DESIGN AND EXPERIMENT OF DOUBLE-ROW WHEEL SELF-PROPELLED CHINESE CABBAGE HARVESTER

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双行轮式自走型大白菜收获机设计与试验

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ABSTRACT

Aiming at the problems of low harvesting level of Chinese cabbage, high cost of manual operation and lack of special harvesting machinery, a double-row wheeled self-propelled Chinese cabbage harvester was designed on the basis of measuring the physical parameters of 'Zaofeng 01'Chinese cabbage varieties and combining with the main local planting patterns. It can complete the root cutting, pulling, clamping and conveying, packing and collecting of double-row Chinese cabbage at one time. Through the design and selection of the key working parts of the double-row wheel self-propelled Chinese cabbage harvester prototype, the key working parameters of the profiling device, the root cutting-pulling device and the clamping conveying device were determined. The kinematics analysis of the harvester in the profiling, cutting, pulling, clamping and conveying links was carried out, and the field operation performance test of the prototype was completed. The results showed that: when the rotation speed of the cutter was 280 r/min, the rotation speed of the clamping conveyor belt was 240 r/min, and the forward speed of the machine was 1.44 km/h, the maximum qualified rate of harvesting was 95.08 %, the minimum value was 90.65 %, and the average value was 93.79 %. At this time, the working performance of the working machine is stable, the harvesting effect is good, and all performance indicators meet the relevant design requirements and standards. The research results can provide reference for the development and structural improvement of Chinese cabbage low-loss harvesting equipment.

摘 要

针对大白菜收获水平低、人工作业成本高、专用收获机械缺乏等问题，在测定“早丰 01”大白菜品种物理参数并结合当地主要种植模式基础上，设计了一种双行轮式自走型大白菜收获机，一次性可完成双行大白菜的切根、起拔、夹持输送、装箱收集等作业。通过对双行轮式自走型大白菜收获机样机关键作业部件进行设计选型，确定了仿形装置、切根-起拔装置、夹持输送装置的关键工作参数；对收获机在仿形、切根、起拔、夹持输送环节进行了运动学分析，并完成了样机田间作业性能试验。试验结果表明，当割刀转速为 280 r/min，夹持输送带转速为 240 r/min，机具前进速度为 1.44 km/h 时，采收合格率最大值为 95.08 %，最小值为 90.65 %，平均值为 93.79 %，此时作业机具工作性能稳定，收获效果良好，各项性能指标均达到相关设计要求和标准，研究成果可为大白菜低损收获装备开发及结构完善提供参考。

INTRODUCTION

Chinese cabbage is one of the staple vegetables in China. It has a wide range of cultivation areas. Because of its cold resistance, high yield, storage and transportation resistance, and long supply period, it is planted in all seasons in northern and southern China. The largest planting area is in the Yellow River Basin, and the smallest is in North China (*Zhang et al., 2021*). In recent years, the planting area of Chinese cabbage is stable at about 1.8 million hm^2, and the total output is about 3.4 million tons (*Cui et al., 2021; Yang et al., 2020)*. The cultivation of Chinese cabbage is rough, the planting mode is not uniform, and the individual differences of mature plants are large, which leads to the mismatch between the existing harvesting equipment and the planting agronomy, the high loss and damage of harvest, and the lack of special harvesting equipment designed for the physical characteristics of Chinese cabbage (*Cui et al., 2021; Bu L.X. et al., 2020; Zhou et al., 2023; Yao et al., 2007; Zhao et al., 2020*). At present, Chinese cabbage is still mainly harvested manually. Therefore, it is urgent to develop a special harvesting equipment for Chinese cabbage that can closely fit the Chinese cabbage planting specifications and achieve low-loss combined harvesting, in order to reduce production costs, reduce farmers' labor burden, and improve the economic benefits of the Chinese cabbage industry.

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Kanamitsu M. et al., (1994), developed a hand-held Chinese cabbage harvester. In order to improve harvesting efficiency and reduce harvesting damage, a tractor side-suspended Chinese cabbage harvester was designed on this basis. The harvester mainly includes a pulling device, a clamping conveying device and a root cutting device. The harvesting process mainly adopts the method of first pulling, then cutting and then transporting. *Kim H.J. et al., (2020),* of Chungnam University in South Korea developed a crawler self-propelled Chinese cabbage harvester, which uses double disc pulling device and double lateral clamping and conveying device to complete the functions of Chinese cabbage pulling, root cutting, conveying, header and so on. Aiming at the problems of easy blockage, leakage and high damage rate in the clamping and conveying process of Chinese cabbage harvester, the Agricultural Science Research Institute of Korea Rural Development Department (*Lee Y.S. et al., 2018),* simulated and optimized the conveying device and determined the suitable conveyor belt material. *Wang Shengsheng et al, (2021)*, designed a flexible threshing device for cabbage seeds with a combination of flexible round-ended spike teeth and circular tube concave plate. *Yao Huiling et al, (2007)*, designed a spiral lifting device and a disc cutter with good sliding cutting performance in combination with the mechanical properties of the local main Chinese cabbage varieties to ensure that the roots and stems of Chinese cabbage can be smoothly transported backwards after being cut. A crawler self-propelled single-line Chinese cabbage harvester was designed by *Zhang Jing et al (2022)*. The machine adopts the method of cutting root first and then pulling out. It can realize many operations such as root cutting, clamping, longitudinal transportation lifting, lateral transportation and lateral loading of Chinese cabbage at one time. The field test effect is good.

Due to the intensive scale planting mode, many countries have conducted extensive research on the operation mode and performance of Chinese cabbage harvesters, mainly focusing on Japan, South Korea and other countries (*Li, 2013*). In China, due to the policy orientation of vegetable production and the upgrading of agricultural machinery and equipment, as well as the improvement and perfection of the management system of Chinese cabbage production, universities and scientific research institutions have carried out independent innovation on the basis of absorbing foreign advanced scientific and technological methods, and have successively carried out series of exploration and research on the theory and equipment of Chinese cabbage harvesting (*Zheng, 2023*). In summary, in recent years, Chinese cabbage harvesting equipment has gradually developed towards the direction of joint harvesting operations, especially for commercially promoted models, which generally require harvesting functions to integrate multiple functions such as harvesting, containerization, and transportation. The whole machine is more efficient, automated, and intelligent. However, due to the problems of many Chinese cabbage cultivars, low standardization of cultivation modes, and extensive agronomic management, most of the above models remain in the laboratory or prototype stage and are not used for actual production promotion. The development and promotion of Chinese cabbage harvesters still have a long way to go.

In view of the above problems, this paper takes the main variety of Chinese cabbage 'Zaofeng 01' as the research object, and improves the suitable mechanization scheme based on the agronomic requirements of Chinese cabbage planting in Yucheng City, Shandong Province. A double-row wheel self-propelled Chinese cabbage harvester integrating profiling root cutting, flexible clamping and vertical conveying is developed. The key components such as profiling device, root cutting-pulling device, clamping and conveying device are designed, and the working performance of the prototype is tested in combination with field verification test, in order to improve the level of mechanized harvesting equipment for Chinese cabbage.

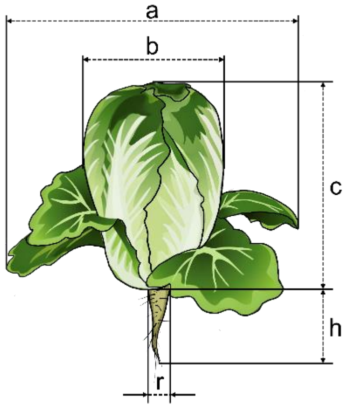
MATERIALS AND METHODS

Basic physical parameters and planting patterns of Chinese cabbage

- **Determination of basic physical parameters of Chinese cabbage**

In order to reduce the loss and improve the harvesting efficiency, the design of Chinese cabbage harvester needs to fully consider the basic physical parameters of Chinese cabbage. In this paper, the main cultivar of Chinese cabbage 'Zaofeng 0 ' was selected as the test object, and the basic physical parameters of 100 mature Chinese cabbages with no damage on the surface and complete rosette leaves and roots were selected by the principle of randomness, diagonal principle and classification principle. As shown in Figure 1, the measurement parameters include Chinese cabbage diameter, plant height, rhizome diameter, rhizome length, expansion degree and total mass.

The measurement results are shown in Table 1:



a - expansion degree; b - diameter; c - plant height; h - rhizome length; r - rhizome diameter

Fig. 1 - Determination of geometric characteristics of Chinese cabbage

Table 1

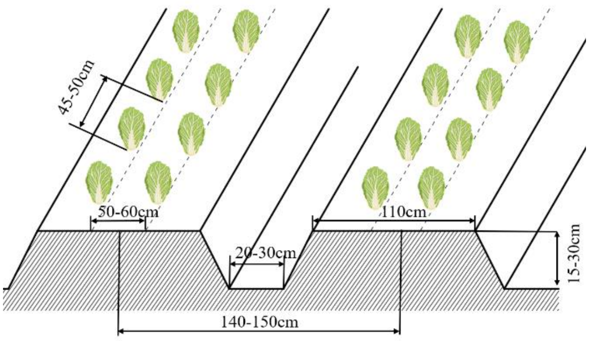
Measurement results of geometric characteristics of Chinese cabbage

Chinese cabbage cultivars	Statistical indicators	Expansion degree /mm	Diameter /mm	Plant height /mm	Rhizome length /mm	Rhizome diameter /mm	Total mass/kg
Zaofeng 01	Average value	543	155	164	60.55	28.36	2.77
	Maximum value	647	162	190	74.32	32.63	3.18
	Minimum value	438	148	138	50.68	42.57	2.35
	Standard deviation	104.5	7	3.41	11.87	7.29	0.42
	Coefficient of variation	0.19	0.05	0.07	0.20	0.26	0.15

- **Planting pattern**

There are two common planting patterns of Chinese cabbage: flat planting and ridge planting, ridge planting can provide a more stable growth environment for Chinese cabbage and reduce the adverse effects of external environmental factors on the quality of Chinese cabbage, such as soil erosion, weathering and water loss (*Tong.,2023; Wang.,2020*). At the same time, the Chinese cabbage in the ridge planting mode allows customizing the plant spacing and row spacing of Chinese cabbage according to the requirements of mechanized harvesting, reducing the hybrid and cross-growth between Chinese cabbage plants. This uniformity greatly improves the convenience of mechanized harvesting, thereby improving the harvesting efficiency of Chinese cabbage.

Therefore, combined with the local main varieties and planting patterns, the planting pattern of Yucheng City, Shandong Province was improved to obtain better mechanized harvesting effect. The specific planting requirements are as follows: Ridge planting, single ridge double row (ridge surface 1.1 m wide), row spacing 50-60 cm, plant spacing 45-50 cm (leaf expansion can cover all soil surface, reduce weed growth probability, reduce field management difficulty), ditch depth 15-30 cm, ditch width 20-30 cm.



(a). Planting pattern diagram

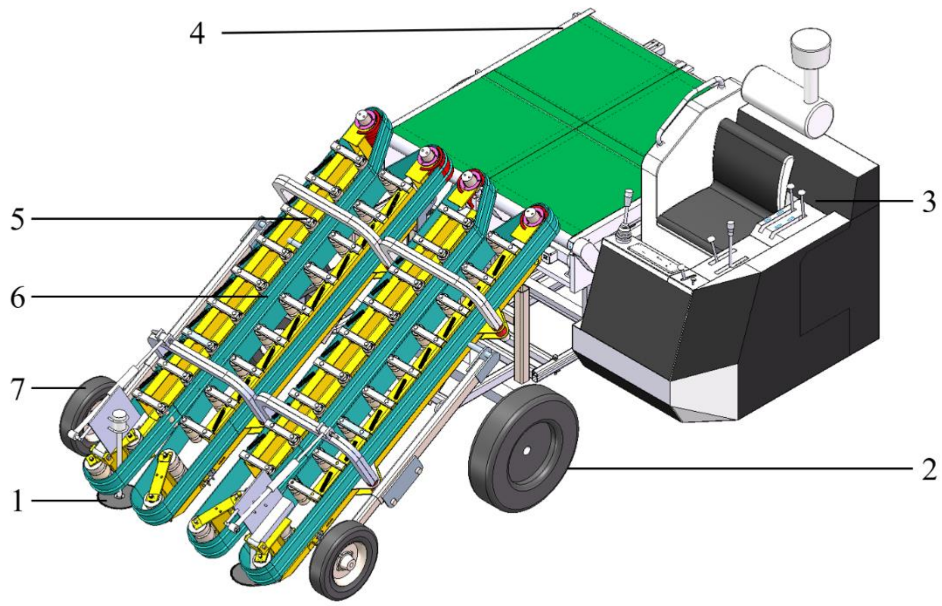
(b). Model for standardized cultivation

Fig. 2 - Ridge double row planting pattern diagram

The Complete machine structure and working principle of Chinese cabbage harvester

- **Complete machine structure**

The double-row wheeled self-propelled Chinese cabbage harvester is mainly composed of wheeled walking chassis, harvesting header and aggregate box. The Chinese cabbage harvesting platform is mainly composed of profiling device, root cutting-pulling device, clamping and conveying device, hydraulic transmission system and so on. The harvesting platform is placed on the wheeled walking chassis, hinged by the three-point suspension structure, and arranged longitudinally based on the symmetrical center surface. The schematic diagram of the whole structure of the Chinese cabbage harvester is shown in Figure 3.



1 - root cutting device; 2 - guide wheel; 3 - cockpit; 4 - transverse conveying platform; 5 - tension pulley; 6 - clamping conveyor belt; 7 - profiling device

Fig. 3 - Double wheel self-propelled Chinese cabbage harvester machine structure diagram

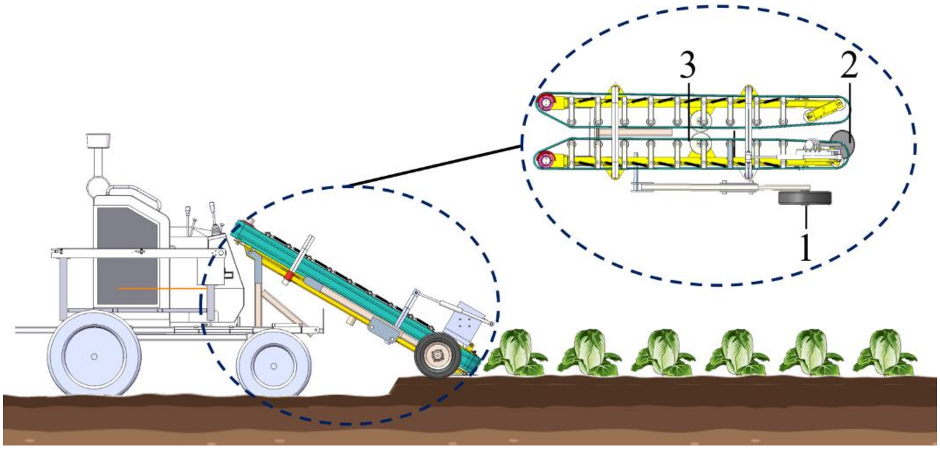
Table 2

Main parameters of harvester

Technical Parameters	Numerical Value
Structural Forms	Self-propelled on wheels
Overall dimensions (L×W×H)/mm	4100×2200×2500
Auxiliary Power kW	45
Walking Speed/(km·h^{-1})	2～3
Number of Rows Harvested/-	2
Harvesting Row Spacing /mm	450～650
Working Width /mm	1400
Machine weight /kg	1640

- **Working Principle**

The working area of the harvesting cutter is mainly divided into three parts: the profiling area, the root cutting-pulling area and the clamping conveying area. When the harvester is working, the height of the cabbage harvester cutting table needs to be adjusted first, so that the cutting tool is close to the ground, so that the roots can be cut accurately. During the whole operation process, the engine of the traveling chassis drives the directly connected hydraulic pump, which controls the hydraulic motors of the different working parts through the electronically controlled valve group. These hydraulic motors drive the various parts of the harvesting cutter to work in unison to realize a series of functions such as lifting, root cutting, gripping, conveying and collecting the cabbage. The whole process ensures effective cabbage harvesting and improves work efficiency at the same time.



1 - profiling area; 2 - root cutting- lifting area; 3 - clamping and conveying area

Fig. 4 - Working Principle

Profiling Area: in the process of advancing, the machine moves along the contour of the terrain and adapts to the changes in the undulation of the ground so that the cutter is always close to the ground, ensuring the consistency of cutting roots and improving the quality and efficiency of harvesting.

Root Cutting-Lifting Area: when the machine works, the cutter is attached to the land surface, placed under the cabbage outer wrapping leaves, through the synergistic effect of the machine forward and the cutter rotation, the cabbage is subjected to upward sustained traction, prompting the roots to separate from the soil, so as to complete the cabbage pulling up and cutting the root operation.

Clamping and Conveying Area: after completing the root cutting and pulling operation, the cabbage is steadily gripped and lifted by the tensioning mechanism and the clamping conveyor belt, this process is designed to reduce the risk of mechanical damage to the cabbage during the conveying and lifting phase and to smoothly feed the cabbage to the transverse conveying platform to complete the collection operation after removing the excess outer leaves of the cabbage.

Design of key components of Chinese cabbage harvester

- **Profiling device**

Profiling is the key process in the harvesting process of Chinese cabbage. Because the soil quality of Chinese cabbage growing environment is relatively soft, the ridge height and ridge surface fluctuate greatly. Therefore, a profiling device is designed to realize the real-time adjustment of the position of the harvesting header with the fluctuation of the ridge surface, so as to avoid the body tilt caused by the wheel sinking caused by the self-weight during the cross-ridge operation and the phenomenon that the position of the cutter is too high or too low during the harvesting process, which leads to the cutting of Chinese cabbage and the incomplete cutting of Chinese cabbage. The structure diagram and physical diagram of the profiling device are shown in figure 5.

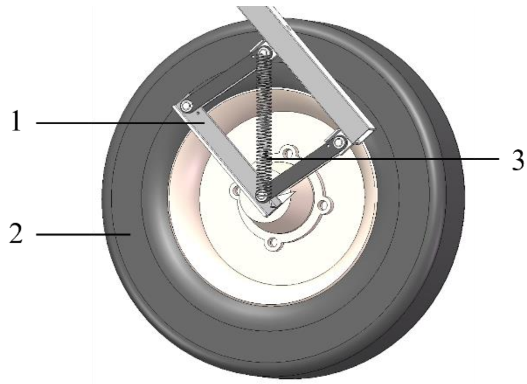


Fig. 5 - Schematic diagram of the structure of the profiling device

1 - profiling brackets; 2 - profiling wheel; 3 - profiling sprung

- **Swing arm design for profiling device**

In order to make the Chinese cabbage harvester cutting platform for harvesting operations as smooth as possible, the requirements of the imitation wheel force change as little as possible. The imitation device force sketch is shown in Figure 6, and the force equilibrium conditions are:

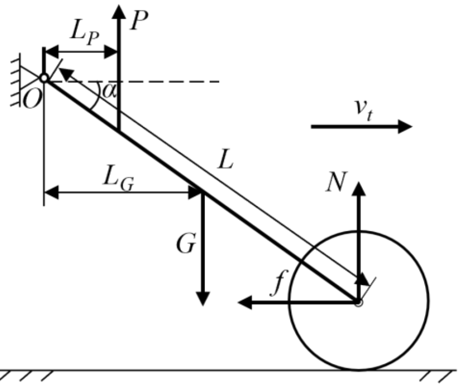


Fig. 6 - Force analysis diagram of the profiling device

$$\begin{cases} PL_P + NL\cos\alpha = GL_G + fL\sin\alpha \\ f = \mu N \\ F = \sqrt{N^2 + f^2} = N\sqrt{1+\mu^2} \end{cases} \tag{1}$$

It can be obtained from Equation (1):

$$F = \frac{GL_G - PL_P}{L(\cos\alpha - \mu\sin\alpha)}\sqrt{1+\mu^2} \tag{2}$$

where: P is the balance spring tension, [N];

N is the positive pressure of the ground on the profiling wheel, [N];

f is rolling resistance of profiling wheel, [N];

G is overall gravity of profiling device, [N];

μ is coefficient of rolling resistance;

F is the force of ground on profiling wheel, [N];

L is harvesting header length, [mm];

L_P is force arm of spring tension *P* to *O* point;

L_G is the force arm of the profiling device to point *O* as a whole;

α is the cutting table that can adjust the swing angle, [°].

It can be seen from Equation (2) that the force F of the ground to the profiling wheel is mainly related to the overall gravity G of the profiling device, the length L of the harvesting header and the swing angle *α* of the header. The overall gravity of the profiling device and the length of the harvesting header are fixed values. The position where the profiling wheel falls into the low-lying road and is not affected by the ground force is taken as the maximum force position of the profiling spring. At this time, the tension P of the profiling spring is balanced with the gravity G of the profiling device. In order to make the harvesting header work smoothly, the smaller the variation range of F should be, the smaller the variation range of the adjustable swing angle *α* of the header should be.

According to the design requirements of agricultural equipment profiling range requirements (*China Academy of Agricultural Mechanization Sciences. Handbook of Agricultural Machinery Design: Volume II*), the upper and lower profiling amount is generally ± (8 ~ 12) cm. As shown in Figure 7, when the harvesting header is at the upper and lower limit positions, the total profiling quantity can be expressed as:

$$h = L[\sin(\Delta\alpha_1 + \alpha_0) + \sin(\Delta\alpha_2 - \alpha_0)] \tag{3}$$

where: α_0 is the initial angle of adjustable swing arm of harvesting cutting table, [°];

$\Delta\alpha_1$ is the change from the initial position of the harvesting cutting table to the lowest swing Angle, [°];

$\Delta\alpha_2$ is the change from the initial position of the harvesting cutting table to the highest swing Angle, [°].

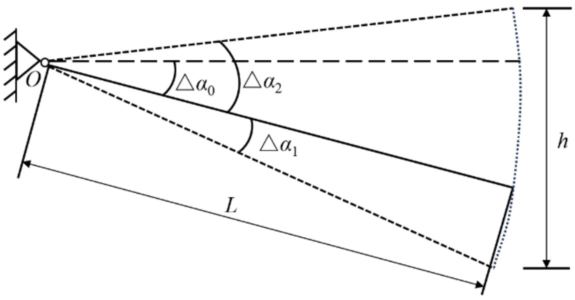


Fig. 7 - Harvesting cutting table contour diagram

According to Equation (2) and (3), under the condition that the total copying quantity *h* is constant, the longer the swing arm of the harvesting cutting table, the smaller the variation range of the adjustable swing Angle *α*, and the smaller the variation range of the force *F* of the ground facing the copying wheel, the more stable the harvesting cutting table will be during the harvesting operation. Therefore, in order to ensure the harvesting effect and the more stable the position change during the cutting table copying, the length of the swing arm of the copying device of Chinese cabbage harvesting cutting table designed in this paper is 1800 mm.

- **Contour wheel diameter design**

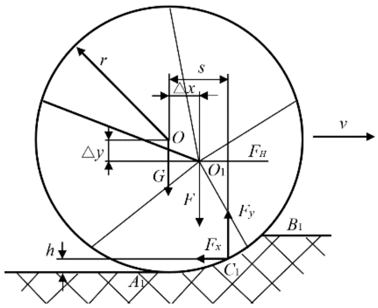


Fig. 8 - Force diagram of profiling wheel

The profiling effect of profiling wheel has a great correlation with its own diameter. The smaller the diameter is, the shorter the profiling time is, and the profiling effect is not ideal. If the diameter is too large, it is easy to produce the phenomenon of soil dragging.

In order to determine the reasonable diameter of the profiling wheel, it is necessary to analyze the force of the profiling wheel during the operation process. The schematic diagram of the force analysis is shown in Figure 8.

According to the torque relationship, it can be obtained :

$$\begin{cases} H(r-\Delta y) - F\Delta x + R_x h + R_y s = 0 \\ Gs - F(s-\Delta x) - H(r-\Delta y) = 0 \end{cases} \tag{4}$$

It can be obtained from Equation (4):

$$H(r-\Delta y) = F\Delta x - R_x h - R_y s = Gs - F(s-\Delta x) \tag{5}$$

where: F_H is the tractive force, [N];

G is the profiling wheel gravity, [N];

R is the profile wheel radius, [mm];

F is the gravity load of profiling wheel, [N];

h is the depth of subsidence from point C to the lowest point, [mm];

s—when the contour wheel sinks *h*, the forward length of the wheel, [mm];

F_x is the horizontal ground reaction force, [N];

F_y is the vertical ground reaction force, [N];

*v is t*ool forward speed, [m/s];

Δx is the horizontal distance from the original center when copying the profile wheel, [mm];

Δy is the vertical distance from the original center when copying the profile wheel, [mm].

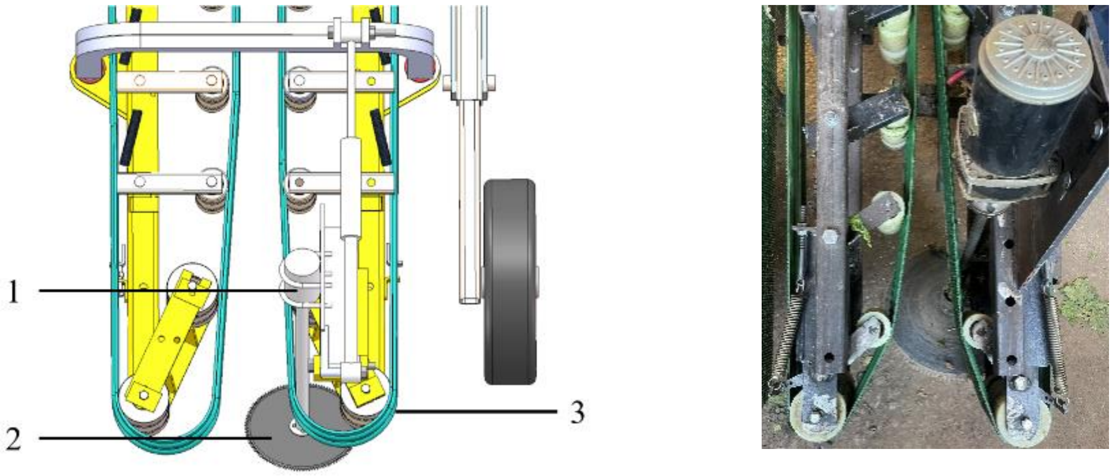
It can be seen from Equation (12) that when the traction and load are constant, at a certain speed, the eccentric distance of the central axis, that is, Δx and Δy is constant without considering the vibration of the spring. Under this condition, the smaller the wheel diameter is, the smaller the forward length s of the profiling wheel is, the smaller the profiling time t is, and the profiling effect is not ideal, which will lead to the phenomenon that the root cutting position is too high or too low. Therefore, the diameter of the profiling wheel is generally 200-500 mm (*Hu et al., 1996*). At the same time, in order to ensure that the profiling mechanism inside the profiling wheel has enough profiling stroke, the diameter of the profiling wheel is determined to be 400 mm after comprehensive consideration and analysis.

Design of root cutting-pulling device

- **Root cutting device design**

When the machine is pulling-cutting, the cutter is attached to the surface of the land. As the machine continues to move forward, the cutter extends into the bottom of the Chinese cabbage and rotates inward. After the front end of the clamping conveyor belt contacts the Chinese cabbage, the root of the Chinese cabbage is separated from the soil under the synergistic effect of the cutter and the front end of the conveyor belt, and the pulling-cutting operation of the Chinese cabbage is completed.

The root cutting device is shown in figure 9. Based on the planting mode of Chinese cabbage and the geometric size characteristics of the root of Chinese cabbage designed in this paper, a single disc saw-tooth root cutting device is adopted in this paper. In the cutting process, the saw-tooth disc cutter has the advantages of low speed drop value, high cutting ratio and high root cutting quality compared with other forms of disc cutter. It is installed at the center position deviating from the Chinese cabbage clamping and conveying route, in order to minimize the stress imbalance of Chinese cabbage in the cutting process.

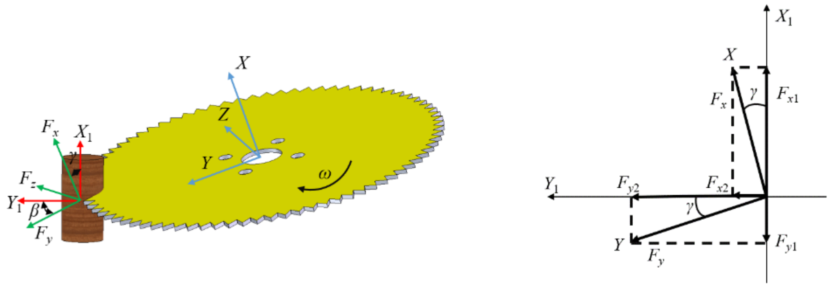


(a). 1 - root cutting device motor; 2 - saw-tooth disc cutter; 3 - clamping device. *(b). The physical diagram of the root cutting device*

Fig. 9 - Root cutting device

In the process of root cutting, the Chinese cabbage rhizome is subjected to the root cutting force F_x, F_y, F_z in the three directions of *X* axis, *Y* axis and *Z* axis, as shown in Figure 10a, and the stress analysis on the *X* axis and *Y* axis is shown in Figure 10b.

Due to the combined action of the cutter and the front end clamping force of the conveyor belt in the *Z* axis direction, most of the root cutting forces offset each other, but there is still a part of the cutting ability F_z. It can be seen from Figure 10b that the total longitudinal component force in the X_1 axis direction is the sum of the two components F_{x1} and F_{y1} in the opposite direction, so the total longitudinal component force is small, while the extraction of Chinese cabbage requires a large extraction force, and the rhizome is not easy to be pulled out. The total transverse component force on the Y_1 axis is the sum of the two component forces F_{x2} and F_{y2} with the same direction, and the total transverse component force is larger. Because the pitch angle γ is small, it can be seen that F_{x2} is small, so the total lateral component is mainly determined by F_{y2}, that is, it is mainly determined by F_y. Therefore, F_y can be approximated as a root-cutting force. In addition, considering the actual installation and use, the angle β of the vertical plane is set to zero, and only the influence of the same pitch angle γ is considered in order to determine the best cutting parameters.



(a). Three-dimensional force analysis *(b). Force analysis of X and Y axis direction*

Fig. 10 - Stress analysis diagram of Chinese cabbage rhizomes

The quality of Chinese cabbage root cutting is closely related to the root cutting force (*Jiang., 2013*). Therefore, by designing reasonable structural parameters of the cutting disc cutter and selecting the appropriate cutting angle, the stability of root cutting can be ensured. As shown in Figure 11, the Chinese cabbage rhizome to be cut is idealized as a positive circle, and its diameter is idealized as D_1. When the serrated disc cutter works, the serrated mouth at the edge will clamp and cut the Chinese cabbage root. Combined with Figure 10b, the cutting force R_x and the clamping force Q_y are analyzed by the force analysis in the figure.

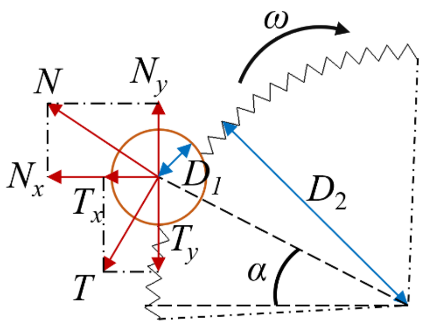


Fig. 11 - Force analysis diagram of root cutting process

The following equations are obtained by orthogonal decomposition:

$$F_y = R_x \tag{6}$$

$$\begin{cases} R_x = T_x + N_x \\ Q_y = T_y - N_y \end{cases} \tag{7}$$

where:

N -the horizontal component of the normal reaction force of the cutter on the rhizome is N_X, and the vertical component is N_Y, [N];

T - the horizontal component of the friction force of the cutter is T_X, and the vertical component T_Y, [N];

In order to make the Chinese cabbage rhizome be held by the cutter, the following conditions need to be met:

$$Q_y > 0 \tag{8}$$

It can be referred that $T_y > N_y$, and $T = N \cdot f$, which means:

$$N\cdot f\cos\alpha > N\cdot f\cos\alpha \tag{9}$$

At this time, when $f > \tan\alpha$, saw-tooth disc cutter has good clamping performance:

$$\alpha = \arccos\frac{D_2}{D_2 + D_1} \tag{10}$$

where:

f is the friction coefficient between disc cutter and Chinese cabbage rhizomes, generally taking 0.4~0.7;

α is the angle between the normal reaction force of disc cutter on Chinese cabbage rhizome and X axis, [°];

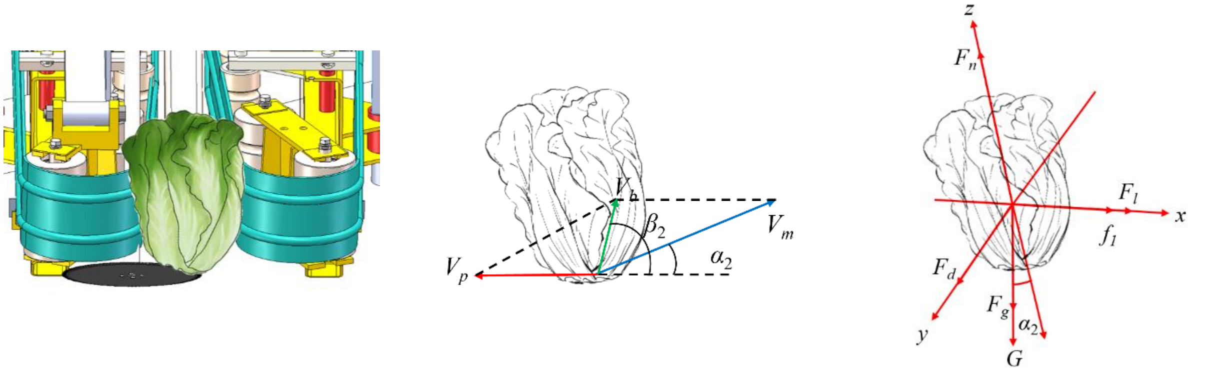
D_1 is the diameter of the root of Chinese cabbage at the cutting place, [mm];

D_2 is the diameter of disc cutter, [mm].

In order to avoid the incomplete cutting of Chinese cabbage roots, the cutter keeps a certain distance from the conveying structure, so as to ensure the flatness and integrity of the roots. The diameter of the cutter head of the disc cutter designed in this paper is 225 mm, and the angle ' α ' ≈ 31.02°. At this time, $f > \tan\alpha$, which can well meet the requirements of clamping performance.

- **Motion Analysis of Pulling Process**

After the Chinese cabbage is cut by the cutter clamp, the Chinese cabbage is successfully completed under the synergistic effect of the front end of the conveyor belt and the internal rotation of the cutter, and is clamped by the conveyor belt for longitudinal lifting movement. The speed and force analysis of the Chinese cabbage pulling process are shown in Figure 12:



(a). Schematic diagram of lifting process *(b). Pull-up speed analysis diagram* *(c). Force analysis of pulling process*

Fig. 12 - Analysis diagram of lifting process

Figure 12b shows the speed analysis diagram of Chinese cabbage during the pulling process. The direct relationship between speed and angle is as follows:

$$V_m \cos\alpha_2 > V_p \tag{11}$$

The movement of Chinese cabbage was analyzed, and the speed synthesis relationship of Chinese cabbage was as follows:

$$\vec{V}_b = \vec{V}_m + \vec{V}_p \tag{12}$$

According to the trigonometric function relationship, the following relationship can be obtained:

$$\frac{V_m}{V_p} = \frac{\sin\beta_2}{\sin(\beta_2 - \alpha_2)} = K \tag{13}$$

where:

V_p is the forward speed of Chinese cabbage harvester, [m/s];

V_m is the clamping speed of lower clamping, [m/s];

V_b is the moving speed of Chinese cabbage, [m/s];

α_2 is the angle between the working part of Chinese cabbage harvester and the ground, [°];

β_2 is the angle between the absolute speed of Chinese cabbage and the ground, [°].

According to the Equation (13), when K is less than 1, the β_2 angle is greater than 90°, which will lead to a forward movement trend of Chinese cabbage, resulting in a deviation of the cutting position. When K is greater than 1, β_2 is less than 90°, which will lead to a certain angle of Chinese cabbage plant tilted backwards, so that the axis of Chinese cabbage is perpendicular to the linear position where the header is located, which can improve the harvesting quality.

Therefore, the angle between the header and the ground of the Chinese cabbage harvester designed in this paper is 15°, and the K value is greater than 1, which meets the design requirements.

Figure 12c shows the force analysis when the cutter extends into the bottom of the Chinese cabbage and the conveyor belt holds the root of the Chinese cabbage during the pulling process of the Chinese cabbage:

$$\begin{cases} \sum F_x = F_d + f_1 - F_g \sin\alpha_2 - G\sin\alpha_2 \\ \sum F_z = F_n - G\cos\alpha_2 - F_g \cos\alpha_2 \end{cases} \tag{14}$$

Further derived:

$$\begin{cases} \sum F_x = 2\mu_1 F_d + \mu_2 F_n - F_g \sin\alpha_2 - mg\sin\alpha_2 \\ \sum F_z = F_n - mg\cos\alpha_2 - F_g \cos\alpha_2 \end{cases} \tag{15}$$

In order to make the Chinese cabbage be able to be pulled up smoothly, the conditions that need to be met are that the force of the Chinese cabbage in the *x* direction is greater than or equal to 0, and the force in the *z* direction is equal to 0. In the *z* direction, the Chinese cabbage is supported by the cutter to the Chinese cabbage. Force F_n and its own gravity G, soil cohesion F_g in the *z* direction, and F_n is a reaction force, its size changes with the change of the gravity of the Chinese cabbage and soil cohesion, so the force balance of Chinese cabbage in the *z* direction:

$$\begin{cases} 2\mu_1 F_d + \mu_2 F_n - F_g \sin\alpha_2 - mg\sin\alpha_2 \ge 0 \\ F_n - mg\cos\alpha_2 - F_g \cos\alpha_2 = 0 \end{cases} \tag{16}$$

Further derived:

$$\mu_2 \ge \frac{\sin\alpha_2 \left(F_g + mg\right) - 2\mu_1 F_d}{\cos\alpha_2 \left(F_g + mg\right)} \tag{17}$$

where:

F_n is the Chinese cabbage in the process of being pulled out by the cutter to the Chinese cabbage plant support, [N];

f_1 is the friction force on Chinese cabbage due to cutter rotation, [N];

F_d is the extrusion Pressure of Conveyor Belt on Root of Chinese Cabbage, [N];

F_l is the pulling force of conveyor belt on Chinese cabbage, [N];

F_g is the soil Adhesion to Chinese Cabbage, [N];

G is the gravity of Chinese cabbage itself, [N];

μ_1 is the friction coefficient between Chinese cabbage and conveyor belt;

μ_2 is the friction coefficient between Chinese cabbage and cutter;

m is the quality of Chinese cabbage itself, [kg].

It can be seen from Equation (17) that the friction force of the cutter on Chinese cabbage is proportional to the support force. When the cutter inclination angle α_2 is 15°, the success rate of Chinese cabbage pulling and root cutting is the highest.

In summary, the saw-tooth disc cutter designed in this paper has a diameter of 225 mm, a thickness of 3 mm, a material of 65 Mn, and a cutter inclination angle of 15°. At this time, $f > \tan\alpha$, which can well meet the requirements of lifting and root cutting operations.

- **Design of clamping conveying device**

The double-row Chinese cabbage harvester designed in this paper adopts the new mechanism and new method of "vertical clamping with flexible conveying", and adopts the loss reduction method of flexible feeding and flexible clamping to improve the adaptability of Chinese cabbage with different ball diameters and realize the low loss conveying of Chinese cabbage.

The analysis of the movement process of Chinese cabbage in the clamping and conveying device is shown in figure 13, of which '1' is the Chinese cabbage feeding link, '2' is the clamping and conveying link, and '3' is the conveying and harvesting finished product link.

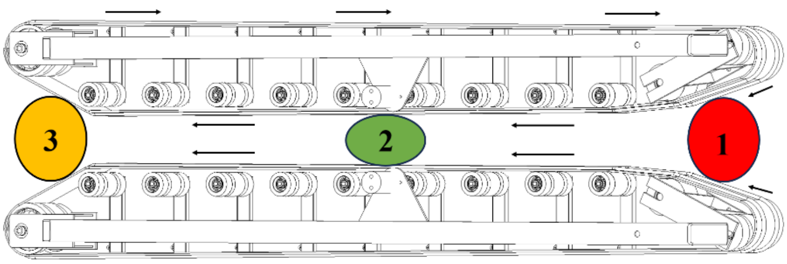
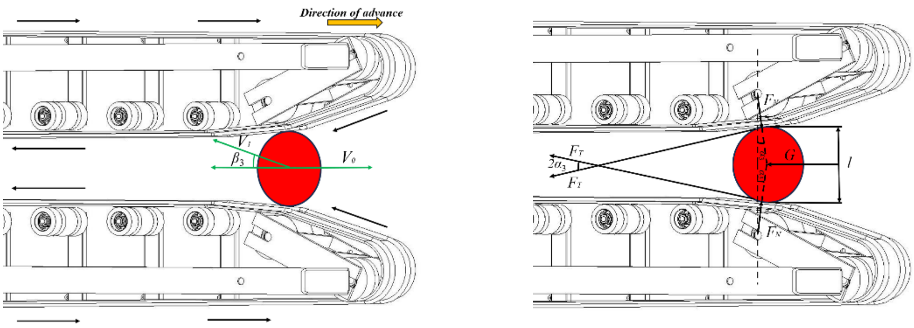


Fig. 13 - Chinese cabbage clamping conveying process

The motion analysis and force analysis of the Chinese cabbage feeding link are shown in Figures 14a and 14b.



(a). Motion analysis of feeding link *(b). Force analysis of feeding link*

Fig.14 - Chinese cabbage feeding process

In order to make Chinese cabbage pass through the feeding inlet smoothly and enter the clamping and conveying device without blockage in the feeding link, the following conditions need to be met:

$$V_1 \sin\beta_3 > V_0 \tag{18}$$

$$\tan\alpha_3 \le \frac{F_T}{T_N} = \mu \tag{19}$$

Further derived:

$$\mu \ge \sqrt{\frac{(D+d)^2-(D+l)^2}{(D+l)^2}} \tag{20}$$

where:

V_1 is the clamping conveyor belt line speed, [m/s];
β_3 is the clamping conveyor belt lifting angle, [º];
α_3 is the angle between the extrusion pressure of Chinese cabbage and the horizontal direction, [º];
V_0 is the machine operation speed, [m/s];
F_T is the frictional force, [N];
F_N is the clamping conveyer tensioning wheel pressure on Chinese cabbage, [N];
μ is the Clamping conveyor belt and Chinese cabbage friction coefficient;
D is the tension wheel diameter, [mm];
d is the diameter of Chinese cabbage, [mm];
l is the tension wheel spacing, [mm].

The clamping position of the feeding inlet of the clamping conveyor should be the waist of Chinese cabbage. In this study, 'Zaofeng 01' Chinese cabbage was used as the research object. The single plant weight was 2.3~2.7 kg, and the ball diameter was 140~180 mm. The feeding inlet spacing of the clamping conveyor designed in this study was set to be adjustable spring type, and the minimum spacing was 120 mm. Therefore, the friction coefficient between the clamping conveyor belt and Chinese cabbage can be obtained by calculation:

$$\mu \ge \sqrt{\frac{(120+180)^2-(120+140)^2}{(120+140)^2}} = 0.57 \tag{21}$$

The maximum extrusion pressure of Chinese cabbage is:

$$F_{N\max} = 2 \times \frac{G}{\mu} = 87.72N \tag{22}$$

At this time, the maximum extrusion pressure is far less than the extrusion pressure of 1166.06 N when the Chinese cabbage is damaged (*Zhang, 2022*), so the design of the clamping conveying device is reasonable.

The deformation of Chinese cabbage when clamping the conveying device interval is shown in Figure 15, and the local deformation of Chinese cabbage in the figure is analyzed as shown in Figure 16.

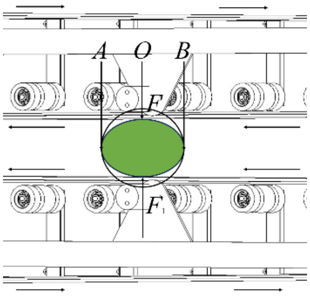


Fig.15 - Chinese cabbage pinching link deformation diagram

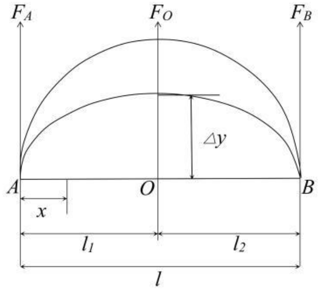


Fig.16 - Local deformation diagram of Chinese cabbage

It can be seen from Figure 15 that the extrusion force of Chinese cabbage at point *O*, the force of point *A* and point *B* are F_A and F_B respectively:

$$F_A = F_B = \frac{Fl_1}{l} \tag{23}$$

According to the equilibrium equation, the reaction force of point *O* is:

$$F_O = \frac{Fl_2}{l} \tag{24}$$

The deformation bending moment of Chinese cabbage is obtained as follows:

$$M_x = \frac{Fl_2}{l}x - F\left(x - l_1\right) \qquad \left(l_1 \le x \le l\right) \tag{25}$$

In the ideal state, the bending moment on both sides of Chinese cabbage is the same, so the bending moment on one side is integrated:

$$EJ\frac{d^2y}{dx^2} = \frac{Fl_2}{l}x \tag{26}$$

The winding curve equation can be obtained as follows:

$$y = \frac{Fl_2x}{6lEJ} = x^2 - l_2{}^2 + l^2 \text{ b} \tag{27}$$

Because $x = l_1 = l_2$, so the Chinese cabbage clamping deformation deflection Δy is:

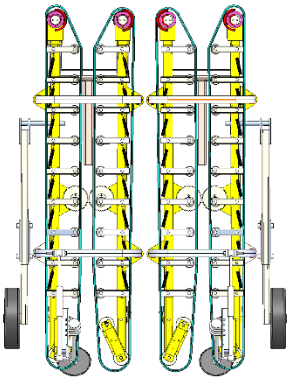
$$\Delta y = \frac{Fl_2l_1l}{6EJ} \tag{28}$$

where: E is the elastic modulus;
J is the moment of inertia;
l is the length of *AB*, [mm];
l_1 is the length of *AO*, [mm];
l_2 is the length of *BO*, [mm].

According to Equation (18), the speed of conveyor belt is closely related to the working speed of the machine. If the speed of conveyor belt and the working speed are too low, the conveying efficiency will be reduced, which will cause the feeding inlet to be blocked, resulting in the subsequent clamping not smooth, and the qualified rate of Chinese cabbage harvest will be reduced.

According to the preliminary experimental observation, the damage forms of Chinese cabbage in the process of clamping and conveying mainly include extrusion, wear, collision and other forms. The main reason is that the deformation of Chinese cabbage is too large under the action of belt, tension wheel and other components in the process of clamping and conveying, which in turn makes the deformation deflection Δy of Chinese cabbage larger, and Chinese cabbage is easy to be damaged, thus reducing the qualified rate of harvest. It can be seen from Equation (28) that the deformation deflection of Chinese cabbage is related to the elastic modulus. In order to minimize the damage of Chinese cabbage, the clamping and conveying device selects the conveyor belt of *XNBR* flexible material for clamping and conveying, as shown in Figure 17. While reducing the friction with Chinese cabbage, the deformation of Chinese cabbage by the tensioning mechanism is transferred to the flexible conveyor belt. In the process of clamping and conveying, the flexible conveyor belt absorbs part of the deformation deflection, and the deformation deflection of Chinese cabbage also becomes smaller, which plays a certain role in preventing damage to Chinese cabbage, and ensures that Chinese cabbage will not slide during the clamping and conveying process.

As shown in Figure 17, the center spacing of the Chinese cabbage clamping and conveying device designed in this paper is adjustable to a maximum of 240 mm, and the spacing of the feeding mechanism is between 140-200 mm, so as to ensure that the Chinese cabbage with different ball diameters passes through the clamping and conveying device smoothly.



(a). Clamping conveying mechanism

(b). Clamping conveying mechanism physical diagram

Fig.17 - Clamping device

Field experiment of Chinese cabbage harvester

- **Test condition**

As shown in Figure 18, the prototype of the double-row wheel self-propelled Chinese cabbage harvester developed in this paper was tested in Yucheng City, Shandong Province on November 16, 2023. The test site adopts the single ridge double row planting mode designed in this paper (ridge surface 1.1 m wide, row spacing 50~60 cm, plant spacing 45~50 cm, ditch depth 15~30 cm, ditch width 20~30 cm).

The test object was ' Zaofeng 01 '. It took about 90 days from planting to harvest. The mature Chinese cabbage plant expansion was about 450~510 mm, the ball height was about 260~280 mm, the outer leaf was about 10~12 pieces, and the single ball quality range was 2.1~2.4 kg. Suitable for fertile clay loam or alluvial soil, soil pH value of about 6~7 is appropriate.

(a). Harvesting operation

(b). Planting pattern

Fig.18 - Field test

- **Test method**

Before the harvesting operation of the Chinese cabbage harvester, according to the Chinese cabbage varieties and planting patterns in the test site, the distance between the feeding inlets of the Chinese cabbage harvester and the height from the ground were adjusted, and the pre-test was carried out in the vegetable field outside the test site to ensure that the structure of the key components of the Chinese cabbage harvester remained optimized.

There are no relevant standards and regulations for the mechanical harvesting of Chinese cabbage. Therefore, this test refers to the Heading Chinese Cabbage Production Technical Specification (GB/Z26582-2011), combined with the Beet Harvesting Machinery Test Method (JB/T 6276-2007) and other relevant national standards. The relevant indicators of the test method select the harvesting pass rate as the standard for the harvesting test.

Mechanized harvesting standard of Chinese cabbage: When the Chinese cabbage leaf ball reaches tight real-time harvesting, 2 outer leaves (rosette leaves) are retained to protect the leaf ball during harvesting, so that the epidermis is clean without damage and no crack ball.

Harvest qualification rate: According to the production technical specifications of Chinese cabbage and the harvest quality requirements of stem and leaf vegetables, the harvest qualification rate of Chinese cabbage must meet the following conditions : (1) The mechanical root cutting section must be flat and cannot be broken or cut out of two sections; (2) The cutting position should be 15-20 mm above the outer leaf of Chinese cabbage, and the outer leaf should be cut off at the same time; (3) After harvest, 2-3 outer leaves were retained to protect the head; (4) There is no obvious cracking ball, extrusion damage, cutting damage and so on caused by mechanical harvesting operation. The formula of qualified rate of harvesting is as follows:

$$N = \frac{N_1}{N_0} \times 100\% \tag{29}$$

where: N is the harvest qualified rate, [%];

N_1 is the single determination test harvest Chinese cabbage qualified number, [tree];

N_0 is the total number of Chinese cabbages in single determination test, [tree].

Combined with the pre-test harvesting effect, the rotation speed of the cutter was adjusted to about 280 r/min, and the rotation speed of the clamping conveyor belt was about 240 r/min. Under the same test conditions, the forward speed of the machine was 1.08 km/h, 1.44 km/h, and 1.80 km/h, respectively. Three groups of field harvesting performance verification tests were carried out. In each test, the ridge surface with excellent growth status of Chinese cabbage was selected (about 60 m in length), and about 240~260 Chinese cabbages were planted on each ridge. Each group of tests was repeated five times. The number of qualified Chinese cabbages and the number of damages were counted, and the qualified rate and damage rate of harvest were calculated.

RESULTS AND DISCUSSION

Design results of key components of Chinese cabbage harvester

- **Design results of profiling device**

In order to realize the harvesting cutting platform with the ridge surface undulation real-time position adjustment, to avoid that the cutter position is too high or too low to cause the Chinese cabbage cut scattered and too low to cause the Chinese cabbage cut root incomplete phenomenon, this paper design of the Chinese cabbage harvesting cutting platform profiling device swing arm length of 1800 mm. At the same time, in order to ensure that the profiling wheel inside the profiling mechanism has enough profiling stroke, the profiling wheel diameter was determined to be 400 mm.

- **Design results of root cutting-pulling device**

In order to reduce the force imbalance in the process of cutting-pulling and improve the Chinese cabbage harvest qualification rate, a single disc saw-tooth root cutting device is adopted in this paper. In the cutting process, the saw-tooth disc cutter has the advantages of low speed drop value, high cutting ratio and high root cutting quality compared with other forms of disc cutter, the saw-tooth disc cutter designed in this paper has a diameter of 225 mm, a thickness of 3 mm, a material of 65 Mn, and a cutter inclination angle of 15°. At this time, $f > \tan\alpha$, which can well meet the requirements of lifting and root cutting operations.

- **Design results of clamping conveying device**

The double-row Chinese cabbage harvester designed in this paper adopts a new mechanism and new method of ' vertical clamping + flexible conveying '. In order to improve the adaptability of Chinese cabbage with different ball diameters and minimize the damage of Chinese cabbage, the material of the conveying device in this paper is *XNBR* flexible material. At the same time, the center spacing of the Chinese cabbage clamping and conveying device designed in this paper is adjustable to a maximum of 240 mm, and the spacing of the feeding mechanism is between 140-200 mm, so as to ensure that Chinese cabbage with different ball diameters passes through the clamping and conveying device smoothly.

Field experiment statistics and analysis of test results

When the forward speed of Chinese cabbage harvester is 1.08 km/h, 1.44 km/h and 1.80 km/h, the harvesting results are shown in Table 3.

Table 3

Harvesting test results statistics

Operating speed / km·h^{-1}	Serial number	Total number of test Chinese cabbage / tree	Number of cut-offs / tree	The number of split balls, abrasions, etc. /tree	Total number of damage / tree	Harvest qualified /tree	Harvest qualified rate /%
1.08	1	258	4	14	18	240	93.02
	2	246	6	17	23	223	90.65
	3	227	9	5	14	213	93.83
	4	272	8	15	23	249	91.54
	5	246	5	15	20	226	91.87
	mean value						92.18
1.44	1	244	4	11	15	229	93.85
	2	238	3	12	15	223	93.70
	3	269	7	13	20	249	92.57
	4	257	6	10	16	241	93.77
	5	264	7	6	13	251	95.08
	mean value						93.79
1.80	1	242	3	25	28	214	88.43
	2	265	5	18	23	242	91.32
	3	284	9	30	39	245	86.27
	4	246	7	17	24	222	90.24
	5	229	4	16	20	209	91.27
	mean value						89.51

Discussion

According to the data of the harvesting test in Table 3, when the Chinese cabbage harvester was harvested at the forward speed of 1.08 km/h and 1.44 km/h, the qualified rate of Chinese cabbage harvest was greater than 90%, the maximum value was 95.08%, the minimum value was 90.65%, and the average qualified rate of harvest was 92.18% and 93.79% respectively. When the working speed of Chinese cabbage harvester was 1.80 km/h, the qualified rate of Chinese cabbage began to decline, with the maximum value of 91.32% and the minimum value of 86.27%. Analyze the reasons: when the machine operation speed is slow and moderate, at this time, the working parameters of the key components of the Chinese cabbage harvester are matched with the working speed of the machine, and the fit is high, so the qualified rate of Chinese cabbage harvesting is high ; when the operating speed of the Chinese cabbage harvester increases to 1.80 km/h, the operating speed of the machine is too fast, and the working time of the Chinese cabbage harvester is less when harvesting the Chinese cabbage, resulting in the previous Chinese cabbage not being completely cut. The root of the next Chinese cabbage has been cut and pulled, and the Chinese cabbage is squeezed between each other to feed the harvesting header to the inlet. At the same time, it will also cause damage to the mechanical structure of the Chinese cabbage harvester during the harvesting process, thereby reducing the test evaluation index. As shown in Figure 19, the harvesting effect of the Chinese cabbage harvester is very obvious, and there is no leakage phenomenon.

(a). Before harvesting *(b). After harvesting* *(c). Harvesting qualified Chinese cabbage*

Fig. 19 - Comparison of Chinese cabbage before and after harvesting

Figure 20 shows the damage types of Chinese cabbage during the harvesting process. The causes of Chinese cabbage damage were analyzed by field test results. First, the collision between the uprooting-cutting mechanism and Chinese cabbage caused the damage of Chinese cabbage. Second, due to the difference of individual physical characteristics, the position of Chinese cabbage is too high or too low after entering the clamping and conveying mechanism, so that the cutting position is not fixed and the Chinese cabbage is cut. Thirdly, the mutual extrusion of Chinese cabbage during the harvesting process will also cause damage.

(a). Blastomere *(b). Abrasion* *(c). Cut loss*

Fig. 20 - The damage types of Chinese cabbage during harvesting

CONCLUSIONS

In this paper, based on the determination of the physical parameters of 'Zaofeng 01' Chinese cabbage varieties and combined with the main local planting patterns, a double-row wheeled self-propelled Chinese cabbage harvester was designed, which could complete the root cutting, pulling, clamping and conveying, packing and collecting of double-row Chinese cabbage at one time. Through the design and selection of the key working parts of the double-wheel self-propelled Chinese cabbage harvester prototype, the key working parameters of the profiling device, the root-cutting-pulling device, and the clamping and conveying device were determined. The specific conclusions are as follows:

(1) The basic physical characteristics of the main Chinese cabbage cultivar 'Zaofeng 01 ' in Yucheng City, Shandong Province were collected. The data of diameter, plant height, rhizome diameter, rhizome length, expansion degree and total mass were measured to provide data support for the design of key components of Chinese cabbage harvester.

(2) Based on the characteristics of local Chinese cabbage planting mode in Yucheng City, Shandong Province, the mechanization improvement was carried out. By optimizing the ridge height and customizing the row spacing and plant spacing of Chinese cabbage according to the basic physical shape of the main Chinese cabbage variety ' Zaofeng 01 ', the mechanical equipment can be operated smoothly and the loss and damage during the harvesting process can be reduced. According to the field verification test, the model significantly improved the efficiency and quality of mechanized harvesting of Chinese cabbage.

(3) A mechanized harvesting process of Chinese cabbage was proposed to improve the harvesting efficiency and reduce the loss. The structure of the prototype of the double-row wheel self-propelled Chinese cabbage harvester was determined, and its profiling device, lifting-cutting device, clamping and conveying device were designed and selected, and its dynamics and kinematics were analyzed. Finally, the key components were integrated to create a double-row wheel self-propelled Chinese cabbage harvester.

(4) The field performance test of the double-row wheel self-propelled Chinese cabbage harvester prototype showed that when the cutter speed was 280 r/min, the clamping conveyor belt speed was 240 r/min, and the forward speed of the machine was 1.44 km/h, the maximum harvesting pass rate was 95.08%, the minimum value was 90.65%, and the average value was 93.79%. The harvesting effect is the best at this time.

The follow-up research will further optimize the test to improve the qualified rate of Chinese cabbage harvest. The research results can provide reference for the development and structural improvement of Chinese cabbage harvesting equipment.

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