of the AVT can be improved, and other inefficiencies within the mechanisms can be reduced through ongoing research, development, and testing in this field.

Conclusions

This paper detailed the development of a mechanism for cutting seedling plug trays for AVT. The goal was to replace the existing seedling pick-up mechanism and use seedlings prepared in paper-based, biodegradable seedling plug trays instead of plastic-based ones. The SPCM comprises three sub-mechanisms: the first two align plug cells with the seedling discharge point by moving plug trays laterally and longitudinally, while the third cuts and separates the plug cell, enabling seedlings to be transplanted into the field. The developed mechanism was integrated into a commercial transplanter and tested in the field, with positive results for both the SPCM and the AVT. The AVT achieved a transplanting performance of 74% during testing with pepper and cabbage seedlings. The field capacity ranged from 0.032 to 0.035 ha h^{-1}, with an average field efficiency of 68%. Using the developed AVT requires 73% less labor than manual seedling transplanting. The seedling transplanting performance in the field was satisfactory, with the majority of pepper seedlings (85%) transplanted with a planting angle of less than 10° and around 7% inclined for cabbage seedlings. The seedlings' planting depth depends on the height of the bund, with an average depth of 53 mm for pepper seedlings and 48 mm for cabbage seedlings, sufficient to bury the biodegradable plug trays into the soil. The developed SPCM prototype showed low field efficiency and capacity, being the first of its kind. Efforts will focus on enhancing performance by increasing speed, reducing errors, and addressing financial challenges. Despite these challenges, the advanced mechanism offers further research and development opportunities, promising increased efficiency, planting accuracy, and sustainability.

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