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Research article

Mechanism design and analysis of six-bar linkage structure for vegetable transplanting

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Abstract

This study presents a new vegetable farming mechanism with a six-bar linkage structure installed on a watering crane so that this mechanism can be adjusted for the spacing between plants by changing the anchor points of link 5 without any adjustment of the angular speed of the input cranks. This is beneficial in terms of convenience, simplicity and low cost compared to other mechanisms that mainly need adjustment to the angular speed of the input cranks that is complicated and expensive. In addition, this new mechanism provides adjustment for three planting distances (200 mm, 250 mm, 300 mm). Kinematics were analyzed to determine the speed of the planting duckbill, the crane, the anchor points of link 5, planting distances and the zero-speed of the planting duckbills. The results showed that transplanting with the six-bar mechanism installed in the crane produced the planting distances as required and the plants had vertically straight stems and were healthy and well grown.

Introduction

Despite an increase in vegetable consumption, Thailand's vegetable farming has been based heavily on labor (Seeniang and Thaipakdee, 2013). Farming technologies, including rice transplanters and vegetable seedling transplanters, have been widely used in many countries and in Thailand, a good number of rice transplanters have been imported due to their popularity among farmers (Eam o-pas and Goto, 1990). However, international vegetable seedling transplanters or vegetable planting machines are not as popular in Thailand due to local differences in the soil properties between in Thailand and other countries. Most of the soil in Thailand is hard and dry making it difficult to successfully use imported transplanters (Eam o-pas et al., 1988). Different models of vegetable planting machines have been invented. Hu et al. (2013) suggested a planting mechanism with planetary gears which has a gear installed to rotate the duckbill at the end of the arm. Jia et al. (2019) proposed a four-bar linkage vegetable transplanter with a duckbill at the end of the arm. However, this model did not have an adjustable planting distance. Xiao et al. (2014)

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proposed a vegetable transplanting mechanism with two sets of four-bar linkages combined as dual parallelograms, using two sets of drivers to rotate two input cranks. Liu et al. (2016) and Jin et al. (2018) suggested models of five-bar linkage vegetable seedling transplanters for planting beds with plastic mulching as the linkage could stop the motion of the planting duckbills while the transplanter moved at constant speed. In addition, they proposed a mechanism with several radial arms, with a seedling-taking clamp on the end of each arm. The clamps were designed to take a seedling from the tray and place it in a hole.

Materials and Methods

The researcher designed a new mechanism of transplanter with a six-bar linkage structure that is able to adjust the distance between seedlings. It is installed in a crane that runs above the planting bed and is driven by an electric motor. This new model (Fig. 1) consists of: 1) an input crank or link 2 connected to the electric motor that rotates counter clockwise at a constant speed; 2) a planting duckbill link or link 6 working as a tube to transport seedlings to 3) the planting duckbill or link 7 that contains a cam and follower for controlling opening or shutting the planting duckbill; (4) a vertical link or link 3; 5) an upper link or link 5; and 6) a lower link or link 4. When the input crank rotates with an angular velocity, the planting duckbill on the planting duckbill link moves down to the planting bed and pokes a hole. Then, the planting duckbill opens, moves upward and releases the seedling into the hole. However, it is essential that the horizontal velocity of planting duckbill is consistent with the crane that rotates at a constant speed to control the planting duckbill so that it stays on the row while digging holes. The planting distance was controlled by changing the holding point of the upper link or link 5 at C_1, C_2, C_3 and the other end of the upper link at D_1.

Kinematics modeling

This part presents an analysis of the vegetable planting mechanism and identifies the mathematical equations of the position and velocity of E which is located at the end of the planting duckbill. When link 2 turns and makes an angle, the position and direction of E compared to the frame {w} is ${}^{w}\mathbf{x}_E = \begin{bmatrix} {}^{w}x_E & {}^{w}y_E & {}^{w}J_E \end{bmatrix}$ where frame {w} refers to the jointed frame at O_A, as shown in Fig. 2.

According to the triangle $\Delta O_A O_B A$ in Fig. 2, the distance Z can be determined using Equations 1 and 2:

$$z = \sqrt{l_1^2 + l_2^2 - 2l_1 l_2 \cos(\theta_2 + 111.6°)} \tag{1}$$

$$\beta = \frac{180}{\pi}\left[\cos^{-1}\left(\frac{z^2 + l_1^2 - l_2^2}{2zl_1}\right)\right] \tag{2}$$

where l_1 is the distance between O_A and O_B, l_2 is the length of link 2 and θ_2 is the angle of link 2.

According to the triangle O_ABA, the angle α can be determined using Equation 3:

$$\alpha = \frac{180}{\pi}\left[\cos^{-1}\left(\frac{z^2 + l_4^2 - l_3^2}{2zl_4}\right)\right] \tag{3}$$

where l_4 is the distance between O_A and B.

According to the 4-bar mechanism pattern of link 3, link 4, link 5 and link 6, the angle θ_4 can be determined using Equations 4 and 5:

$$\theta_4 = 68.4° - (\alpha + \beta) \tag{4}$$

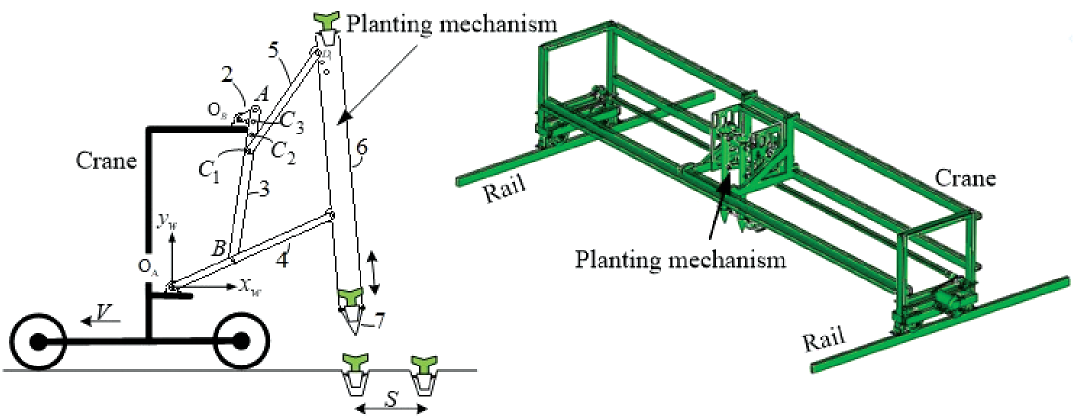

Fig. 1 New vegetable planting mechanism installed on crane

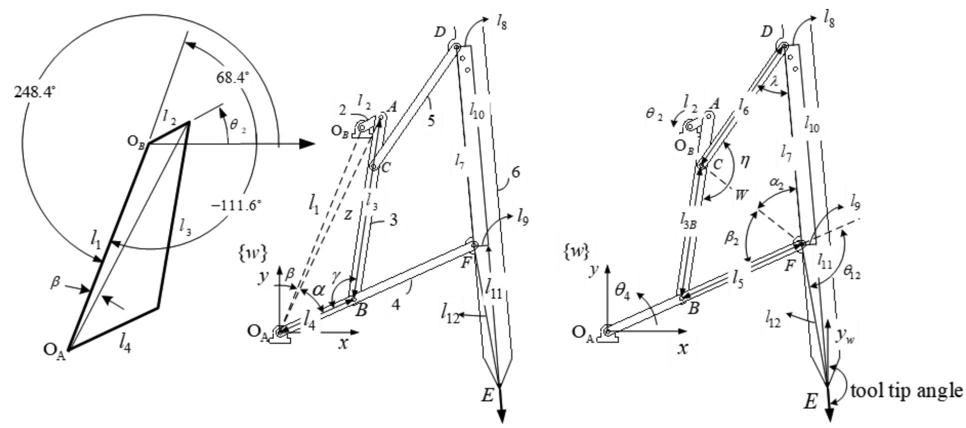

Fig. 2 New vegetable planting mechanism with six-bar linkage structure

where -111.6° ≤ θ_2 ≤ 68.4°, so that 0° ≤ β ≤ 180° (Fig. 2)

$$\theta_4 = 68.4° - (\alpha - \beta) \tag{5}$$

where 68.4° ≤ θ_2 ≤ 248.4°, so that 180° < β < 360° (Fig. 2)

According to triangle $\Delta O_A BA$, the angle γ can be determined using Equation 6:

$$\gamma = \frac{180}{\pi}\left[\cos^{-1}\left(\frac{z^2 - l_3^2 - l_4^2}{-2 l_3 l_4}\right)\right] \tag{6}$$

According to triangles ΔCDF and ΔBCF, the angles α_2, β_2 and w can be determined using Equations 7–10, respectively:

$$\alpha_2 = \frac{180}{\pi}\left[\cos^{-1}\left(\frac{w^2 + l_7^2 - l_6^2}{2 w l_7}\right)\right] \tag{7}$$

$$\beta_2 = \frac{180}{\pi}\left[\cos^{-1}\left(\frac{w^2 + l_5^2 - l_{3B}^2}{2 w l_5}\right)\right] \tag{8}$$

$$w = \sqrt{l_{3B}^2 + l_5^2 - 2 l_{3B} l_5 \cos(180° - \gamma)} \tag{9}$$

$$\theta_{12} = (\alpha\_2 + \beta\_2\ ) - 9.69° \tag{10}$$

Then, based on Fig. 2 and Fig. 3, the position of E compared to frame {w} can be determined using Equations 11 and 12:

$${}^{w}x_E = (l_4 + l_5)\cos(\theta_4) + l_{12}\cos(\theta_4 - \theta_{12}) \tag{11}$$

$${}^{w}y_E = (l_4 + l_5)\sin(\theta_4) + l_{12}\sin(\theta_4 - \theta_{12}) \tag{12}$$

Since the positions derived using Equations 11 and 12 are measured compared with the point installed on the horizontally moving crane with velocity V, the position and direction of point E compared to the ground or frame {0} can be determined using Equations 13–15:

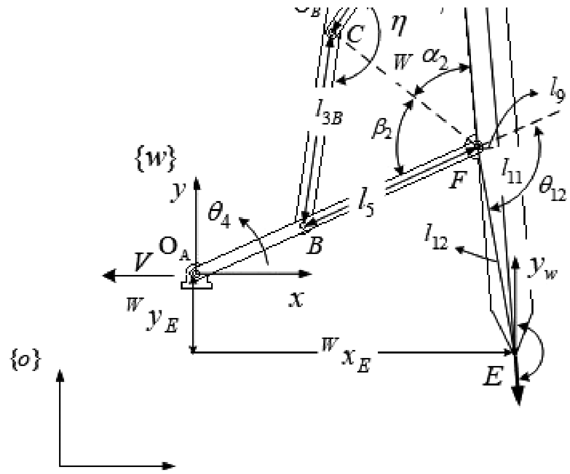

Fig. 3 New vegetable planting mechanism with six-bar linkage structure and frame {0}

$${}^{0}x_E = {}^{w}x_E + Vt \tag{13}$$

$${}^{0}y_E = {}^{w}y_E \tag{14}$$

$${}^{0}J_E = {}^{0}J_E = \cos(90 - \theta_4 + \theta_{12}) \tag{15}$$

The speed of point E has to be determined on the axes x and y of frame {w} using Equations 16–20:

$$\frac{d\,{}^{w}x_E}{dt} = {}^{w}\dot{x}_E = -\dot{\theta}_4(l_4 + l_5)\sin(\theta_4) - l_{12}(\dot{\theta}_4 - \dot{\theta}_{12})\sin(\theta_4 - \theta_{12}) \tag{16}$$

$$\frac{d\,{}^{w}y_E}{dt} = {}^{w}\dot{y}_E = \dot{\theta}_4(l_4 + l_5)\cos(\theta_4) + l_{12}(\dot{\theta}_4 - \dot{\theta}_{12})\cos(\theta_4 - \theta_{12}) \tag{17}$$

where

$$\dot{\theta}_{12} = \left(\left(\frac{l_7\cos(\alpha_2) - w}{w l_7 \sin(\alpha_2)}\right) + \left(\frac{l_5\cos(\beta_2) - w}{w l_5 \sin(\beta_2)}\right)\right)\left(-\left(\frac{l_5 l_{3B}\sin(180° - \gamma)}{w}\right)\frac{z\dot{z}}{l_3 l_4 \sin(\gamma)}\right) \tag{18}$$

$$\dot{\theta}_4 = -\left(\begin{array}{l} \left(\dfrac{l_4\cos(\alpha)-z}{zl_4\sin(\alpha)}\right)\dfrac{l_1l_2\sin\left(\theta_2+111.6^\circ\right)}{\sqrt{l_1^2+l_2^2-2l_1l_2\cos\left(\theta_2+111.6^\circ\right)}}\dot{\theta}_2+.. \\ \left(\dfrac{l_1\cos(\beta)-z}{zl_1\sin(\beta)}\right)\dfrac{l_1l_2\sin\left(\theta_2+111.6^\circ\right)}{\sqrt{l_1^2+l_2^2-2l_1l_2\cos\left(\theta_2+111.6^\circ\right)}}\dot{\theta}_2 \end{array} \right) \tag{19}$$

when $-111.6^\circ \le \theta_2 \le 68.4^\circ$ and

$$\dot{\theta}_4 = -\left(\begin{array}{l} \left(\dfrac{l_4\cos(\alpha)-z}{zl_4\sin(\alpha)}\right)\dfrac{l_1l_2\sin\left(\theta_2+111.6^\circ\right)}{\sqrt{l_1^2+l_2^2-2l_1l_2\cos\left(\theta_2+111.6^\circ\right)}}\dot{\theta}_2-.. \\ \left(\dfrac{l_1\cos(\beta)-z}{zl_1\sin(\beta)}\right)\dfrac{l_1l_2\sin\left(\theta_2+111.6^\circ\right)}{\sqrt{l_1^2+l_2^2-2l_1l_2\cos\left(\theta_2+111.6^\circ\right)}}\dot{\theta}_2 \end{array} \right) \tag{20}$$

when $-68.4^\circ \le \theta_2 \le 248.4^\circ$, where z and w can be determined using Equations 1 and 9, respectively. Consequently, the velocity of point E along axes x and y compared to the frame {0} can be calculated using Equations 21 and 22:

$$ {}^0\dot{x}_E = {}^w\dot{x}_E + V \tag{21}$$

$$ {}^0\dot{y}_E = {}^w\dot{y}_E \tag{22}$$

Motion planning

The conditions for an effective vegetable planting mechanism are: 1) The velocity of point E at its lowest point has to be at 0 (Liu et al., 2016; Chen et al., 2011) to minimize any damage that might occur to the planting duckbill and the seedlings that are released through it; 2) at its highest, point E should be higher than the seedlings in the beds to protect the seedlings from the tip of the planting duckbill and in the current study, the position was determined from the stroke of the planting duckbill using Stroke = ${}^W y_E(\max) - {}^W y_E(\min)$; and 3) as there are three vegetable planting distance (200 mm, 250 mm, 300 mm), the transplanting mechanism has to be able to efficiently adjust to the required distance.

Zero-speed seedling

To adjust the velocity, compared to frame {0} of point E, to 0 while E is at the lowest position, the study is based on Equation 21: ${}^0\dot{x}_E = {}^w\dot{x}_E + V = 0$. In other words, the crane speed and axis X speed, compared to frame {w} of point E at the lowest position, are the same but in opposite directions as $V = -{}^w\dot{x}_E$. The lowest position of E can be determined using Equation 17: ${}^w\dot{y}_E = \dot{\theta}_4\left(l_4+l_5\right)\cos\left(\theta_4\right)+l_{12}(\dot{\theta}_4-\dot{\theta}_{12})\cos\left(\theta_4-\theta_{12}\right)$. Then E's lowest point occurs when $\theta_2 = 270^\circ$, and E's highest point occurs when $\theta_2 = 90^\circ$.

Planting distance

The adjustable vegetable seedling transplanting distancing mechanism was designed in by changing the anchor point positions of the upper link or link 5 on C_1, C_2 and C_3, where the other end of the link is attached at the anchor point. Due to the reciprocating motion of the planting duckbill, the planting distance can be determined using Equation 23:

$$ s = \frac{V}{N} \tag{23}$$

where s is seedling distance in the planting bed (measured in millimeters), V is the crane speed (in millimeters per second) and N is the rotation speed of the input crank (in revolutions per second).

According to Equation 23, the crane speed is the speed of the lowermost E point and this can be used to identify the positions of the anchor points C_1, C_2, C_3 and D_1.

Characteristic coefficient

Han et al. (2019) proposed the characteristic coefficient λ, where if λ is less than 1, the holes dug by the planting duckbill are likely to be too big for the seedling to be placed and stand in a vertical position. On the other hand, when λ is greater than 1, seedlings grow up straight better due to the smaller hole and easier opening motion of the planting duckbill. λ is determined from $\lambda = \frac{{}^w\dot{x}_E}{V}$. In this study, λ was set to 1 so that the seedlings could be released easily and grow straight, and so that the planting duckbill could open easily.

Results

Results and analysis

Based on the conditions of the transplanting mechanism described above, the following could be determined: the velocities of point E at the lowermost point and of the crane, the stroke of the planting duckbill, the characteristic coefficient and the positions of anchor points C_1, C_2, and C_3 or l_{3B}. The input crank rotates at an angular speed or 24 rpm using an Suntech gear motor with 0.25 horsepower. The planting duckbill or link 6 has a length of 205.19 mm, while link 1 is 310.10 mm long, link 2 is 30.0 mm long, link 3 is 260.50 mm long, link 4 is 113.88 mm long, link 5 is 186 mm long and links 6, l_7 and l_{12} are 205 mm, 281.15 mm and 476 mm long, respectively. The result showed that the distance of l_{3B} can be determined for anchor points C_1, C_2, and C_3. The point E velocity at the lowermost point, the crane velocity, the stroke, λ (the characteristic coefficient) and the stroke were analyzed, as shown in Table 1.

The motion of the planting duckbill when the crane velocity is 0 and the inclination angle or direction of the planting duckbill are shown in Fig. 4. The motion of the planting duckbill when the crane velocity is the same as the velocity at point E at the lowermost point is shown in Fig. 5. At anchor point C_1, l_{3B} must equal 184.21 mm to provide a planting distance of 200 mm. This requires the point E velocity at the lowest point to be 80 mm/s. The lowest point of E at -474.6 mm resulted in a crane velocity of 80 mm/s and a stroke of the planting duckbill of 187.5 mm.

For anchor point C_2, to have a seedling planting distance of 250 mm, l_{3B} is required to be 214.89 mm, resulting in a velocity of point E at the lowermost point of 100 mm/s, with the lowest point at -478.07 mm and a required crane velocity of 100 mm/s and a planting duckbill stroke of 168.8 mm.

For anchor point C_3, to have a seedling planting distance of 250 mm, l_{3B} is required to be 249.3 mm, resulting in a velocity of point E at the lowermost point of 120 mm/s, with the lowest point at -479.67 mm and a required crane velocity of 120 mm/s and a planting duckbill stroke of 159.6 mm.

When changing the positions of anchor points C_1, C_2 and C_3, the lowest point and the velocity of E are different, since the length of l_{3B} has been altered; the lowest point and the velocity of E can be determined using Equations 12 and 17, respectively.

Figs. 4 and 5 determine the ground level and the vegetable tip level. As the holes dug by planting duckbill are 30 mm deep and the vegetable seedlings are 30 mm tall, the distances from the tip of the seedlings to the highest point of planting duckbill, C_1, C_2 and C_3 are 127.5 mm, 108.8 mm, and 99 mm respectively. As a result, the planted seedlings are not knocked down by the planting duckbill, and taller seedlings are also able to be planted. Furthermore, the planting duckbill is able to stop moving when moving to the lowest position. In other words, the planting duckbill does not slide while the crane is moving.

Table 1 Analysis of velocity, stroke, anchor point positions and characteristic coefficient

Planting distance	200 mm	250 mm	300 mm
Anchor point position	C_1	C_2	C_3
Velocity of E at the lowermost point (mm/s)	80.00	100.00	120.00
Velocity of crane (mm/s)	80.00	100.00	120.00
Stroke (mm)	187.5	168.8	159.6
l_{3B} (mm)	184.21	214.89	249.3
λ (characteristic coefficient)	1	1	1

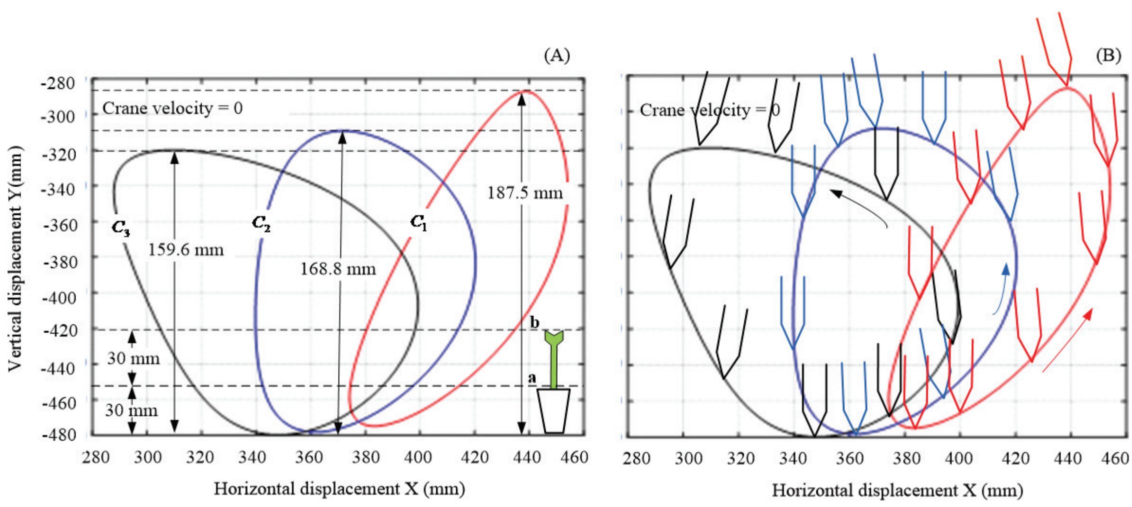

Fig. 4 Analysis of seedling transplanting mechanism with six-bar linkage: (A) motion of planting duckbill compared to crane velocity at 0; (B) direction of planting duckbill

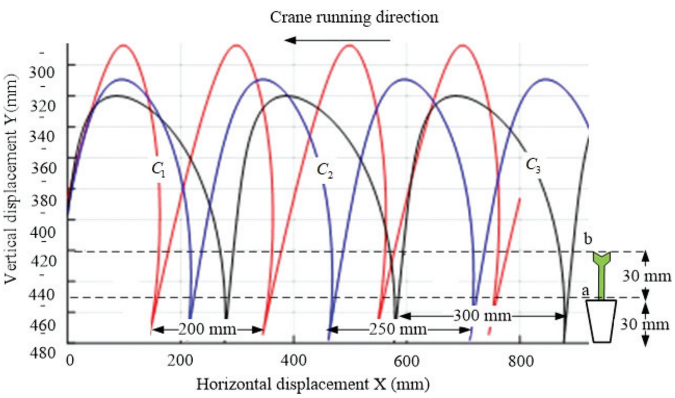

Fig. 5 Effects of changing length of l_{3B} on seedling distance and stroke

Experimental results

A model of the vegetable seedling transplanting mechanism was constructed to determine its efficiency, as shown in Fig. 6. The mechanism was installed on a crane moving on metal rails that straddled a planting bed. The crane and the mechanism were powered by 90-watt AC electric motors with a 100:1 gear reducer and a power transmission system consisting of a set of pulleys and belts for adjusting the crane velocity and input crank. Lettuce seedlings aged 20 d in seedling cups were used in the test. The height of the seedlings from the cup bottom to the seedling tip was approximately 65 mm. The seedlings with the cups were transplanted together, as shown in Fig. 7A.

The testing was controlled by a controller sitting on the crane, who picked and placed the seedlings into the planting duckbill link while the crane and the mechanism were moving. The plating medium was a skeletal soil consisting of gravel, clay, and sand, with a pH of 6.0–6.5, and was considered a low fertility soil. For the soil to be able to fall back to cover the roots of the seedlings without extra tools after transplanting, the soil is required to have an average water content while planting of 10%. In total, 1,200 lettuce seedlings were planted (Figs. 7B and 7C).

The results from planting 400 seedlings (Fig. 8) showed that when anchor point was set for 200 mm, the seedlings in the planting bed were on average 200 mm apart with an approximately perpendicular rate of 96% and a planting depth of 30 mm. No seedling damage was observed due to being knocked down by the duckbill, as shown in Fig. 8A. When the anchor point was set at 250 mm, the 400 seedlings in the planting bed were on average 250 mm apart with an approximately perpendicular rate of 96% and a planting depth of 30 mm. Again, no seedling damage was observed due to being knocked down by the duckbill, as shown in Fig. 8B. When the anchor point was set at 300 mm, the 400 seedlings in the planting bed were on average 301 mm apart with an approximately perpendicular rate of 97% and a planting depth of 30 mm. No seedling damage was observed due to being knocked down by the duckbill, as shown in Fig. 8C. After transplanting, the researcher watered and applied fertilizer to the vegetables regularly to investigate growth and losses. All vegetables appeared to be growing well and there was no mortality. The new mechanism was able to plant 1,466 seedlings/hr compared to 500 seedlings/hr as a standard planting rate using hand labor.

Discussion

The new vegetable transplanting mechanism with a six-bar linkage structure and adjustable adjust transplanting distance without any angular velocity adjustment of the input crank,

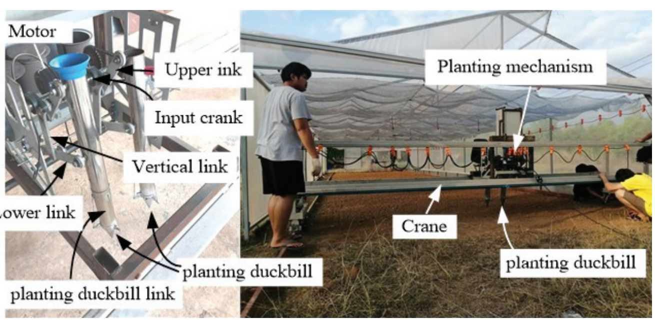

Fig. 6 New vegetable transplanting mechanism with six-bar linkage structure installed on crane for field testing

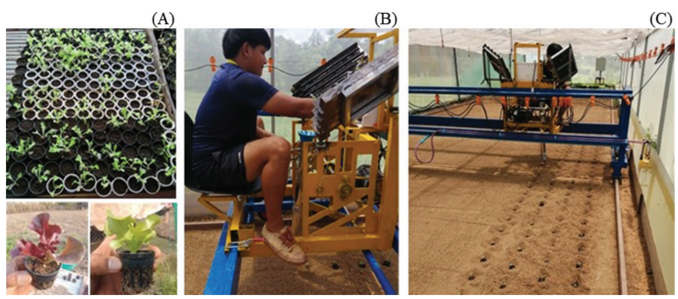

Fig. 7 New vegetable transplanting mechanism with six-bar linkage structure installed on crane for field testing: (A) lettuce seedlings aged 20 d in cups and ready to be transplanted; (B) controller placing the seedlings into planting duckbill link while the mechanism and crane are moving; (C) seedlings transplanted by transplanting mechanism

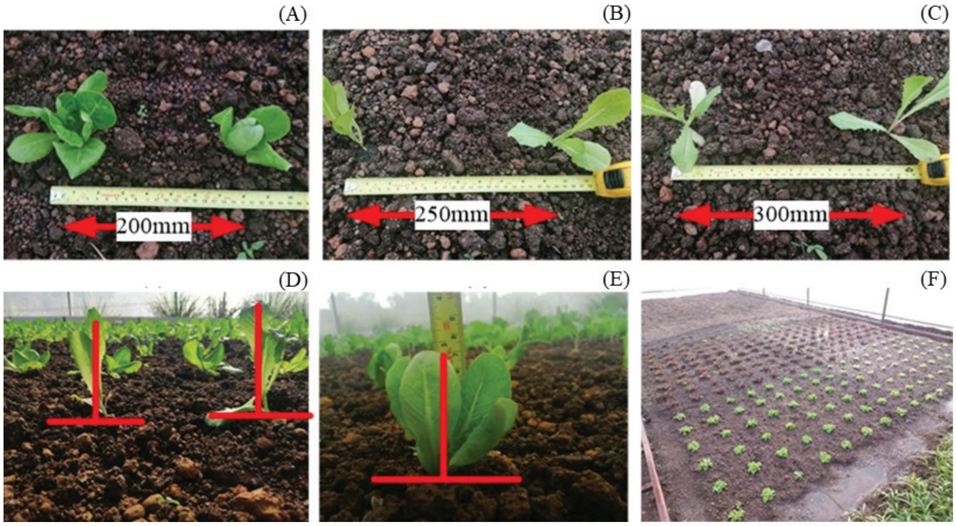

Fig. 8 Results of experiments: (A) lettuce seedlings 200 mm apart with anchor point C_1; (B) lettuce seedlings 250 mm apart with anchor point C_2; (C) lettuce seedlings distance 300 mm apart with anchor point C_3; (D) and (E) plants are planted vertically; (F) seedlings growing well after transplanting with vegetable transplanting mechanism with six-bar linkage structure installed on crane

was designed and developed for installation on a crane moving along rails straddling the planting bed. A thorough analysis of the motion (Carter, 1950; Pennock and Israr, 2009) of the planting duckbill was conducted to identify the relationships among velocity, motion distance and distance of anchor point on link 3 so that the transplanting mechanism could perform efficiently under the required conditions, including zero-speed seedlings, stroke, planting distance, characteristic coefficient and 96% of transplanted seedlings having healthy and straight stems. This new vegetable transplanting mechanism with a six-bar linkage structure can be adjusted for planting at three seedling distances (20 cm, 25 cm, 30 cm) by selecting anchor points C_1, C_2 and C_3, respectively, while rice transplanters (Eam o-pas et al., 1988; Eam o-pas and Goto, 1990) can plant at two distances (20 cm, 30 cm). In addition, the new vegetable transplanting mechanism with a six-bar linkage structure could grow 36 plants/m^2 which was more than the soil-free culture capacity reported by Wattanapreechanon and Sukprasert (2012) of 25 plants/m^2. Therefore, this new transplanting mechanism could be applied to planting various kinds of vegetables. In addition, the results of the analysis and the field testing were similar, with the seedlings showing good subsequent growth. In conclusion, this new vegetable transplanting mechanism with its six-bar linkage structure could transplant vegetables into the ground effectively.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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