Spanish Journal of Agricultural Research
21 (3), e0207, 13 pages (2023)
eISSN: 2171-9292
https://doi.org/10.5424/sjar/2023213-20245
INIA-CSIC

RESEARCH ARTICLE

OPEN ACCESS

Analysis of operating speed and power consumption of a gear-driven rotary planting mechanism for a 12-kW six-row self-propelled onion transplanter

Md Nasim REZA[1,2], Mohammod ALI[1], Eliezel HABINEZA[2], Md Sazzadul KABIR[2], Md Shaha Nur KABIR[1,3], Seung-Jin LIM[4], Il-Su CHOI[5] and Sun-Ok CHUNG[1,2,*]

[1] *Chungnam National University, Graduate School, Dept. of Agricultural Machinery Engineering, Daejeon 34134, Korea.* [2] *Chungnam National University, Graduate School, Dept. of Smart Agricultural Systems, Daejeon 34134, Korea.* [3] *Hajee Mohammad Danesh Science and Technology University, Dept. of Agricultural and Industrial Engineering, Dinajpur 5200, Bangladesh.* [4] *TYM Co., Ltd., Iksan 54576, Korea.* [5] *Rural Development Administration (RDA), National Institute of Agricultural Science, Jeonju 54875, Korea.*

*Correspondence should be addressed to Sun-Ok Chung: sochung@cnu.ac.kr

Abstract

Aim of study: To determine the optimal working speed of a gear-driven rotary planting mechanism for a self-propelled riding-type onion transplanter in order to choose an adequate forward speed for effective onion (*Allium cepa* L.) seedling planting.

Area of study: Daejeon, Korea.

Material and methods: The gear-driven rotary planting mechanism was composed of six planting hoppers that received free-falling onion seedlings through the supply mechanism and deposited them into the soil. To determine the optimal working speed for accurate transplantation of the seedlings, mathematical working trajectory modelling of the planting mechanism, virtual simulations, and validation field experiments were carried out.

Main results: According to the model simulation, a forward speed of 0.15 m s^{-1} of the transplanter and a rotating speed of 60 rpm of the planting mechanism were favourable for seedling uprightness and minimum mulch film damage. For the proposed transplanting mechanism, the free-falling distance was calculated as 0.08 m, and the accuracy for the seedling deposition into the hopper was demonstrated as 97.16% through the validation test. From the field tests, a forward speed of 0.15 m s^{-1} combined with a transplanting frequency of 60 seedlings min^{-1} was found to be optimum for obtaining a high seedling uprightness (90º), a low misplant rate (7.66%), a low damage area on mulch film, and low power consumption (36.53 W).

Research highlights: The findings of this research might be helpful in improving the design of the onion transplanting mechanism and accelerating the automation process for seedling transplantation.

Additional key words: agricultural machinery; *Allium cepa*; transplanting mechanism; working speed; working trajectory.

Citation: Reza, MN; Ali, M; Habineza, E; Kabir, MS; Kabir, MSN; Lim, SJ; Choi, IS; Chung, SO (2023). Analysis of operating speed and power consumption of a gear-driven rotary planting mechanism for a 12-kW six-row self-propelled onion transplanter. Spanish Journal of Agricultural Research, Volume 21, Issue 3, e0207. https://doi.org/10.5424/sjar/2023213-20245

Received: 13 Feb 2023. **Accepted:** 12 Jul 2023.

Funding agencies/institutions	Project / Grant
Korea Institute of Planning and Evaluation for Technology in Food, Agriculture, and Forestry (IPET) through the Agriculture, Food and Rural Affairs Convergence Technologies Program for Educating Creative Global Leaders, funded by the Ministry of Agriculture, Food and Rural Affairs (MAFRA), Korea	No. 320001-4

Competing interests: The authors have declared that no competing interests exist.

Introduction

Onion (*Allium cepa* L.) is one of the world's most important vegetable crops, containing unique oil and sulphur compounds, that contribute to the distinct odour, flavour, and taste (Liguori et al., 2017; Dossa et al., 2018). Onion is the second most valuable vegetable crop in terms of total global production after tomato (FAO, 2021; Geisseler et al., 2022). Since ancient times, onion has been recognized as a food and medicinal plant, and it is widely cultivated as a vegetable crop in many countries around the world, including China, India, the United States, Japan, Korea, and Brazil (Dossa et al., 2018; Pareek et al., 2018). The global demand for onions is increasing due to the continuous increase in world population; however, the shortage of agricultural workers and the lack of mechanization in transplanting operations leads to a drawdown in onion yield (Baloch et al., 2014; Gavino & Tiw-an, 2020; Chowdhury et al., 2021). The total area used for onion cultivation worldwide was expanded from less than 2 million ha in 1990 to more than 5 million ha in 2019, and onion production increased by almost 130% between 1996 and 2019. Although mechanized vegetable transplanters are still being developed in a number of countries worldwide (Han et al., 2021; Pérez-Ruiz & Slaughter, 2021; Jin et al., 2022), very few are for the transplantation of onion seedlings.

In recent years, the advancement of onion planting mechanisms has been further classified into wheel type, rotary gear driven type, linkage type, and linkage cam type transplantation mechanisms (Dong et al., 2013; Jo et al., 2018; Ye et al., 2020; Rasool et al., 2021). It was found that all of the mechanisms mentioned above were effective in the planting process. Min et al. (2015) used structure and motion trace route trajectory analysis for four various transplanting mechanisms to design an onion transplanter. According to Jo et al. (2018), a technique for increasing the efficiency of transplantation by analysing the location and proper length of the linking mechanism of the transplanter has been developed. Actual and simulated trajectories from charged-couple device (CCD) camera images and commercial software were analyzed and validated. Average planting angle, soil intrusion diameter and planting depth were improved by 4.96°, 11.30 mm and 0.68 mm. Modifying linkages of the vegetable transplanter can enhance its efficiency. An innovative multipurpose vegetable transplanting machine featuring a diamond-shaped and a flat-type duckbill was developed by Shao et al. (2019). The cam-linkage type planting mechanism was found to be the most effective method of onion plantation with a 100% planting efficiency and a transplanting rate of 87 seedlings min^{-1} for a unit assembly of the mechanism. In relation to the seedling-standing ratio and mechanical damage degree of the plastic film, the diamond duckbill planter outperformed the flat duckbill planter. Gear driven rotary planting mechanism was also developed for planting applications. These implementations designed with different kinds of non-circular gear pairs showed better performance (Ying et al., 2015). Comparing the planting nozzle trajectory, pose, and speed with theoretical calculations confirmed the effectiveness of the structural design and precision machining. Field planting simulations demonstrated a remarkable seedling deposition rate of 95% for the planting mechanism. An automated seedling collection system for cotton seedlings was developed by Zhao et al. (2014) using a rotating planting device. The mechanism features a distinctive planetary gearing system comprising blended high-order deformed elliptic gears. The coordination among the seeding pick-up mechanism, seeding box, and seeding transplanting mechanism was thoroughly analyzed, and software optimization techniques were employed to determine the optimal parameter values for the components. Li et al. (2017) presented a seedling picking mechanism based on gear-link type semi-automatic transplanting machine. With an average transplanting depth of 7.9 cm, the transplanting depth achieved a qualification rate of 93.5% for depth consistency. The incidence of injury during transplanting was minimal, and the film surface experienced negligible mechanical damage, averaging only 3.4 mm m^{-2}. The quality of transplanting on the film conforms entirely to industry standards. The current research path in the advancement of onion planting mechanisms includes further exploration and development of various types. Researchers are focusing on improving the efficiency, precision, and overall performance of these mechanisms. Additionally, efforts are being made to optimize the design, enhance seedling placement accuracy, minimize mechanical damage, and improve the adaptability of the planting mechanisms to different soil conditions.

Several research studies have concentrated on increasing the working speed of different plating mechanisms based on the field conditions and other agronomic factors such as planting depth, soil damage, and plant position. To ensure efficient transplantation at the required depth and planting interval, the working speed or forward speed of a transplanter must be synchronized with the picking, conveying, and planting mechanisms (Islam et al., 2020; Ye et al., 2020). Iqbal et al. (2021) investigated the speed of operation of a gear-driven dibbling mechanism used in an automated pepper transplanter. The rotating speed for pepper transplanting was determined to be 60 rpm for the dibbling mechanism, with a planting frequency of two seedlings s^{-1} row^{-1}. Ji et al. (2013) investigated the planting mechanism of a semi-automatic vegetable seedling transplanter capable of transplanting 50-70 plants min^{-1}. Appropriate working speed of the mechanism is also essential for upright direction deposition of the seedling. Based on the literature, the acceptable range of straight upright orientation of the transplanted seedlings is 90° ± 20° (Han et al., 2019; Xue et al., 2020). In addition, it is important to maintain planting depth, planting interval, and soil moisture content within the ranges of 40-50 mm, 30-50%, and

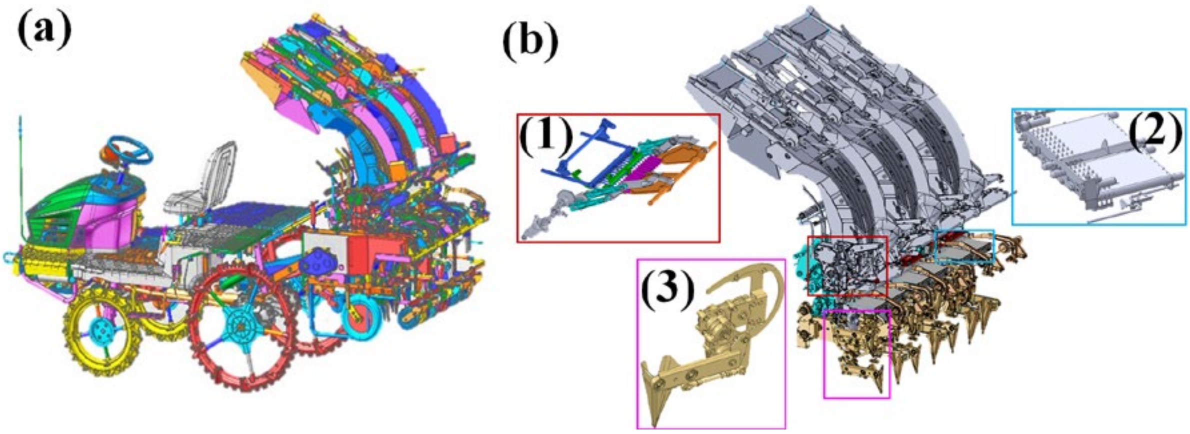

Figure 1. Overall structure of the onion transplanter: (a) 3-D model of a 12-kW self-propelled riding-type automatic onion transplanter, (b) major components of the transplanting part: (1) seedling picking, (2) conveyor mechanisms, and (3) rotary planting.

15-25%, respectively, while moving at a forward speed of 0.15-0.35 m s^{-1} throughout the transplanting operation (Liu et al., 2019; Yin et al., 2019; Zhou et al., 2020). The upright orientation of the seedlings and vertical deposition are important factors in determining the growth rate and development of plants (Ji et al., 2013; Manes et al., 2013). To accomplish the appropriate planting interval and depth, the forward speed of an autonomous onion transplanter should be matched with seedling pickup, supply, and punching and implanting the seedlings (Islam et al., 2020; Ye et al, 2020). Consequently, it is vital to calculate a proper operating speed for the planting mechanism after taking into account the seedling pickup and supply frequencies. A proper operating speed of the planting mechanism is vital for ensuring seedlings are implanted with proper upright positioning and minimal physical damage, which are the key factors influencing plant development and yield (Ji et al., 2013; Iqbal et al., 2021). Also, the efficiency of the transplanter throughout the planting process is essential for achieving regular plant spacing while also minimizing power usage (Khadatkar et al., 2021). Additionally, innovative approaches such as the use of non-circular gear pairs and advanced planetary gearing systems have been explored. However, there is still a need for further research and innovation in the field to enhance the efficiency and productivity of onion transplanting.

In the context of onion transplanting in Korea, the mechanization rate is currently quite low, ranging from 2% to 5% (Rasool et al., 2021). To address this limitation, the development of an onion transplanter with a gear-driven transplanting mechanism is currently underway. The focus is on designing a high-efficiency and simple transplanting mechanism that can effectively overcome the challenges posed by working speed and enhance the overall efficiency of the planter.

The specific objective of this study was to determine the optimal working speed for the gear-driven rotary-type planting mechanism in a self-propelled riding type onion transplanter. This research aimed to identify the most suitable forward speed that ensures efficient planting of onion

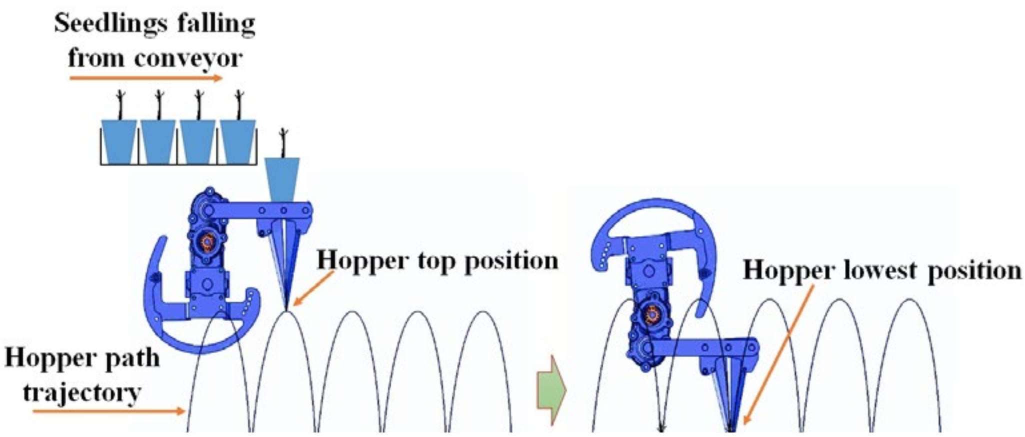

Figure 2. Schematic view of seedling collection and transplantation into the soil.

Table 1. Notations, definitions, and units of the variables.

Notation	Definition and unit
P_l	Primary link of the planting mechanism, m
C_l	Connecting link of the planting mechanism, m
H	Planting hopper length, m
v_t	Forward speed of the planter, m s^{-1}
ω	Angular velocity of the planting hopper rad s^{-1}
θ	Angle between the vertical axis and the planting hopper, rad
λ	Characteristic coefficient, numeral
R_t	Rotational radius, m
R_{st}	Required seedling supply rate, seedlings min^{-1}
P_i	Desired planting interval, m
N_t	Number of row planted by transplanter, integer
n	Rotational speed of the planting mechanism, rpm
C_d	Air drag coefficient of the seedling, numeral
A	Frontal area of seedlings, m^2
S	Average weight of the seedling, g
g	Gravitational acceleration, m s^{-2}
ρ	Density of air at 27°C, g m^{-3}
F_t	Free falling time of the seedling, s
v_s	Free falling velocity of seedling, m s^{-1}
α	Constant, numeral
h	Free-falling height of seedling, m

seedlings while minimizing any potential damage to the plants, all while considering the comfort of the operator.

Material and methods

Overall working principle of the rotary planting mechanism

The overall 3D structure of the 12-kW self-propelled riding-type automatic onion transplanter investigated in the study, which comprises two key components: an operator-driven four-wheel vehicle and a transplanter, is shown in Fig. 1a. The onion transplanting steps include three primary mechanisms, the same as other vegetable transplanters, which are seedling picking, rotary seedling conveying and planting (Chowdhury et al., 2021; Reza et al., 2021). The six-row onion transplanter is composed of six picking assembly units, conveyors, and a rotary planting mechanism, as shown in Fig. 1b. The picking mechanism (Fig. 1b-1) combines the mechanism of pushing pins and the seedling conveying mechanism. The conveyor system (Fig. 1b-2) delivers seedlings to the rotating planting hopper. Three primary linkages and a planting hopper compose the rotating planting mechanism (Fig. 1b-3). The rotary planter requires a constant supply of onion seedlings at a certain speed to ensure regular planting. Each rotating hopper assembly transplants one seedling during a single transplantation cycle. There are two wheels for each row of seedlings, so the soil is finally pressed down to make sure there is no mulch film damage and that the seedlings are standing upright. Six seedlings are taken from the tray throughout a complete cycle of the pushing bars unit assembly and are then conveyed to the seedling conveyor via the seedling carrying assembly.

The seedlings are pushed into the hopper by the pushing bar lever, which operates in tandem with the seedling conveyor to provide continuous motion between the conveyor and the pushing bar. Due to the constant motion of the conveyor, it is necessary for the planting mechanism to move in a continuous manner in both the upward and downward directions. Pushing and carrying assemble, on the other hand, experience motion pauses during the vertical motion of the tray and at the picking position of the seedling, respectively.

An elliptical motion trajectory is produced by the proposed vertical and horizontal rotary planting mechanisms. When the hopper reaches its top position during the motion, it receives the falling onion seedlings from the conveyor. At the bottom of the rotation cycle, the hopper punches the seedlings into the soil. Fig. 2 illustrates the schematic view of the seedling collection from the conveyor and their subsequent transplantation into the soil. The rotational speed of the planting mechanism and the forward speed of the

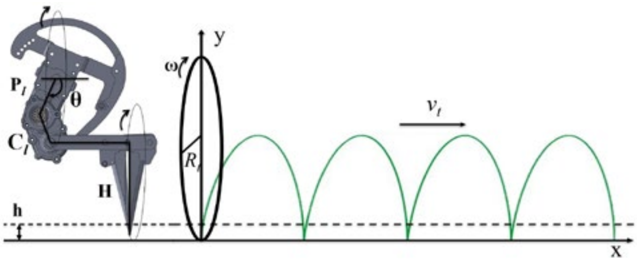

Figure 3. Working speed trajectory of the planting mechanism. P_l: primary link of the planting mechanism. C_l: connecting link of the planting mechanism. θ: angle between the vertical axis and the planting hopper. H: planting hopper length. h: free-falling height of seedling. Ω: angular velocity of the planting hopper. Rt: rotational radius. v_t: forward speed of the planter.

transplanter are the key factors in determining the optimal working speed for the transplanter.

Theoretical analysis

Rotating speed of the planting mechanism

In order to design the planting mechanism, it is vital to know the rotational and forward speeds. The rotational speed of the planting mechanism depends upon the forward speed of the transplanter and the required plant-to-plant distance for a specific crop. The proposed transplanter consisted of six rows with a spacing of 0.15 m between them, and the required planting interval was 0.13 to 0.14 m. A planting mulch bed of 0.09 m width could be considered for the transplantation of onion seedlings (Reza et al., 2021). Table 1 shows notations and definitions with the units of the variables used in this study.

The rotating speed (n, rpm) of the planting mechanism can be calculated using Eq. (1), which is a function of the planting interval (P_i, m) and the forward speed of the transplanter (v_t, m s^{-1}):

$$n = \frac{30\, v_t}{P_i} \quad (1)$$

Srivastava et al. (2006) suggested Eq. (2) to determine the planting supply rate (R_{st}, seedlings min^{-1}) of the mechanism:

$$R_{st} = \frac{60\, v_t N_t}{P_i} \quad (2)$$

Another crucial criterion for the transplanting operation is the insertion of seedlings into the hopper, with the straight and vertical orientation of the seedlings being vital. Successful feeding of the onion seedlings into the hopper is dependent on the free-falling distance, the seedling supply rate, and the amount of time necessary to fall. During the planting procedure, the most crucial factor to consider is the synchronization of all of these parameters with the rotating speed of the hopper. The deposition should take place at the highest vertical position in order to reduce the amount of seedling fall time. The required falling time (F_t, s) of the onion seedlings can be found using Eq. (3):

$$F_t = \frac{60}{8n} \quad (3)$$

The free-falling velocity (v_s, m s^{-1}) of the seedlings is limited by the aerodynamic drag and is determined by the physical characteristics of the seedlings, as in Eqs. (4) and (5) (Manilla & Shaw, 1987):

$$v_s = \left(\frac{\sqrt{g}}{\alpha}\right) \tanh\left(F_t \alpha \sqrt{g}\right) \quad (4)$$

where α is a constant which can be calculated as in Eq. (5):

$$\alpha = \frac{\rho g C_d A}{2S} \quad (5)$$

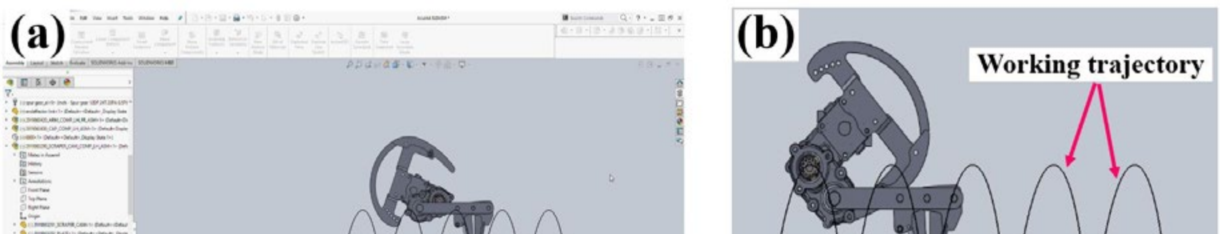

Figure 4. Motion and working speed simulation: (a) SOLIDWORKS software simulation window, and (b) possible working trajectory and the deposition of the seedlings.

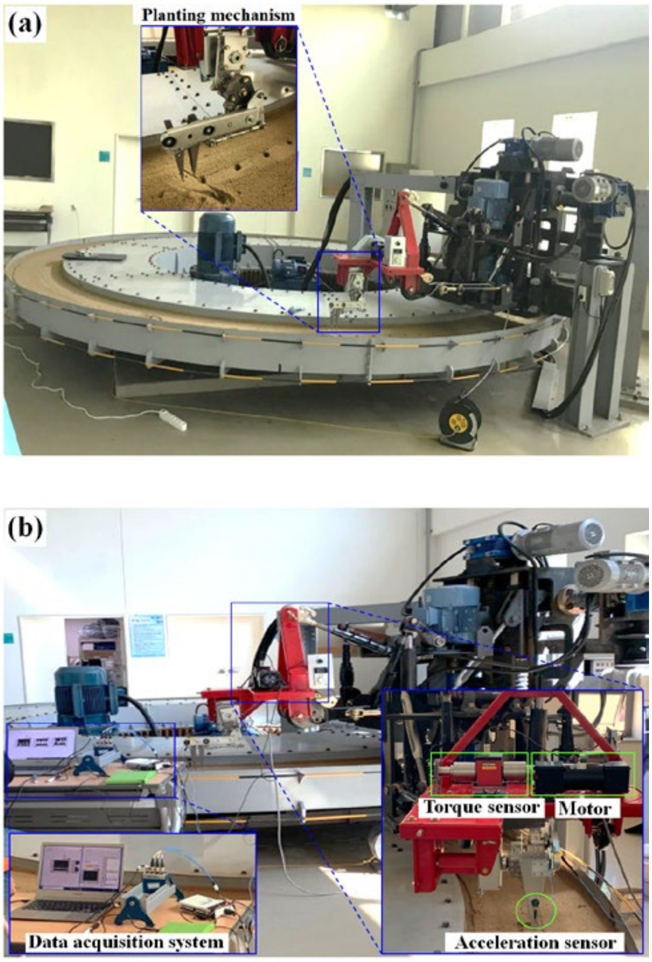

Figure 5. Experimental test bench with the planting device at Rural Development Administration (RDA), Jeonju, Korea: (a) test bench with planting mechanism, and (b) working speed test experiment setup with the sensor setup and data acquisition box (DAQ) system.

This study used 50-day-old onion seedlings to analyze the physical properties of the onion seedlings because it has been proven that this age is most suitable for mechanical transplanting (Kim et al., 2015; Dihingia et al., 2016).

Constant horizontal speed of the planting mechanism

Constant horizontal velocity, also called zero velocity, occurs at the maximum lower position of the planting hopper, where the seedling undergoes the deposition process into the soil. The hopper velocity should match the forward speed of the planter in order to release the seedling at the desired depth (Manilla & Shaw, 1987). Due to the constant horizontal velocity, there is no acceleration at the lowest point of the hopper, which enables the hopper to deposit seedlings at the desired depth into the soil surface. As a result, constant horizontal velocity should be equal but opposite to the onion transplanter's forward speed. Eq. (6) shows the relationship between the forward velocity of the transplanter (v_t, m s^{-1}) and the horizontal velocity of the hopper (v_x, m s^{-1}):

$$-P_l \sin\theta_1 \omega_1 - C_l \sin\theta_2 \omega_2 = v_x = -v_t \quad (6)$$

During the transplanting operation, the working speed trajectory of the mechanism may provide a more precise outline for measuring the zero-speed delivery of the seedlings. To develop the working speed trajectory of the planting mechanism (Fig. 3), a mathematical model was derived using a Cartesian coordinate system. The forward speed of the onion transplanter was considered the negative direction of the horizontal x-axis and the positive direction along the vertical y-axis, and the lowest point of the hopper was considered the origin

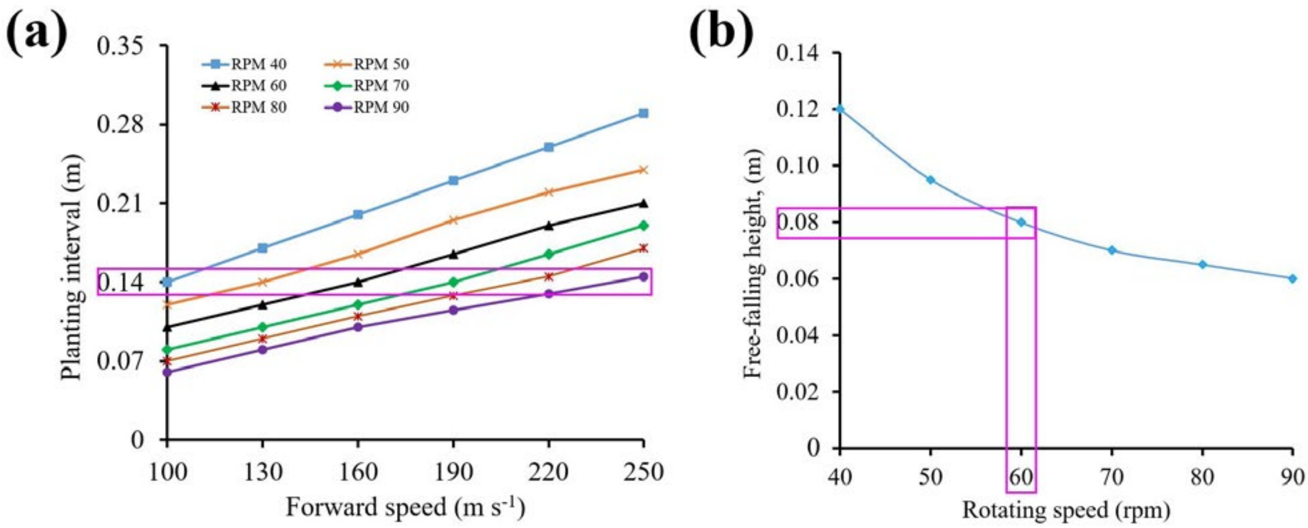

Figure 6. Relationship between (a) the planting interval and the rotational speed of the planting mechanism at various forward speeds and (b) the free-falling height and the rotational speed of the planting mechanism.

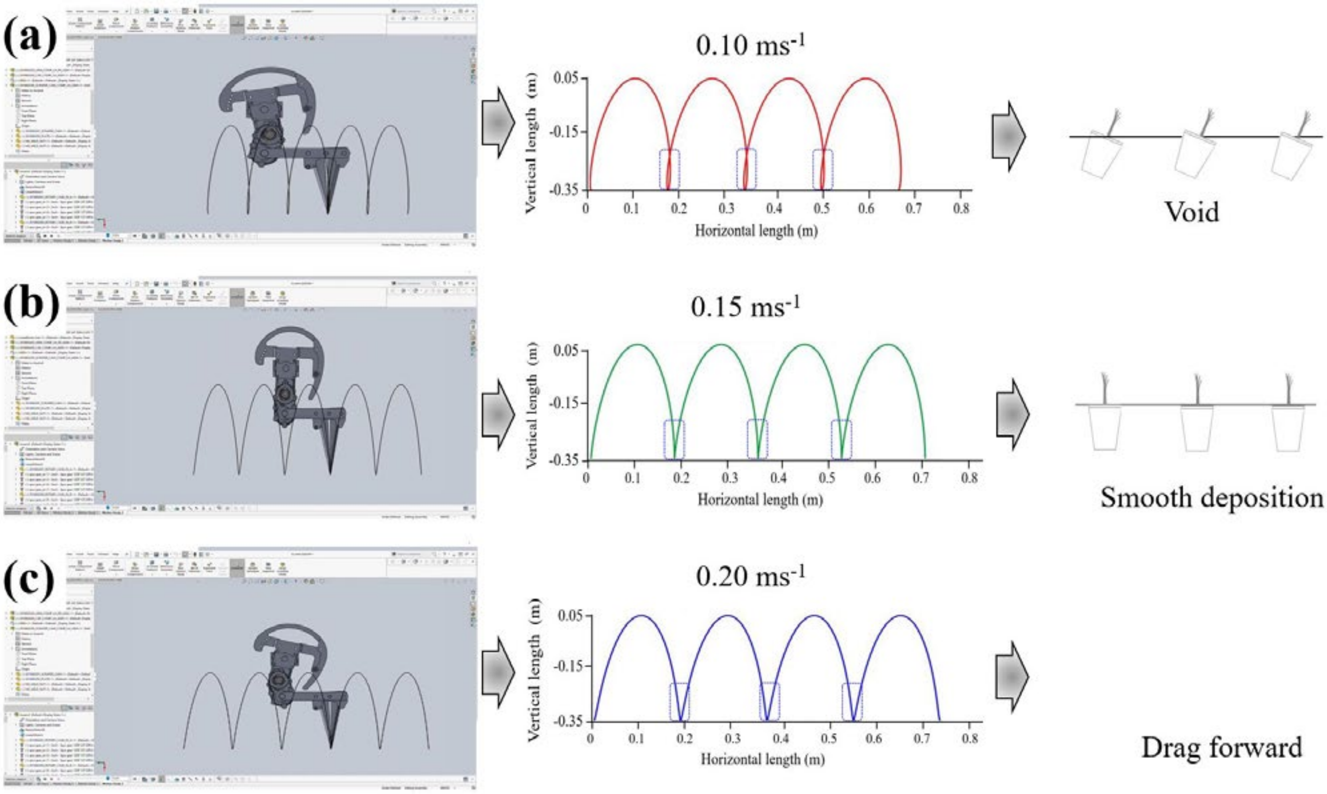

Figure 7. Simulation trajectory of planting mechanism at (a) 0.10, (b) 0.15, and (c) 0.20 m s^{-1} forward speeds at 60 rpm.

point. The mathematical model can be expressed using Eqs. (7) and (8):

$$x = -v_t + R_t sin\omega t \quad (7)$$

$$y = R_t - R_t cos\omega t \quad (8)$$

where R_t is the rotational radius. The rotational radius can be calculated using Eq. (9) of the rotary planting mechanism:

$$R_t = P_l sin\theta + C_l \cos 2(\pi - \theta) + Hsin(\pi - \theta) \quad (9)$$

In order to minimize the damaging effects of the mulching film on the planting bed, the characteristic coefficient factor (λ) was considered, which is the ratio between the circumferential speed of the planting mechanism and the forward speed of the transplanter (Du et al., 2018), expressed using Eq. (10):

$$\lambda = \frac{R_t \omega}{v_t} \quad (10)$$

The plastic mulch damage is minimal when the above-mentioned ratio is equal to 1. In this scenario, the circumferential rotational speed should be the same as the forward rotational speed. As a result, it is essential to choose a working speed that is compatible with the circumferential speed while also satisfying the required characteristic coefficient factor requirement.

Simulation and validation procedures

Simulation of motion and working speed

To determine the working speed of the proposed planting mechanism, a design and motion study were conducted using a commercial simulation software package (SOLIDWORKS 2018, Dassault Systems SolidWorks Corp., Waltham, MA, USA). A virtual 3D prototype model was developed, as shown in Fig. 4, and tested at different forward speeds (0.10, 0.15, and 0.20 m s^{-1}) within the optimum human working comfort range. The rotating speed of the mechanism and the forward speed of the transplanter were the two most important simulation factors. Trajectories of several forward speeds were recorded and analyzed in order to determine the forward speed that resulted in the least amount of mulch film damage during the operation. The rotating speed of the transplanter mechanism and the forward speed of the transplanter were found to be 40 to 80 rpm, and 0.10 to 0.20 m s^{-1}, respectively. The optimal working speed of the planting mechanism was determined.

Validation with a prototype

The field tests were done at the Rural Development Administration (RDA) in Jeonju, Korea (lat. 35.84°N, long. 127.13°E). To validate the simulation findings, a prototype of the gear-driven rotating planting mechanism was

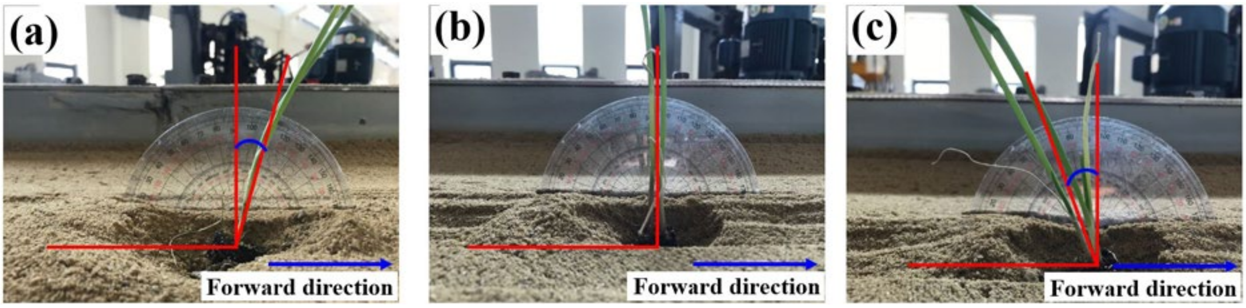

Figure 8. Vertical deposition of the onion seedlings after transplantation at (a) 0.10, (b) 0.15, and (c) 0.20 m s^{-1} forward speeds at 60 rpm.

fabricated and operated on a rotational soil bed test bench (Fig. 5). To ensure effective seedling deposition in the hopper, 50-day-old onion seedlings with an average height of 237.3 ± 12.4 mm and weight of 11.23 ± 1.5 g (plant and soil) were used.

The diameter, width, and depth of the rotating soil bed were 6.5 m, 0.45 m, and 0.2 m, respectively. The soil bed rotated at a speed of 0.3 to 1.8 m s^{-1}, and the planting mechanism was driven by a 120 W 9BDG5 electromagnetic braking motor (DKM Motors Co. Ltd., Incheon, Korea). A SV-iG5A inverter (LS Industrial Systems Co., Anyang, Korea) was used to regulate the speed of the electric motor.

The soil properties on the test bench were tested with five replications. The soil sample on the test bench was sandy loam, comprising 78 ± 8% sand, 14 ± 2% silt, and 8 ± 6% clay. Soil temperature, water content, electrical conductivity, and cone index were measured. A handheld cone penetrometer Penetrologger 6.00 (Eijkelkamp, Giesbeek, The Netherlands) was used to measure the Cone index up to 0.15 m with the error less than 1%. The soil temperature, water content, and soil electrical conductivity (EC) were measured with an error less than ± 0.5°C, ± 1%, and ± 0.1 dS m^{-1}, respectively, using a WT 1000N soil sensor (RF sensor, Seoul, Korea). The average bulk density, cone index, soil water content, soil temperature and soil EC were found to be 1.31 ± 0.08 g cm^{-3}, 0.58 ± 0.07 MPa, 23.17 ± 0.97%, 29.7 ± 0.45°C, and 1.31 ± 0.15 dS m^{-1}, respectively.

To determine the power requirement of the planting operation, a TRS605 torque sensor (FUTEK Co., Irvine, CA, USA) and a SEN041F tri-axial acceleration sensor (PCB Piezotronics, Inc., Depew, NY, USA) were installed in the power transmission line, between the motor and the planting mechanism, and in the planting hopper jaws, respectively. A NI 6212 data acquisition device (National Instruments, Austin, TX, USA) was used to acquire the signals from the sensor. We used a LabVIEW 2018 software tool (National Instruments, Austin, TX, USA) to collect torque and acceleration data. The data obtained from the torque sensor underwent a smoothing process using a symmetric moving average method (Rohrer et al., 2018) with a window size of 20 points. Another software package MATLAB R2019a (The MathWorks, Natick, MA, USA) was used to analyse the collected data. All sensors were mounted on the planting mechanism of the test bench, as illustrated in Fig. 5b.

To assess the effectiveness of the planting mechanism, onion seedlings were planted at forward speeds of 0.10, 0.15, and 0.20 m s^{-1}, with a rotational speed of 60 rpm. The study focused on measuring two key parameters: the misplanting rate and the uprightness of plant. The misplanting rate refers to instances where the seedlings were not positioned correctly. Plant uprightness was determined by examining the angle between the stem and the ground, considering angles below 30° as indicating proper upright positioning by Han et al. (2019). The transplanting oper-

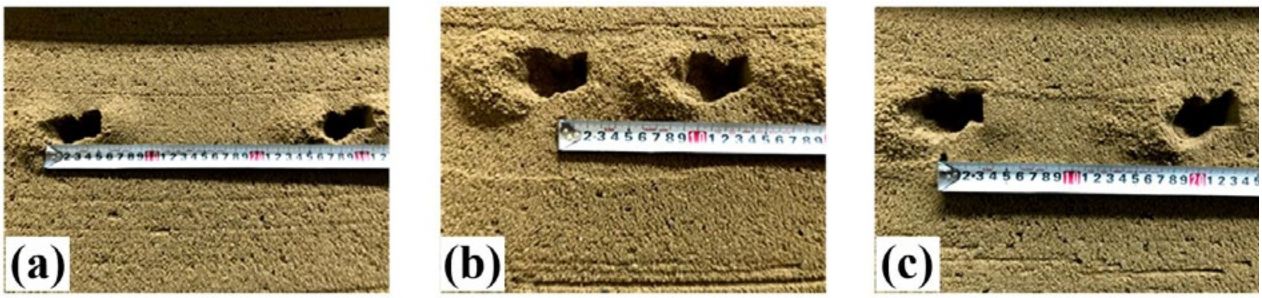

Figure 9. Planting interval for the rotary planting mechanism determined using (a) 0.10, (b) 0.15, and (c) 0.20 m s^{-1} forward speeds at 60 rpm.

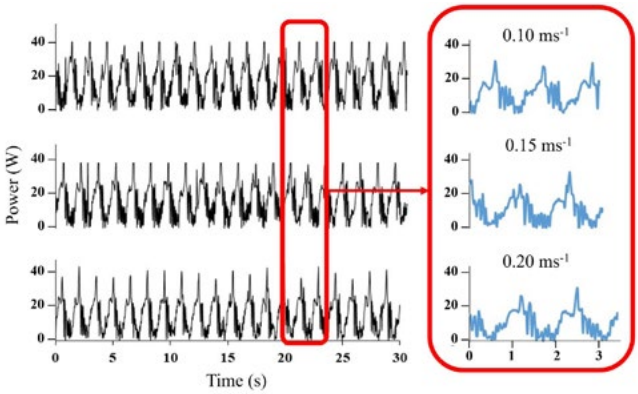

Figure 10. Power consumption of the planting mechanism of the transplanter during the transplanting operation at various forward speeds.

ation was performed five times on the test bench, as depicted in Fig. 5. During the experiment, the misplanting rate and planting interval uniformity were evaluated. Plant intervals were measured using a measuring tape, while the angle between the stem and ground (plant uprightness) was measured using a protractor. To ensure accuracy, all measurements were taken with five replications. Descriptive statistical analysis methods (average, one-way ANOVA, least significant difference (LSD) all-pairwise comparisons test) were used in this study. A software package Statistix 10 (Analytical Software, Tallahassee, FL, USA) were used for the statistical analysis.

Results and discussion

Optimum rotational speed of the planting mechanism

The rotational speed of the planting mechanism in the onion transplanter is influenced by the forward speed of the machine and the desired planting interval between onion seedlings. In this study, considering a range of forward speeds from 0.10 to 0.25 m s^{-1} and a required planting interval of 0.14 m for the onion seedlings, the calculated range of rotational speeds for the planting mechanism was found to be between 50 and 70 rpm as shown in Fig. 6a.

To ensure proper seedling drop into the hopper, the height at which the seedlings fall is a critical factor. Higher falling heights result in increased air drag on the seedlings, potentially causing improper seedling placement. Additionally, the clearance between the seedling release point and the hopper's operating route needs to be considered. Considering these factors, a free-falling height of 0.08 m was determined. The planting hopper speed was then calculated to be 60 rpm, as illustrated in Fig. 6b.

Validation tests conducted at a free-falling height of 0.08 m demonstrated a high success rate of 97.16% for seedling deposition into the hopper. The experiment revealed that seedlings with a straight shape and fewer leaves exhibited a higher percentage of accurate placement. It was also observed that the vibration of the transplanter during the operation played a significant role in seedling displacement during free fall. These findings provide valuable insights for optimizing the rotational speed of the planting mechanism, ensuring proper seedling placement and minimizing errors during the onion transplanting process.

Seedling deposition of the planting mechanism by forward speed

Fig. 7 presents the simulated trajectories of the planting mechanism for the transplanter forward speeds of 0.10, 0.15, and 0.20 m s^{-1}, at 60 rpm of the rotational speed of the planting hopper. The analysis revealed that the optimal performance, characterized by smooth and accurate seedling deposition, was achieved at a forward speed of 0.15 m s^{-1} which provide most favourable outcome in terms of successful seedling placement.

Three different scenarios were investigated for the value characteristics coefficient, namely, $\lambda>1$, $\lambda=1$, and $0<\lambda<1$ for transplanter forward speeds of 0.10, 0.15, and 0.20 m s^{-1}, respectively. The planting mechanism trajectories for these scenarios are depicted in Figs. 7a, 7b, and 7c.

In the first scenario, when the forward speed of the transplanter was 0.1 m s^{-1}, the characteristic coefficient was higher than 1. The trajectory of the planting mechanism was affected by the void deposition of the onion seedlings. There was an inflection point at the lowest position of the cycloid created under the soil surface. The direction of the horizontal speed on the cycloid was the same as the direction of the transplanter's forward speed, with the exception of the point of inflection. The speed at the point of inflection can meet the condition of the constant horizontal speed principle. However, the seedlings were rammed forward because the point of inflection was located at the lowest position of the trajectory, and the cycloid immediately moved forward after delivering the seedlings at the point of inflection. Because of the height of the seedlings, it took time for them to pass away from the cycloid. The seedlings with the cycloid progressively going ahead had not entirely gone away from the cycloid, causing damage to the seedlings during the operation. Additionally, the planting mechanism created a hole for depositing the seedlings within the soil. It entered at one location and exited at another, resulting in unwanted mulch film damage. As shown in Fig. 7a, the condition of $\lambda>1$ was not optimal for delivering the onion seedlings.

With the scenario of $\lambda=1$, when the transplanter's forward speed was 0.15 m s^{-1}, the trajectory beneath the soil became a straight line, indicating that the hopper entered and exited at the same point in the soil after releasing the seedlings. This is because the speed of the planting hopper at the seedling deposition point was equal to and opposite the forward speed of the transplanter. The seedlings were deposited at a constant horizontal speed, as shown in Fig. 7b, and the seedlings were able to maintain the appropriate degree of uprightness throughout the depositing process. Since the planting mechanism entered and departed from the same point, there was a little damage to the mulch coating. The characteristic coefficient $\lambda=1$ was an absolute requirement for the onion transplanter to function properly, which was assumed to move at a forward speed of 0.15 m s^{-1}.

The direction of the movement of the seedling could be indicated by the tangent point on the working trajectory. In the scenario of $0<\lambda<1$, where the forward speed of the planter was 0.20 m s^{-1}, the trajectory of the hopper tip beneath the soil surface created a short cycloid as shown in Fig. 7c. It was observed that the direction of horizontal speed at each location on the short cycloid was identical to the direction of forward speed of the transplanter. This shows that the horizontal speed and the angle of the onion seedling deposition were critical, as there was little time to deposit and drag out of the soil. Thus, constant horizontal speed delivery is impossible in this case, and different impact points caused damage to the mulch coating by the transplanter.

Furthermore, the cycloid movement has the potential to retain the seedlings in an upright position. In the field test, it was found that this circumstance resulted in the highest straightness of the transplanted seedlings, as shown in Fig. 8. Moreover, the cycloid movement could keep the seedlings in an upright orientation. In the field test, maximum uprightness of the planted seedlings was also found in this condition (Fig. 8). As the planting mechanism's entry and exit points were the same, the mulch film's damage was minimal. Thus, having the characteristic coefficient equal to 1 was a necessary prerequisite for performing typical transplantation procedures with the machine. According to these findings, for the onion seedlings to be planted straight and perpendicular, it is necessary to maintain a 1:1 ratio between the rotational speed of the planting mechanism and the forward speed of the transplanter throughout the operation. During the transplanting work in the field, it would also be helpful to minimize the physical labor and seedling damage.

Planting interval by forward speed

Plant-to-plant distance for onion seedling transplantation depends upon the rotational speed (rpm) of the rotary mechanism and the forward speed of the transplanting machine. Plant interval was measured for different combinations of rotational speed (rpm) of the planting mechanism, and the forward speed of the transplanter is shown in Table 2. Fig. 9 shows the results of the several planting intervals measured during the field experiments.

The usual plant-to-plant distance proposed for onion transplantation was 0.13-0.14 m. Therefore, the planting interval obtained with the combination of 60 rpm rotational speed and 0.15 m s^{-1} of forward speed of the planting mechanism is 0.13 m, which is suitable for successful transplantation of the onion seedlings. A transplanting rate of 60 seedlings min^{-1} can be obtained using above-mentioned combination.

Power consumption of the planting mechanism

During the transplantation process, the performance of the transplanter was evaluated at three distinct forward speeds (i.e., 0.10, 0.15, and 0.20 m s^{-1}), and the necessary input power was measured at each of the three different forward speeds. The measured power data for the planting mechanism exhibited a constant reciprocating curve throughout the transplanting process, as shown in Fig. 10.

For the three different forward speeds, the power consumptions of the dibbling mechanism were recorded as 43.07 ± 1.23 W, 36.53 ± 1.34 W, and 42.72 ± 2.29 W, respectively. The power consumption was found to be low when the transplanter was operating at a forward speed of 0.15 m s^{-1}. The horizontal speed of the planting hopper was developed to the dibbling point where it was able to counterbalance the forward speed. As a result, there was no external force acting on the planting hopper throughout the seedling delivery process due to the forward speed. For the operating forward speeds of 0.10 and 0.20 m s^{-1}, the planting hopper was pulled in both the backward and forward orientations, respectively. Soil contact with the planting hopper occurred during the seedling's deposition into the soil, and the tension on the planting hopper changed according to the forward speed conditions. When the for-

Table 2. Planting interval (m) with the rotary planting mechanism by forward speed and hopper operating speed.

Forward speed (m s^{-1})	Operating speed of the planting hopper (rpm)						
	30	40	50	60	70	80	90
0.10	0.15	0.13	0.11	0.11	0.10	0.10	0.10
0.15	0.20	0.18	0.16	0.13	0.12	0.10	0.10
0.20	0.30	0.21	0.20	0.18	0.17	0.13	0.12

Table 3. Field experiment results of various transplanting operation conditions and different forward speed.

Treatment	Seedling upright angle (°)	Misplanted rate (%)	Max. power consumption (W)
T_1	-13.26 ± 4.37[c]	13.290± 0.17[b]	43.07 ± 1.23[a]
T_2	90.00 ± 2.79[a]	7.660± 0.14[c]	36.53 ± 1.34[c]
T_3	16.42 ± 3.88[b]	16.410± 0.08[a]	42.72 ± 2.29[b]
LSD	2.26	0.25	0.18
CV%	5.00	1.40	0.31
Sig	***	NS	NS

[a,b,c] Different letters in the same column indicate different data levels ($p \leq 0.05$). T_1: forward speed 0.10 m s^{-1}, T_2: forward speed 0.15 m s^{-1}, T_3: forward speed 0.20 m s^{-1}, LSD: least significant difference CV: coefficient of variance (%), Sig: level of significance (*** highly significant, ** moderately significant, *significant, NS: non-significant).

wards speeds were 0.10 m s^{-1}, the planting hopper created a cycloid inside the soil, forcing it to dig a larger hole with a relatively large area, costing more power. With a forward speed of 0.20 m s^{-1}, a larger whole area was also dug, but as it towed forward, a part of the forward speed assisted in lowering the power usage. This explained the cause of the power consumption of the planting mechanism was somewhat lower at 0.20 m s^{-1} than at 0.10 m s^{-1} forward speed.

The planting mechanism completed one cycle of planting in less than one second. Therefore, it shows the minimum and maximum power values were found at the picking and planting positions, respectively (Fig. 10). At the picking and planting positions, the plating mechanism was held in the air and the hopper struck the soil, resulting in a minimum and maximum power consumption, respectively.

Field test results with the forward speeds of 0.10, 0.15, and 0.20 m s^{-1} and a rotational speed of 60 rpm of the planting mechanism are shown in Table 3. Table 3 presents the results of a statistical analysis aimed at assessing the impact of forward speed on various parameters of the transplanter, including seedling upright angle, misplanted rate, and maximum power consumption. The findings indicate that the forward speed significantly affects the seedling upright angle, implying that the angle at which the seedlings are positioned was greatly influenced by the speed at which the transplanter moves forward.

Furthermore, the analysis reveals that both power consumption and misplanted rate did not exhibit significant variations in relation to the forward speed. This suggests that the rate at which seedlings are improperly placed and the maximum power consumed by the transplanter remained relatively stable, regardless of the speed at which it operates. These findings highlight the importance of selecting an appropriate forward speed to ensure optimal seedling positioning, while also indicating that power consumption and misplanted rate may be less influenced by variations in forward speed.

According to the findings of the comparison between theoretical and experimental data, the forward speed of 0.15 m s^{-1} provided the optimum performance. The upright seedling angle was reported to be 90° ± 2.79°, at a forward speed of 0.15 m s^{-1}, with a success deposition rate of 92.34%. Different studies carried out transplanting operations with several planting mechanisms at 0.15 to 0.25 m s^{-1} forward speed and observed the success rate of transplanting at 90-94% (Tian et al., 2010; Jin et al., 2020; Zhou et al., 2020; Iqbal et al., 2021). To ensure proper placement of seedlings, a free-falling height of 0.08 m was determined. Various studies (Dihingia et al., 2016; Jo et al., 2018) demonstrated that the recommended range for the free falling height of a transplanter is between 0.06 to 0.09 m. The results of the success rate of transplanting in our study were comparable to those of earlier research, despite the fact that the transplanter's forward speed and the seedling types were different. The results of the power consumption experiment revealed that when the characteristic coefficient $\lambda=1$, the planting mechanism used the least amount of power.

Conclusion

In this study, the analysis of a rotary planting mechanism for a self-propelled automatic onion transplanter yielded several important outcomes. The optimal working conditions were determined based on successful seedling deposition in the planting hopper, resulting in a rotational speed of 60 rpm and a transplanting frequency of 60 seedlings min^{-1}. A free-falling height of 0.08 m was identified as necessary for proper seedling placement. The investigation of the working trajectory revealed that the planting mechanism achieved desirable results, including straight and upright seedling orientation with acceptable mulch film damage, at a forward speed of 0.15 m s^{-1}. These findings were further validated through field performance testing using a prototype transplanter mounted on a rotational soil test bed, confirming the consistency between theoretical analysis, simulation, and practical experiments.

The research demonstrated the feasibility of the gear-driven rotary planting mechanism for efficient onion seedling transplantation, highlighting the importance of maintaining a 1:1 ratio between the rotational speed of the planting mechanism and the transplanter forward speed. These outcomes contribute to the advancement of automation in seedling transplantation processes in agricultural fields.

Moving forward, future research could focus on optimizing and refining the gear-driven planting mechanism to enhance its performance and efficiency further. Additionally, exploring the applicability of this technology to other crops and studying its potential integration with other automated agricultural processes could be valuable areas of investigation. Overall, the achieved outcomes have significant implications for the scientific community, as they provide valuable insights into improving the mechanization and automation of seedling transplantation in agriculture. By reducing manual labor and increasing efficiency, this research contributes to the ongoing development of sustainable and technologically advanced farming practices.

Authors' contributions

Conceptualization: M. N. Reza, S. O. Chung
Data curation: M. N. Reza, M. Ali, E. Habineza
Formal analysis: M. N. Reza, M. Ali, E. Habineza, M. S. Kabir, M. S. N. Kabir
Funding acquisition: S. O. Chung
Investigation: S. J. Lim, I. S. Choi, S. O.Chung
Methodology: M. N. Reza, M. S. N. Kabir, S. O. Chung
Project administration: S. O. Chung
Resources: S. O. Chung
Software: M. N. Reza
Supervision: S. O. Chung
Validation: M. N. Reza, M. S. N. Kabir, S. O. Chung
Visualization: M. N. Reza, M. Ali, E. Habineza, M. S. Kabir, S. J. Lim
Writing – original draft: M. N. Reza
Writing – review & editing: M. N. Reza, M. S. N. Kabir, S. O. Chung

References

Baloch RA, Baloch SU, Baloch SK, Baloch HN, Badini SA, Bashir W, et al., 2014. Economic analysis of onion (*Allium cepa* L.) production and marketing in district Awaran, Balochistan. Econ Anal 5(24): 192-206.

Chowdhury M, Gulandaz MA, Kiraga S, Ali M, Reza MN, Kwon HJ, et al., 2021. Turning stability analysis of a 12-kW self-propelled riding-type automatic onion transplanter to ensure user safety. IOP Conf Series: Earth Environ Sci 924(1): 012014. https://doi.org/10.1088/1755-1315/924/1/012014

Dihingia PC, Prasanna Kumar GV, Sarma PK, 2016. Development of a hopper-type planting device for a walk-behind hand-tractor-powered vegetable transplanter. J Biosyst Eng 41(1): 21-33. https://doi.org/10.5307/JBE.2016.41.1.021

Dong Y, Cheng Z, Meng H, Liu H, Wu C, Khan AR, 2013. The effect of cultivar, sowing date and transplant location in field on bolting of Welsh onion (*Allium fistulosum* L.). BMC Plant Biol 13(1): 1-12. https://doi.org/10.1186/1471-2229-13-154

Dossa F, Miassi, Y, Banzou K, 2018. Onion (Allium cepa) production in urban and peri-urban areas: financial performance and importance of this activity for market gardeners in Southern Benin. Curr Anthropol 3(2). https://doi.org/10.32474/CIACR.2018.03.000159

Du S, Yu J, Wang W, 2018. Determining the minimal mulch film damage caused by the up-film transplanter. Adv Mech Eng 10(3): 1-13. https://doi.org/10.1177/1687814018766777

FAO, 2021. FAOSTAT. http://www.fao.org/faostat/en/#data [Nov 13, 2021).

Gavino RB, Tiw-an CC, 2020. Assessment of mechanization level of onion production in Nueva Ecija. CLSU Int J Sci Technol 4(1): 81-98. https://doi.org/10.22137/ijst.2020.v4n1.06

Geisseler D, Ortiz RS, Diaz J, 2022. Nitrogen nutrition and fertilization of onions (*Allium cepa* L.)-A literature review. Sci Hortic 291: 110591. https://doi.org/10.1016/j.scienta.2021.110591

Han C, Hu X, Zhang J, You J Li H, 2021. Design and testing of the mechanical picking function of a high-speed seedling auto-transplanter. Artif Intellig Agr 5: 64-71. https://doi.org/10.1016/j.aiia.2021.02.002

Han LH, Mao HP, Hu JP, Kumi F, 2019. Development of a riding-type fully automatic transplanter for vegetable plug seedlings. Span J Agric Res 17(3): e0205. https://doi.org/10.5424/sjar/2019173-15358

Iqbal MZ, Islam MN, Chowdhury M, Islam S, Park T, Kim YJ, et al., 2021. Working speed analysis of the gear-driven dibbling mechanism of a 2.6 kW walking-type automatic pepper transplanter. Machines 9(1): 6. https://doi.org/10.3390/machines9010006

Islam MN, Iqbal MZ, Ali M, Chowdhury M, Kabir MSN, Park T, et al., 2020. Kinematic analysis of a clamp-type picking device for an automatic pepper transplanter. Agriculture 10(12): 627. https://doi.org/10.3390/agriculture10120627

Ji JT, He YK, Du XW, He ZT, Du MM, Zheng ZH, et al., 2013. Design of the up-film transplanter and kinematic analysis of its planting devices. Proc Int Conf Adv Mechatronic Syst, pp: 312-316. IEEE, New York. https://doi.org/10.1109/ICAMechS.2013.6681800

Jin X, Cheng Q, Zhao B, Ji J, Li M, 2020. Design and test of 2ZYM-2 potted vegetable seedlings transplanting machine. Int J Agr Biol Eng 13(1): 101-110. https://doi.org/10.25165/j.ijabe.20201301.5494

Jin X, Li R, Tang Q, Wu J, Jiang L, Wu C, 2022. Low-damage transplanting method for leafy vegetable seedlings based on machine vision. Biosyst Eng 220: 159-171. https://doi.org/10.1016/j.biosystemseng.2022.05.017

Jo JS, Okyere FG, Jo JM, Kim HT, 2018. A study on improving the performance of the planting device of a vegetable transplanter. J Biosyst Eng 43(3): 202-210. https://doi.org/10.1002/prep.201700174

Khadatkar A, Mathur SM, Dubey K, BhusanaBabu V, 2021. Development of embedded automatic transplanting system in seedling transplanters for precision agriculture. Artif Intellig Agr 5: 175-184. https://doi.org/10.1016/j.aiia.2021.08.001

Kim HC, Cho YH, Ku YG, Bae JH, 2015. Seedling qualities of hot pepper according to seedling growth periods and growth and yield after planting. Hortic Sci Technol 33(6): 839-844. https://doi.org/10.7235/hort.2015.15083

Liguori L, Califano R, Albanese D, Raimo F, Crescitelli A, Di Matteo M, 2017. Chemical composition and antioxidant properties of five white onion (*Allium cepa* L) landraces. Hindawi J Food Qual 2017: 6873651. https://doi.org/10.1155/2017/6873651

Li H, Cao W, Li S, Liu J, Chen B, Ma X, 2017. Development of 2ZXM-2 automatic plastic film mulching plug seedling transplanter for vegetable. T Chin Soc Agr Eng 33(15): 23-33.

Liu J, Zhao S, Li N, Faheem M, Zhou T, Cai W, et al., 2019. Development and field test of an autonomous strawberry plug seeding transplanter for use in elevated cultivation. Appl Eng Agric 35: 1067-1078. https://doi.org/10.13031/aea.13236

Manes G, Anoop D, Arsdeep S, Mahal J, 2013. Feasibility of mechanical transplanter for paddy transplanting in Punjab. AMA Agric Mech As Afr Lat Am 44: 4-7.

Manilla RD, Shaw LN, 1987. A high-speed dibbling transplanter. T ASAE 30: 0904-0908. https://doi.org/10.13031/2013.30496

Min YB, Kang JK, Ryu CS, 2015. Development onion transplanter: analysis a transplanting locus on the type of transplanting devices for a vegetable transplanter. J Agr Life Sci 49(6): 289-294. https://doi.org/10.14397/jals.2015.49.6.289

Pareek S, Sagar NA, Sharma S, Kumar V, 2018. Onion (Allium cepa L.) In: Fruit and vegetable phytochemicals: Chemistry and human health, Vol. II, 2nd ed; Yahia EM (ed). John Wiley & Sons Ltd. https://doi.org/10.1002/9781119158042.ch58

Pérez-Ruiz M, Slaughter DC, 2021. Development of a precision 3-row synchronised transplanter. Biosyst Eng 206: 67-78. https://doi.org/10.1016/j.biosystemseng.2021.03.014

Rasool K, Ali M, Chowdhury M, Kwon HJ, Swe KM, Chung SO, 2021. Theoretical analysis of velocity, acceleration and torque calculation of a five-bar onion transplanting mechanism. IOP Conf Series: Earth Environ Sci 733(1): 012019. https://doi.org/10.1088/1755-1315/733/1/012019

Reza MN, Islam MN, Chowdhury M, Ali M, Islam S, Kiraga S, et al., 2021. Kinematic analysis of a gear-driven rotary planting mechanism for a six-row self-propelled onion transplanter. Machines 9(9): 183. https://doi.org/10.3390/machines9090183

Rohrer RA, Luck JD, Pitla SK, Hoy R, 2018. Evaluation of the accuracy of machine reported can data for engine torque and speed. T ASAE 61: 1547-1557. https://doi.org/10.13031/trans.12754

Shao Y, Liu Y, Xuan G, Hu Z, Han X, Wang Y, et al., 2019. Design and test of multifunctional vegetable transplanting machine. IFAC-Papers OnLine 52(30): 92-97. https://doi.org/10.1016/j.ifacol.2019.12.503

Srivastava AK, Goering CE, Rohrbach RP, Buckmaster DR, 2006. Engineering principles of agricultural machines, 2nd ed. Am Soc Agr Biol Eng, St. Joseph, MI, USA.

Tian S, Qiu L, Kondo N, Yuan T, 2010. Development of automatic transplanter for plug seedling. IFAC Proc Vol 43(26): 79-82. https://doi.org/10.3182/20101206-3-JP-3009.00013

Xue X, Li L, Xu C, Li E, Wang Y, 2020. Optimized design and experiment of a fully automated potted cotton seedling transplanting mechanism. Int J Agr Biol Eng 13: 111-117. https://doi.org/10.25165/j.ijabe.20201304.5317

Ye B, Zeng G, Deng B, Yang C, Liu J, Yu G, 2020. Design and tests of a rotary plug seedling pick-up mechanism for vegetable automatic transplanter. Int J Agr Biol Eng 13(3): 70-78. https://doi.org/10.25165/j.ijabe.20201303.5647

Yin DQ, Wang JZ, Zhang S, Zhang NY, Zhou ML, 2019. Optimized design and experiments of a rotary-extensive-type flowerpot seedling transplanting mechanism. Int J Agr Biol Eng 12: 45-50. https://doi.org/10.25165/j.ijabe.20191206.5188

Ying W, Jianneng C, Xiong Z, Xincheng S, 2015. Parameter optimization and experiment of planting mechanism driven by planetary non circular gears. T Chin Soc Agr Machin 46(9): 85-93 (in Chinese).

Zhao X, Shen M, Chen J, Dai L, 2014. Kinematic analysis and virtual experiment of rotary pick-up mechanism on cotton transplanter. T Chin Soc Agr Eng 30(8): 13-20.

Zhou M, Shan Y, Xue X, Yin D, 2020. Theoretical analysis and development of a mechanism with punching device for transplanting potted vegetable seedlings. Int J Agr Biol Eng 13: 85-92. https://doi.org/10.25165/j.ijabe.20201304.5404