Development of a transplanter-based transplanter for vegetable seedlings cultured in a cuttable nursery mat

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Abstract

Vegetable transplanters that are fully automated have been developed to reduce the labor-intensive and yield-influencing process of transplanting; however, the majority of these transplanters are heavy and costly. Based on a traditional Japanese rice transplanter, we created a low-cost, high-efficiency vegetable transplanter in this study. Because a rice transplanter can only be utilized in flooded fields, certain mechanical parts have been adjusted to allow for the transplantation of rice on dry fields. In order to precisely slice the nursery mat one by one without harming the seedlings, the rotor case and end-effector parts were modified. Additionally, a long guide and a leaf spring-type retainer were created in order to securely hold heavier and larger vegetable seedlings than those of rice, and a cuttable nursery mat (CNM) was introduced as a new kind of solid nursery bed. The prototype could transplant up to 250 cabbage plants min^{-1} row^{-1} for planting speed of 1.0 m s^{-1}. Conventional plug seedlings (PS) are not as suitable for transplanting and cultivation as CNM seedlings (CNMS). Unlike PS, CNMS were only cultured for a brief period prior to transplantation since the CNM itself has sufficient stiffness, negating the need for root spread. This study is the first demonstration of the possible applications of this rice transplanter-based vegetable transplanting system.

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Introduction

Transplanting seedlings is one of the most important tasks in vegetable cultivation. Transplanting requires precision because it is directly linked to the yield; however, there are still areas where transplantation is performed manually, such as in developing countries (Hwang *et al.*, 2020; Kumar and Raheman, 2008). Automatic transplanting is effective not only in reducing labor intensity and work time but also in improving yield quality and quantity because it can uniform planting angle, depth, and distribution (Bechar and Vigneault, 2017; Rasool *et al.*, 2020; Pérez-Ruiz and Slaughter, 2021). In contrast to semiautomatic transplanters, which require labor to manually transfer seedlings into the cup, fully automatic transplanters are more advantageous and widely used (Khadatkar *et al.*, 2018). For example, PW20R, a fully automatic transplanter employing a pick-up type mechanism manufactured by Yanmar Agribusiness Co., Ltd. (Choi *et al.*, 2002), was well received by farmers. However, its complex mechanism and high initial cost required for setup, including a dedicated tray to culture plug seedlings (PS), have hindered its widespread use. The professional skills required to culture PS have also restricted its use *e.g.*, forming a root ball to pick out from a tray) (Rutledge, 1999; Han *et al.*, 2019).

To address these problems, we developed a fully automatic transplanter based on a conventional Japanese rice transplanter. Rice transplanters were developed in Japan in the 1960s (Ibrahim *et al.*, 2014) (Figure 1A). Nowadays, according to the Ministry of Agriculture, Forest and Fisheries of Japan (2016), >1 million of these transplanters are in operation, with an adoption rate of 77% and 28,000 shipments in 2016. The development of vegetable seedling transplanters based on a rice transplanter has several advantages: first, manufacturing costs are low because most components are shared with rice transplanters its sales are larger than those of vegetable ones. According to the reports by Agriculture & Livestock Industries Corporation (2018), 3,500 vegetable seedling transplanters were shipped in 2016. Second, fuel efficiency and soil compaction are improved because it is lighter than conventional automatic vegetable transplanters (Botta *et al.*, 2010). As shown in *Supplementary Table 1*, manufactured vegetable transplanters with comparable high-speed transplantation to our prototype are more expensive and heavier; much more in the case of transplanters pulled by a tractor. This suggests that rice transplanter-based vegetable transplanters could be low-cost, cheaper, and lighter than existing alternatives.

Mat or plug-type rice seedlings are generally transplanted, with the former being less expensive and more popular than the latter. Mat seedlings are typically cultured after seeds are bedded on a tray filled with nursery soil (Figure 1B). The roots of rice seedlings spread and entangle, enabling the formation of a tough mat that can be mounted on a seedling rack without erosion. During transplantation, 3-5 seedlings are cut at a time by the end-effector and subsequently transplanted onto flooded flat paddy fields after puddling (Figure 1C, D). The transplanting arm is moved by a planetary gear mechanism with noncircular planet pinions (Zhang *et al.*, 2014). Conversely, vegetable seedlings are larger than rice seedlings so their seedling density on a mat and root density are lower than those of rice. Altogether, this suggests that vegetable seedlings cannot form tough mats by root spread alone. Therefore, nursery mats of adequate stiffness are required; however, no solid nursery mats can adapt to our prototype.

This study aimed to develop a vegetable seedling transplanter for cabbage seedlings based on a conventional Japanese rice transplanter. To this end, some mechanical components were modified to adapt for transplantation on dry fields; moreover, components of an end-effector and a rotor case were modified to precisely cut the nursery mat one at a time without damaging the seedlings. To firmly grasp heavier and larger cabbage seedlings, a leaf spring-type retainer and a long guide were developed and a cuttable nursery mat (CNM) was introduced as a new solid nursery bed. CNM itself has adequate stiffness; therefore, root spread is not needed to form a tough mat. To evaluate the CNM performance, transplanting and cultivating tests were performed using PS as a control in a field. The PS was transplanted using PW20R. CNM is an effective material for the dissemination of mechanized vegetable seedling transplants. It makes seedling culturing easier and reduces the cost because forming a root ball and preparing special trays are not necessary.

Materials and Methods

Development of the transplanting mechanism

A single-row prototype vegetable transplanter was developed using a manufactured rice transplanter (YR6D, Yanmar Agribusiness Co., Ltd.) as a base machine (Figures 2A and *Supplementary Figure 1*). To adapt the transplanting system of the rice transplanter for cabbage seedling transplantation, a prototype was developed as described below.

First, to precisely cut the nursery mat one at a time without damaging the seedlings, the planetary gear mechanism with non-circular planet pinions was modified to generate the locus required to uniformly cut CNMS and minimize interference between tines and seedlings (Figure 2B). The position of the seedling tray was adjusted accordingly. Unlike the rice transplanter, top of the transplanting tine was shifted forward by 15 mm (Figure 2B). This allowed the tine to minimize interference between the tine spine and seedlings (Figure 2E, F). In addition, a cam mechanism was modified to eliminate the backlash between an end-effector and a rotor case. Due to the backlash, the centrifugal force caused by the arm rotation changed the place of insertion of the tine into a CNMS. The arm rotation speed varied with transplanting speed and hill distance. This suggested that the size of cut CNMS changes with changes in transplanting speed and hill distance. An excessively big cut CNMS would not fit into the tine and retainer, and if it is too small, it would be dropped from the end-effector. To eliminate the backlash, the cam phase, which shared a shaft with the end-effector, was modified (Figure 2C). The cam pushed the follower maximally just before the tine was inserted into the CNMS. Since the reactive force from the spring also pushed the cam, the backlash between the end-effector and rotor case was eliminated (Figure 2C). The number of end-effectors at the rotor case decreased from two to one, as the vegetable hill distance was wider than that of rice. Next, to transplant heavier and larger vegetable seedlings, a retainer was installed on the end-effector to strongly hold CNMS and the tine (Figure 2D). Solid and leaf spring-type retainers were prepared to confirm the effect of shape on CNMS holding (Figure 2J, K). A solid retainer was fitted to pro-

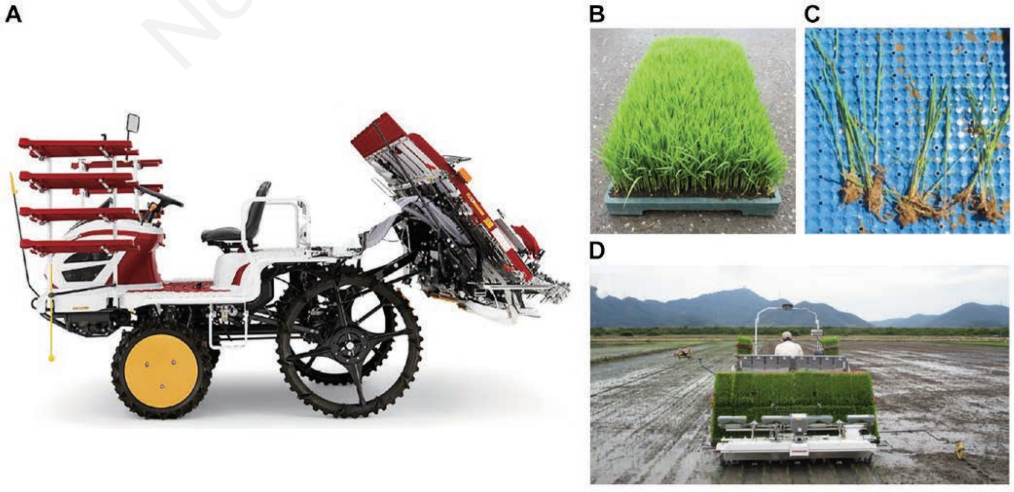

Figure 1. A) Conventional rice transplanter in Japan (YR8DA, Yanmar Agribusiness Co., Ltd.); **B**) rice seedling mat; **C**) seedlings; **D**) rice transplantation on a paddy field after puddling.

vide 0 mm clearance between retainers and CNMS. A leaf spring-type retainer was fitted 5 mm forward compared with solid one. In addition, to prevent seedlings from swinging due to arm rotation, a long guide was equipped in the transplanter frame (Figure 2A). Bars were added at a 29 mm interval along the rack belt, which corresponds to slits on the bottom side of the CNM, preventing it from slipping on the seedling rack (Figure 2A). A ratchet mechanism was developed to regularly feed CNMs.

The working concept of transplanting the rotor arm is shown in Figure 2E-I. When the rotor case is rotated, the tine is deeply inserted into the CNM (Figure 2E, F). The cut CNM is moved to the end-effector by being held between the tine and retainer (Figure 2G). To avoid dropping the block, the holding force must be stronger than the centrifugal force. When the end-effector reaches the bottom dead point, a push cam follower moves into a dent of the push cam, and the push channel rod moves downward; subsequently, the block is extracted by the push plate (Figure 2H). Next, the arm returns to the position, as shown in Figure 2I. CNMS leaves and stem slid along the long guide to effectively prevent their swinging during transplanting, a possible reason for dropping the block. At last, to transplant vegetable seedlings on a dry field, a furrow opener and two soil covers were installed in the prototype (Figure 2A). In addition, to adapt to transplantation on uneven surfaces, a height sensor was mounted at the side of the arm. Instead of a float, a plate attached to the underside of the prototype traced the top of the ridge to detect its height, and the working part was hydraulically raised and lowered to reach the set transplanting depth.

Cuttable nursery mat

To firmly grasp a vegetable seedling and maintain its posture in the end-effector, the grasped part must have adequate stiffness. In preliminary experiments, an interval of >30 mm was required to make culture seedlings suitable for field cultivation. At this

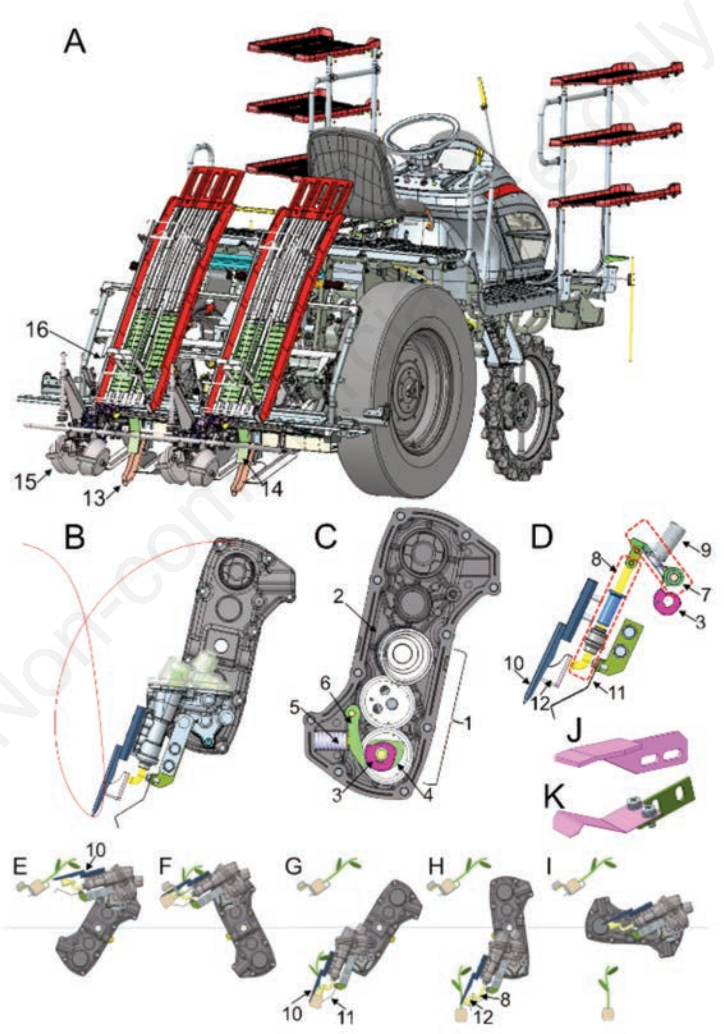

Figure 2. A) Conceptual drawing of the vegetable transplanter proposed in this study. Pictures of the single-row prototype equipped with YR6D wheels used in the experiments in this study are shown in *Supplementary Figure 1*; **B**) structure of the transplanting rotor arm; **C**) noncircular planetary gear mechanism to generate the required locus of the top of the transplanting tine. The arm was primarily composed of a noncircular planetary gear set (1), rotor case (2), cam (3), push cam (4), spring (5), and follower (6) to eliminate backlash between the rotor case and end-effector; **D**) parts of the end-effector, push cam follower (7), push channel rod (8), spring to move the rod stroke (9), transplanting tine (10), retainer (11), and push plate (12); **E** to **I**) conceptual functioning of the transplanting rotor; **J**) rigged plate retainer; **K**) leaf spring retainer, long guide (13), soil covering wheels (14), and furrow opener (15). The seedling tray with belt equipping bars (16) is shown in Supplementary Figure 2A.

seedling density, the roots alone did not form a tough mat; the mat contracted under its own mass on the seedling rack, and even the seedling dropped from the end-effector (data not shown) Thus, CNM was used as a new solid nursery bed in this study (Figure 3). CNM has adequate stiffness, and it does not contract when boarded on the seedling tray of the prototype nor does it collapse when firmly grasped by the end-effector.

The CNM is mainly composed of cocopeat and vermiculite; its adequate stiffness was ensured by combining latex and polyacrylic emulsion as a binder. The mixture was placed into a mold, compacted, and dried until the moisture content was <10% [db]. Its dimension was 580×280×30 mm^3, the same as those of the standard rice seedling mat (Figure 3A). It had 20 slits on both long sides to divide them into 20 columns; each column had 10 holes for seedings. Thus, 200 seeds could be planted on the CNM (Figure 3). The slits on the upper side were V-shaped, with a depth and width of 10 and 8 mm, respectively, which facilitated cutting by the end-effector tine (Figure 2). The slits on the bottom, which were associated with the rack belt, were U-shaped, and their depth and width were 5 mm.

Cabbage (*Brassica oleracea* L. var. capitata) seedlings were used in all experiments. Cabbage seedlings could grow on CNM as PS, and their roots could elongate in the CNM (Figure 3C, E). The seedlings cultured on CNM are hereafter referred to as CNM seedlings (CNMS).

Stiffness test for cuttable nursery mat

A three-point bending test was conducted to evaluate CNM stiffness. A CNM was cut into pieces as described in *Supplementary Figure 2*, submerged in water for 24 h, and then set using a texture analyzer (CT3-1000, Brookfield, MA, USA) with a steel probe (*Supplementary Figure 2B*). The probe compressed the CNM at a rate of 0.5 mm s^{-1} and the breakdown point was measured. This experiment was repeated twice and the average value was recorded. CNMs with varying stiffness could be prepared by changing binder amounts. To confirm the effect of thickness on holding, a 25 mm-thick CNM was also examined.

Cutting test

To evaluate the force necessary to hold CNMS by the end-effector, a cutting test was conducted using the following proce-

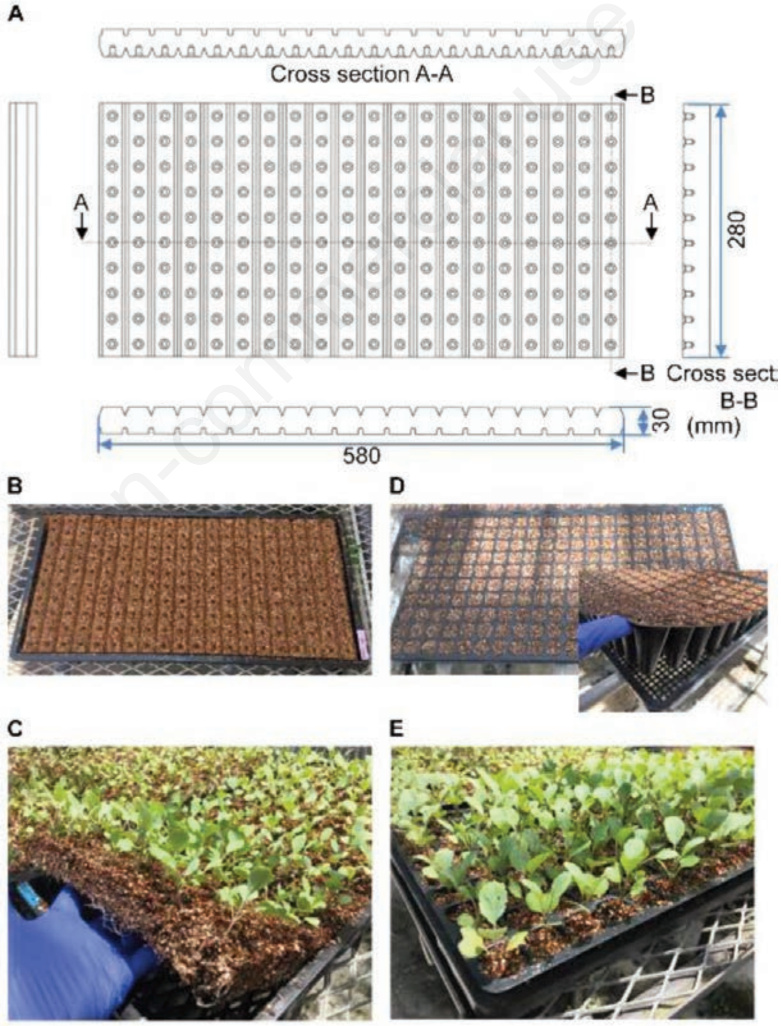

Figure 3. A and **B**) Cuttable nursery mat; **C**) cabbage seedlings cultured for 25 days with cuttable nursery mat, referred to as cuttable nursery mat seedling. A similar size of cuttable nursery mat seedling was used in this study; **D**) a tray filled with nursery soil; **B**) cabbage plug seedlings cultured for 25 days.

dure. CNMS were cut into blocks >100 times in each experimental condition, and the numbers of blocks that dropped from the end-effector before reaching the bottom dead center were counted. The drop rate was calculated as follows:

$$\text{Drop rate } \% = \frac{N_d}{N} \times 100\ (\%)\# \qquad (1)$$

where N_d is the number of dropped blocks and N is the number of cut blocks. To count the number of cut CNMs, cutting was recorded using a high-speed video camera (HAS-L1M, DITECT, Tokyo, Japan). Planting speed and hill distance were set at 1.0 m s^{-1} and 0.24 m, respectively. This experiment was repeated twice. In addition, a long guide and solid and leaf spring-type retainers were tested in this experiment (Figure 2A, J, K).

Indoor transplanting test

The efficiency of transplanting was tested using an indoor soil bin. The bin was filled with two soil texture types: fine soil (11.5% [db]) and coarse soil (9.8% [db]; *Supplementary Figure 3*). To measure the distribution of soil particle sizes in the soil bin, approximately 2 L of the soil in the bin was screened through several mesh-size sieves for 20 s each; then, each portion of screened soil was weighed and the percentage was calculated by dividing by the mass of the total soil. The measurement was performed three times. The CNMS used in the experiments was cultured for approximately 25 days; its height and width were 81.0±5.5 mm and 60.6±10.3 mm, respectively (Figure 3C).

First, transplanting tests were performed at hill distances of 0.24, 0.31, and 0.40 m in the test bin filled with fine soil. The range of hill distances that our prototype can accommodate is 0.24-0.40 m. The planting speed was set at 0.3 m s^{-1}. The test was performed as follows: approximately 40 seedlings were transplanted into the bin. Seedlings whose angle and depth were within 45° and 10 mm were designated as successful. Seedlings whose underground portions were partially or completely floating on the soil were designated as slip or float, respectively. In addition, damaged seedlings were designated as broken.

Second, to evaluate the effect of including a long guide and retainer on holding, CNMS cutting and transplanting tests were performed as described with minor modifications. All the seedlings other than successes were considered failures in the subsequent transplanting tests. The planting speed and the hill distance were set at 1.0 m s^{-1} and 0.24 m, respectively.

Field experiments

To compare the performance of CNMS and PS, they were transplanted and cultivated in a field at Nagahama, Shiga prefecture, Japan (lat: 35.3°N, long: 136.14°E) from August 24 to December 24, 2020. The cultivation area was 720 m^2 (60×12 m). The soil moisture content was 6.8% [db], and the particle size distribution was defined as coarse soil, as shown in *Supplementary Figure 3*. The ridge height was set at 0.25 m, and its top and bottom width were 0.95 and 1.20 m, respectively. CNMS and PS were

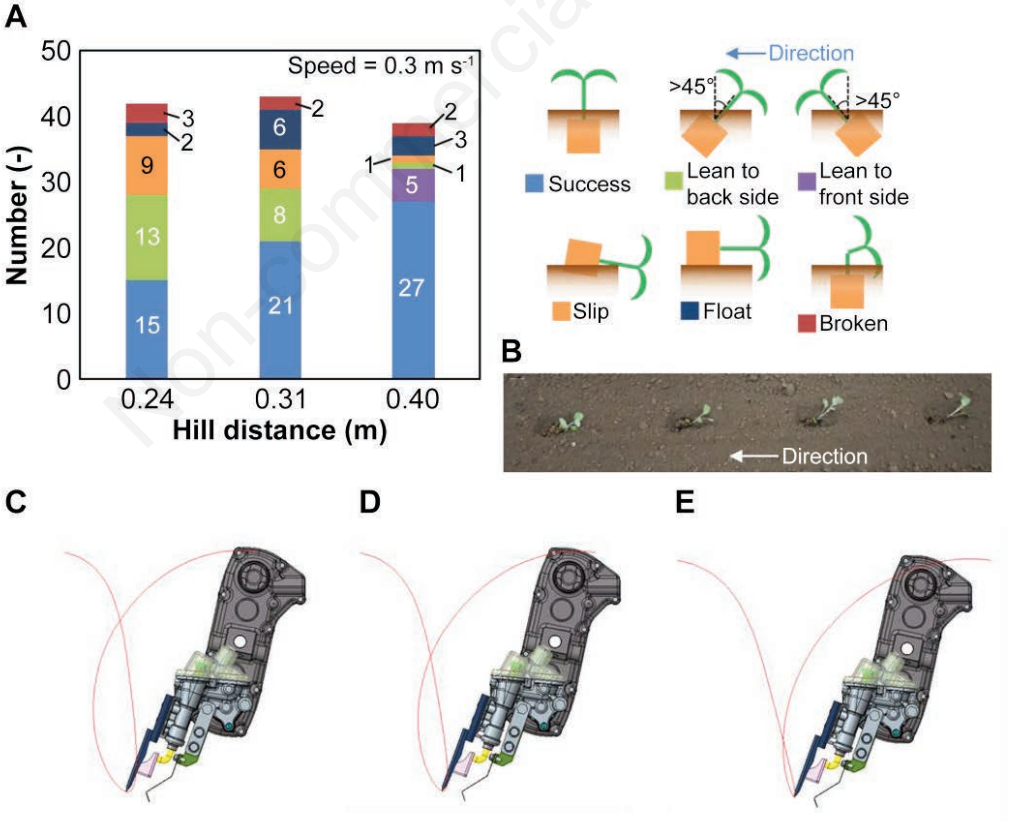

Figure 4. A) Effect of hill distance on transplantation. The block lacking seedlings was ignored; **B)** example of cuttable nursery mat seedling transplanted at a distance of 0.31 m. Locus to the field and hill distance showing: **C)** 0.24 m; **D)** 0.31 m; **E)** 0.40 m hill distances, respectively.

transplanted at rates of 0.3 or 1.0 and 0.5 m s^{-1}, respectively. The hill and row distances were adjusted to 0.3 m and 0.55 m, respectively. Over 150 seedlings were transplanted in each experimental condition. PS was transplanted using a manufactured PS transplanter (PW20R, Yanmar Agribusiness Co., Ltd.). Seedlings cultured for 20 and 25 days were transplanted to check the effect of the culturing period on transplantation and cultivation. In each experimental condition, 10 seedlings were chosen randomly, and their height, width, and leaf number were measured.

In the cultivation test, the survival and head formation rate of the transplanted cabbages were calculated as follows:

$$\text{Survival rate }\% = \frac{N_h + N_n}{\text{N}} \times 100\ (\%)\# \tag{2}$$

$$\text{Head formation rate }\% = \frac{N_h}{\text{N}} \times 100\ (\%)\# \tag{3}$$

where N_h is the number of headed cabbages, N_n is the number of not headed cabbages for vermiculation for instance, and N is the sum of transplanted cabbage. Twenty cabbages were randomly harvested from each experimental condition, and their head size and mass were measured after removing their outer leaves.

Results

Indoor transplanting test: transplanting hill distance

CNMS were transplanted at different hill distances on the test bin to ensure its effect on transplanting success (Figure 4). The success rate increased with hill distance (Figure 4A), and the seedling frequently either leaned to the back side or slipped. In contrast, it sometimes leaned to the front side when transplanted at wider hill distances. A holding force on the CNMS by the end-effector was key in transplanting success. When the centrifugal force generated by arm rotation was stronger than the holding force, the block would be thrown before being pushed out. The centrifugal force at a shorter hill distance should be stronger due to the higher angular rate of the arm. When the block was dropped from the end-effector at an earlier rotation stage, it would slip or float easily on the bin. In addition, the arm locus drew a loop at shorter hill distances, which also had a negative effect on transplanting, including the positioning of seedlings (Figure 4C).

Indoor transplanting test: effect of a long guide and a leaf spring-type retainer

A cutting test was conducted to verify the effects of the long guide and retainer on holding CNMS (Figure 5A). The drop rate decreased with a retainer and long guide, especially with the combination of a long guide and a leaf spring-type retainer (25.0-30.0% *vs*. 0.0-3.1%). A long guide was especially effective at decreasing dropping, implying a relatively strong force was generated by moving leaves and stems during rotation. Owing to the leaf spring-type retainer flexibility, the block could be more deeply inserted into the end-effector and held by more force. The leaf spring-type retainer and a long guide were included in the prototype used in the following field experiment. Notably, a 100% success rate was achieved using the long guide and the leaf spring-type retainer in fine soil. A strong correlation was observed between success and the drop rate ($R^2 > 0.99$), demonstrating that the drop was a primary cause of failure in transplantation (Figure 5B). The transplanting test also showed effective CNMS transplantation (*Supplementary Figure 4*). The success rate in coarse soil was lower than in fine soil; this may be because the furrow opened in coarse soil was deeper than that in fine soil.

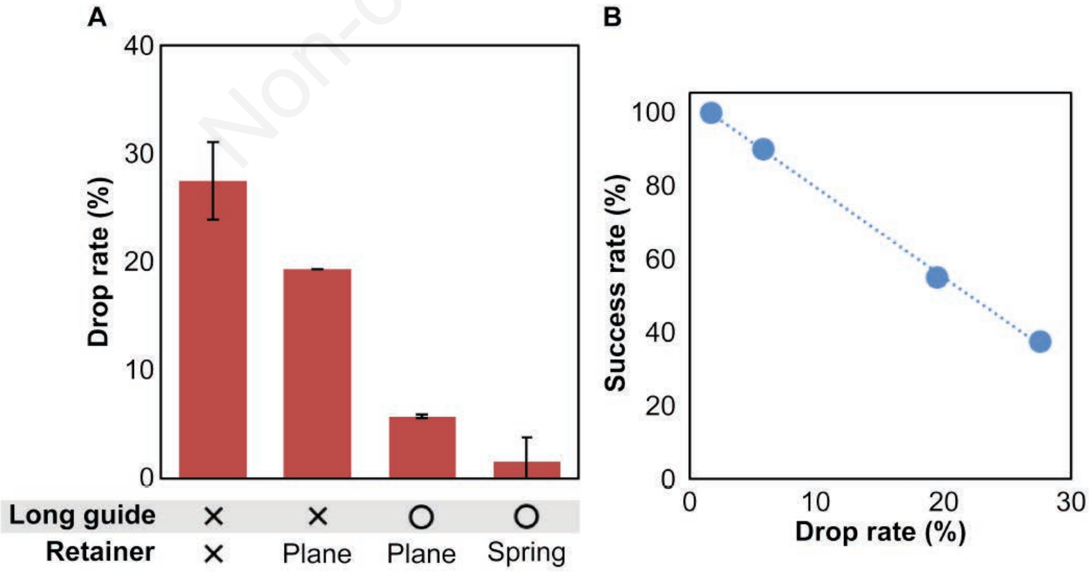

Figure 5. A) Drop rate of cuttable nursery mat seedling from an end-effector including a long guide and retainers. Error bars indicate standard deviations; **B**) relationship between success and drop rates. Plots summarize the results in Figure 5A and *Supplementary Figure 4.*

Cuttable nursery mat stiffness

CNM stiffness also had an important effect on holding force. When its breakdown point was smaller than the force loaded by the end-effector at cutting, the CNM would break and drop. The drop rates of CNMs with different stiffnesses and thicknesses were measured in cutting tests. A negative correlation between the breakdown point and the drop rate indicates that a more rigid CNM was suitable (Figure 6A). A 30 mm-thick CNM displaying 6.8 N at the breakdown point achieved a 0% drop rate. In contrast, the 25 mm-thick CNM seemed to be required >10 N at the breakdown point. This indicates that the 25 mm-thick CNM was frequently dropped compared with 30 mm-thick CNM at similar breakdown points. This suggests that thinner CNMs should be more rigid for transplanting success because the CNM could break easily at cutting. High rigid CNMs are not suitable for transplanting and cultivating, because such CNMs were difficult to cut along its slit and the cutting face became jagged (Figure 6B, C). This caused a drop due to reduced holding force.

Field transplanting and cultivating

To ensure the practicality of the prototype, transplant and cultivation performance were confirmed in the field. The success rates for both CNMS and PS cultured for 25 days were similar (92.7-95.7% *vs.* 99.5%; Figure 7). In contrast, although CNMS cultured for 20 days could also be transplanted with high success rates (both 96.2%), PS could not be extracted from the tray. The properties of the aerial parts of CNMS and PS were similar (*Supplementary Figure 5*); however, owing to the shorter culturing period, most PS

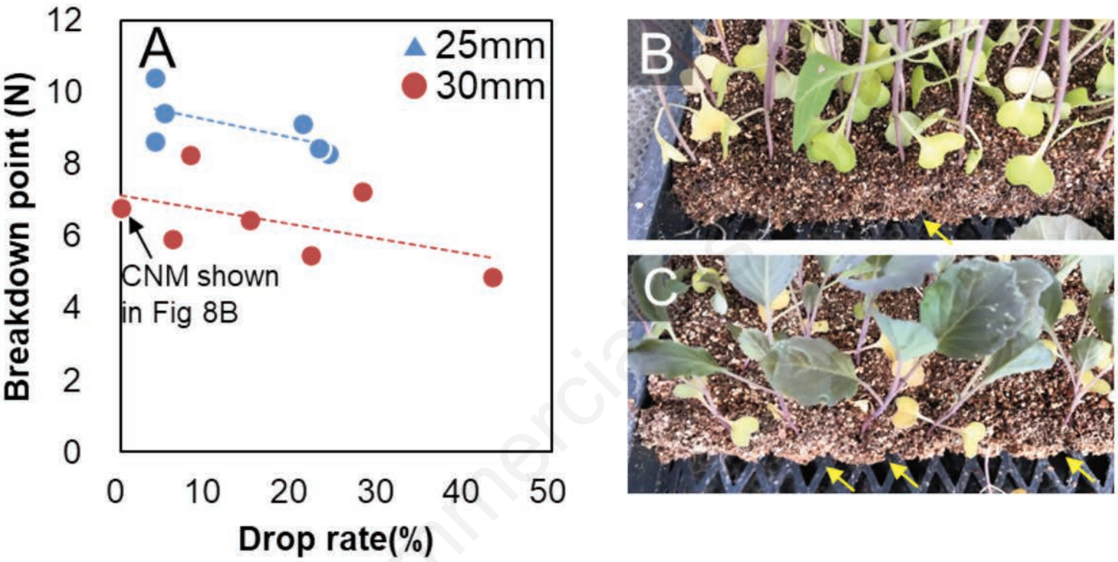

Figure 6. A) Relationship between drop rate and cuttable nursery mat breakdown point; **B**) Cutting surface of cuttable nursery mat exhibiting 0% dropping rate and (**C**) having higher stiffness (breakdown point >100 N). Yellow arrows indicate scars after cutting.

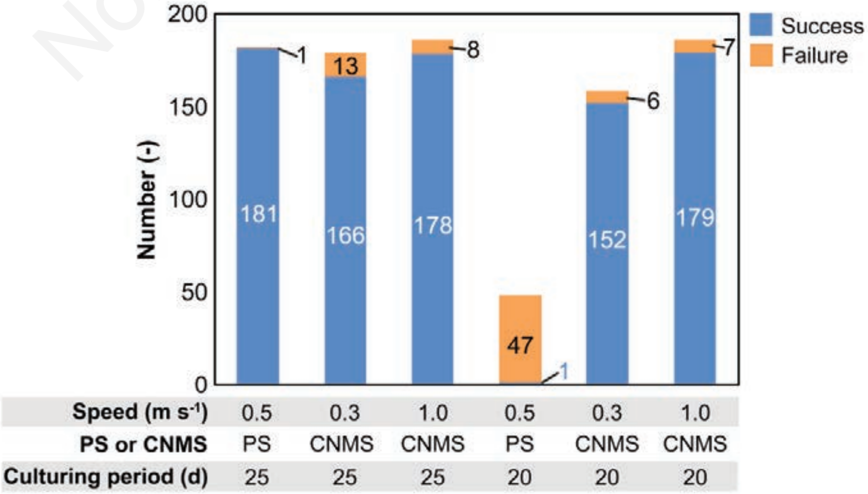

Figure 7. Performance of cuttable nursery mat seedling transplantation in the field. Plug seedling was transplanted using PW20R. The number of plug seedlings cultured for 20 days was lower because most plug seedlings could not be picked out from the tray since it did not form root balls. The block lacking seedlings was ignored.

had not formed root balls yet. The survival rates of CNMS and PS were almost equal, indicating that CNMS could take root in the field (Figure 8A). PS cultured for 20 days were transplanted directly by hand, as previously mentioned. The heading rate of CNMS was lower than that of PS (Figure 8A). Although the diameter and mass of headed cabbages were mostly >170 mm and >1.5 kg, respectively, the coefficients of values tended to be higher for CNMS than for PS (Figure 8B-D).

Discussion

Both a vegetable transplanter based on a conventional Japanese rice transplanter and CNM, a new type of nursery bed for seedlings, were developed in this study. Holding a CNMS was key in transplanting success, such that the transplanter equipment (*i.e.*, end-effector) and CNM stiffness were optimized. Our prototype transplanted CNMS at higher speeds than previously used transplanters. Although PW20R can transplant PS at a rate of ≤115 plants min^{-1} row^{-1}, the prototype could transplant CNMS at a rate of ≤250 plants min^{-1} row^{-1} for a hill distance of 0.24 m and planting speed of 1.0 m s^{-1}. Han *et al.* (2021) developed an autotransplanter comprising a seedling picking system and a basket-type planting system that transplanted pepper PS at a rate of ≤120 plants min^{-1} row^{-1} when the hill distance was 0.25 m. Jin *et al*. (2018) also developed a seedling picking system, achieving 120 plants min^{-1} row^{-1}; however, the transplant success rate decreased due to clamping stability, PS damage, and tray pick-up failure. A tractor-mounted transplanter, the 1 SP manufactured by Agriplant N.V. in Belgium, can transplant PS at a rate of 233 plants min^{-1} row^{-1} (Agriplant N.V., 2023). However, it has a complex transplanting mechanism and is thus larger than our prototype. An increase in agricultural machinery size has been reported to promote soil compaction (Keller *et al*., 2019), reduce crop yields (Koch *et al*., 2008), and increase nitrogen leaching and greenhouse gas emission (Parvin *et al*., 2022). In contrast, our prototype is lighter because of its simple transplanting mechanism, allowing high-speed trans-

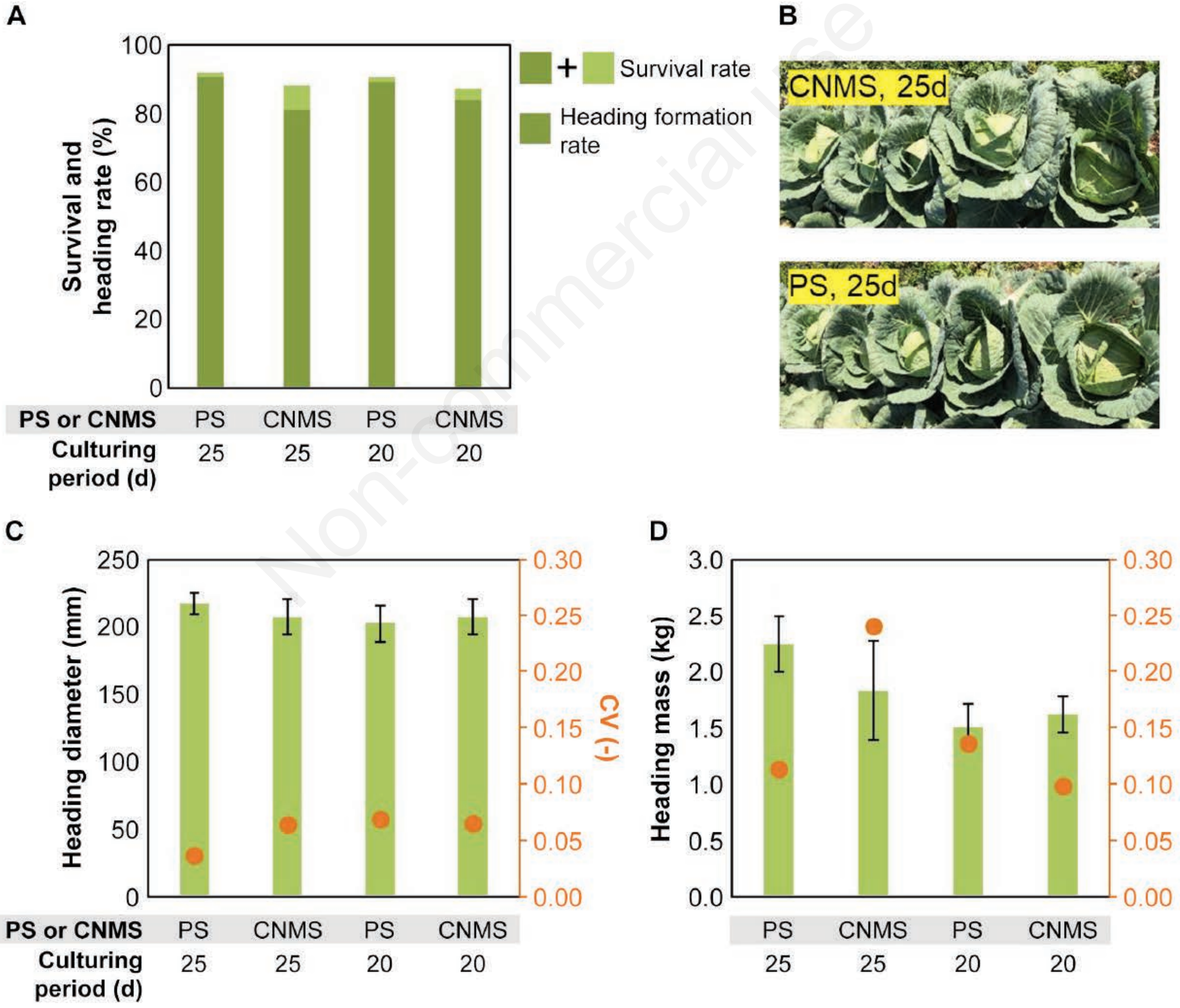

Figure 8. Yield of cabbages cultivated on the field. **A**) Survival and head formation rate of cabbage seedlings transplanted in the experiment shown in Figure 7; **B**) examples of headed cabbages. The yield was assessed based on (**C**) head diameter and (**D**) head mass. The bar and error bar indicate the average and standard deviation, respectively.

plantation of seedlings in multiple parallel rows (Figure 1A and *Supplementary Figure 1*). In addition to the high-speed and light mass, using the wheels of a rice transplanter appeared to cause slipping and skidding in the field. The actual hill distance was approximately 3% shorter in field tests (data not shown). As described in Figure 2A, pneumatic wheels are necessary to improve straight-line performance for autonomous driving. Moreover, since the Japanese rice transplanter used for flooded flat paddy fields soil was improved for use in dry fields, it would be necessary to evaluate its durability for mass production.

This transplanting system could be applied to other vegetables (*e.g.*, broccoli, onion, and tomato). Our YR6D-based prototype could transplant seedlings on ridges with 0-30 cm height and ≤1.2 m width. The maximum ridge height and width depend on wheel diameter and tread width. For onions, since the hill distance is narrow, the number of end-effectors increases to two, like in the rice transplanter. Even if the number of end-effectors increases, the locus does not change. Also, the CNM width should be shorter because the minimum row distance depends on the width. Further research is required to optimize CNM characterization, including shape and stiffness for onion seedling transplantation. To the best of our knowledge, CNM is the first introduced nursery mat for vegetable seedling cultivation. It has adequate stiffness not to contract when boarded on the seedling tray of the prototype, nor to collapse when grasped firmly by the end-effector, and enough to take root for seedlings. Notably, the transplanting mechanism does not require a root ball to form as pick-up seedlings from a plug tray and the CNM itself has adequate stiffness. The difficulty of transplanting young seedlings has been a common problem for conventional transplanters (Han *et al*., 2019). In contrast, our results showed that CNMS can only be transplanted if its aerial parts grow well. This suggests that no professional skills are required to culture seedlings with this transplanting system. Therefore, our transplanting system with CNM is an appropriate technology for farmers to start cultivating vegetables in the field. In the cultivating test, the heading formation rate and coefficient of variance of heading mass of CNMS cultured for 25 days were worse than those of PS cultured for 25 days (Figure 8). This could be attributed to the less uniform CNMS growth compared with that of PS (*Supplementary Material 6*). One reason is the uneven characteristics of CNM (*i.e.*, stiffness and water permeability). As the CNM used in this study was handmade, it resulted in uneven material density. Soil compaction influences root growth and distribution and consequently water and nutrient uptake (Unger *et al*., 1994). This unevenness could be reduced by bulk manufacturing, such as for the nursery soil used herein. In addition, a portion of transplanted CNMS was broken and counted as failures in both indoor and field tests (Figures 4 and 7). This was caused by excess CNMS growth. The leaves and stem can be more easily interfaced with transplanting tine during transplanting. The plug tray configuration and nursery soil fertilization affect seedling shape and growth, including those of the roots (Chen *et al*., 2002; Balliu *et al*., 2017). This suggests that CNM configuration and nutrients could influence CNMS growth. Therefore, further research is required to improve CNM characteristics to optimize seedling cultivation.

Conclusions

Here, we developed a simple, low-cost, and high-speed vegetable transplanter based on a conventional Japanese rice transplanter. To transplant vegetable seedlings with this prototype, a CNM was also developed. Since vegetable seedlings are larger and heavier than rice seedlings, it was difficult to hold CNMS for transplantation by the end-effector. A long guide and a leaf spring-type retainer were developed to strongly hold the CNMS. CNM stiffness also increased. This prototype was capable of transplanting CNMS at a rate of 250 plants min^{-1} row^{-1} for a hill distance of 0.24 m. Field experiments demonstrated that the yield of cabbage cultured using CNMS was similar to that cultured using PS. CNMS cultured for 20 days could be transplanted as if cultured for 25 days, whereas PS cultured for 20 days could not be transplanted due to the lack of a root ball. In addition, this system has the potential for use with other vegetables (*i.e.*, tomato and onion). The minimum row distance could decrease for a shorter CNM width. We expect that this transplanter will be disseminated in various regions, including European countries.

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Online supplementary material:

Figure S1. Pictures of the single-row prototype developed in this study. The rear wheels were the same as those in YR6D. Seedling tray with equipping bars (1), soil covering wheels (2), height sensor (3), and rear wheel (4).

Figure S2. A) Cuttable nursery mat test piece and (B and C) cuttable nursery mat stiffness test: fixture to compress a test piece (a), test piece (b), and plate (c), respectively.

Figure S3. Soil particle size distribution. Two texture types of soil, fine and coarse soil.

Figure S4. Effect of a long guide and retainers on transplanting cuttable nursery mat seedlings in different soil texture types. The block lacking seedlings was ignored.

Figure S5. Characteristics of cuttable nursery mat seedlings and plug seedlings transplanted in the field: A) height; B) width; C) leaf numbers. The bar and the error bar indicate the average and standard deviation, respectively.

Figure S6. A-B) Cuttable nursery mat seedlings; C-D) plug seedlings cultured for transplanting and cultivating on the field. Seedlings were cultured for 25 days.

Table S1. Specifications of manufactured fully automatic transplanters.