DESIGN AND EXPERIMENT OF CLAMPING AND CONVEYING DEVICE FOR TRACKED SELF-PROPELLED CHINESE CABBAGE HARVESTER

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履带自走式大白菜收获机夹持输送装置设计与试验

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DOI: https://doi.org/10.35633/inmateh-75-32

***Keywords:** Chinese cabbage, Mechanical harvesting, Clamping and conveying device, Design optimization, Finite element simulation test*

ABSTRACT

To effectively solve the problem of high damage rates and low operating efficiency of clamping and conveying in the mechanized harvesting of Chinese cabbage, a "vertical clamping+flexible conveying" system was developed. Based on the measurement and analysis of the basic physical characteristics and static compression mechanical properties of Chinese cabbage, the "vertical clamping + flexible conveying" method was applied to arrange the clamping conveyor belts longitudinally. A combination of flexible feeding and soft clamping was used to achieve low-damage transportation. A dynamics coupling simulation model of the Chinese cabbage harvesting components was established. By adjusting the structural and operational parameters of the harvesting components, a simulation test of the Chinese cabbage harvesting operation was conducted to determine the kinematic and dynamic principles of the harvesting process. The designed and developed clamping conveyor device is installed on a cabbage harvester for field performance test verification. Field test results show that the field productivity of the cabbage harvester is 0.12 hm²/h, the average value of the clamping and conveying success rate is 96.38%, and the average value of the harvesting damage rate is 7.43%. The developed clamping and conveying device can effectively meet the requirements of high efficiency, and low energy consumption, low damage during harvesting, while also enhancing adaptability to Chinese cabbages of varying head diameters.

摘 要

为提高大白菜机械化收获装备的作业性能，有效解决大白菜机械化收获过程中夹持输送损伤大、作业效率低的问题，研制了一种"立式夹持+柔性输送" 夹持输送系统。基于测定分析大白菜基本物理特征参数和静载压缩力学特性，采用"立式夹持+柔性输送"方式对夹持输送带进行纵向排布，利用挠性喂入与柔性夹持的配合作业方法实现低损输送。建立大白菜株体-采收部件动力学耦合仿真模型，通过改变采收部件的结构参数和工作参数等，进行大白菜收获作业仿真试验，探明大白菜采收过程运动学、动力学规律。最后，将设计开发的夹持输送装置配置在大白菜收获机上进行田间性能试验验证。结果表明，夹持输送装置采用"立式夹持+柔性输送"的方式，可以实现对大白菜的高效低损输送，提高对不同球径大白菜的采收适应性。通过利用离散元法建立动力学耦合仿真模型，发现夹持输送过程大白菜所受合力大小呈现波动态势，表明夹取过程大白菜与夹持皮带的相互作用力呈动态变化。田间试验结果表明，大白菜收获机田间生产率为 0.12hm²/h，夹持输送成功率均值为 96.38%，采收破损率均值为 7.43%，说明设计开发的夹持输送装置有效地满足高效、低能耗、低损伤的收获要求，提高了对不同球径白菜收获的适应性。

INTRODUCTION

Chinese cabbage (Brassica pekinensis (Lour.) Rupr.) is one of the vegetables with the largest planting area in China, accounting for about 15% and 19% of the total sown area and total output of vegetables in China *(Hu et al., 2022; Liu et al., 2020)*. It has distinctive planting characteristics, because it has a high unit yield, storage, and transportation, long supply period, it is nutrient rich and has other advantages. In China to maintain the supply of vegetables, regulating market prices, and other aspects play a vital role *(Ding et al., 2021)*. Chinese cabbage production methods are relatively rudimentary with low levels of mechanized harvesting and industrialization.

Currently, harvesting operations still rely entirely on manual labor, resulting in low efficiency, high labor intensity, and high operating costs. Additionally, the quality and efficiency of manual harvesting are difficult to control *(Zhou et al., 2023; Zhao et al., 2018)*.

The countries that focus on cabbage harvester-related technology and equipment are mainly Japan, China, South Korea, and other countries. Most of the early cabbage harvester structures first used the spiral extraction device for extraction, and then a fixed single disk knife to complete the root-cutting harvesting, but extraction and root-cutting damage was relatively large *(Park et al., 2021)*. In order to reduce the extraction and root-cutting damage, Japan Yanmar and Osada Nouki jointly developed a tracked self-propelled cabbage harvester, which ensures the stability of the clamping and conveying process as well as the consistency of the root cutting, but the overall structure is more complex and the manufacturing cost is higher *(Xu et al., 2009)*. Researchers from Chungnam University in South Korea, *Kim & Yeongsoo, (2020),* developed a small tracked self-propelled cabbage harvester that demonstrated effective pulling and harvesting performance. However, its integrated pulling and conveying device, along with a complex conveyor mechanism, resulted in poor adaptability to different cabbage varieties *(Park et al., 2021)*. To enhance conveyance efficiency and stability during harvesting while reducing manufacturing costs, efforts have been made to optimize and improve the design of a tractor-mounted cabbage harvesting system *(Ali et al., 2019)*. Han et al. developed a tractor-mounted cabbage harvester, utilizing two tilt-mounted notched disks instead of a screw plucking device. This design proved highly efficient and well-suited for large-scale cabbage planting in northern China. However, the harvester required relatively high supporting power *(Han et al., 2021)*. Myat et al. designed a four-row cabbage harvester that employed a pulling shovel to extract the cabbages, followed by root transportation and cutting using V-shaped clamping belt and a single serrated disk. However, the harvesting process experienced issues such as root slanting cuts and missed cuts, leading to a high vegetable damage rate *(Myat et al., 2021)*.

Due to the tender leaves of cabbage, the clamping conveyor device will cause extrusion damage to the cabbage when clamping, so it is necessary to study the extrusion characteristics of cabbage before designing the conveyor device and design a flexible and adaptive clamping conveyor device to prevent excessive clamping. The most common types of clamping and conveying devices are double screw type and conveyor belt type *(Li et al., 2017; Ji et al., 2023; Ding et al., 2022)*. The double screw rod-type clamping and conveying device consists of a pair of counter-rotating screw rods. After the extraction device removes the cabbage, it is transferred to the double screw rods, where it is clamped and lifted through spiral motion *(Ding et al., 2018; Toncheva et al., 2017)*. Conveyor belt-type clamping and conveying device mainly consists of two conveyor belts, with a spring tensioning mechanism designed inside the belts. This mechanism allows for secure clamping and transportation of cabbages of varying sizes *(Zhou et al., 2024)*. Shandong Agricultural University has developed a self-propelled cabbage harvester with broad adaptability. This harvester adopts a conveyor belt-type conveying and lifting system, utilizing an elastic tensioning mechanism to automatically adjust to cabbages with different physical characteristics *(Zhang et al., 2022)*.

It is necessary to improve and optimize the structural parameters of the clamping and conveying mechanism of the cabbage harvester, explore the interactions during the clamping and conveying process, and develop a low-damage, high-efficiency, and automated cabbage harvesting technology. The main objectives of this study are: (1) To determine and analyze the basic physical parameters and static load compression mechanical properties of cabbage; (2) To conduct kinematic and dynamic analysis of the cabbage clamping and conveying process, optimize the structural parameters, and complete the design of the clamping and conveying mechanism; (3) To establish a dynamically coupled simulation model of the Chinese cabbage harvesting components and analyze the kinematics and dynamics of the harvesting process; (4) To validate the machine prototype through field trials, verifying its actual field performance and identifying an optimized low-loss, high-efficiency, automated harvesting technology.

MATERIALS AND METHODS

Experimental materials and equipment

Chinese cabbage is the primary focus of harvesting machinery. Studying its basic physical characteristics and mechanical properties is essential for establishing a meaningful statistical scale model, providing a design basis and theoretical foundation for the development of cabbage harvesting equipment. Cabbages that had reached maturity and met harvesting standards were selected as test samples. To ensure reliability, only cabbages with an undamaged appearance and intact roots were chosen based on the principle of randomization and five-point sampling.

The test instruments and types of equipment used to measure the basic physical characteristic parameters of cabbage mainly include a tape measure, electronic digital display vernier caliper, electronic balance, beaker, measuring cylinder, and so on. Fifty plants were randomly selected for the measurement of basic physical characteristics and statistics. First of all, the electronic digital display vernier caliper was used to determine the total height of the cabbage plant, head height, head diameter, and other dimensions. Then, an electronic balance and electronic scales were used to measure the physical parameters of each sample three times, and the average value and standard deviation were calculated. These samples were placed horizontally between two rigid parallel plates, with 30 randomly selected cabbages tested using a GHS2000 universal testing machine under a specific loading rate. The instruments and equipment used for determining the basic physical characteristics and static compression properties of cabbage are listed in Table 1.

Table 1

Test equipment and instruments

Equipment Name	Model Specification/Unit	Range	Accuracy
Electronic Balance	CZ3002/g	0-300g	0.01
Electronic Universal Testing Machine	GHS2000/N	0-2000	0.001
Electronic Weigher	/kg	0-10kg	0.01
Tape Rule	/m	0-3m	1
Three-key Digital Vernier Calipers	SF2000/mm	0-200mm	0.1

Physical and mechanical characteristics of Chinese cabbage

- ***Research on the physical characteristics of cabbage cultivation soil***

Soil firmness was measured directly by a soil firmness meter, soil water content was measured by the drying method, and soil bulk weight was determined by the ring knife method. Soil physical properties were selected as evaluation indexes, including soil compactness, soil water content, and soil bulk density. Ten soil samples were randomly collected from the field using the five-point sampling method.

Fig. 1 - Research on soil compactness and soil water content testing

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

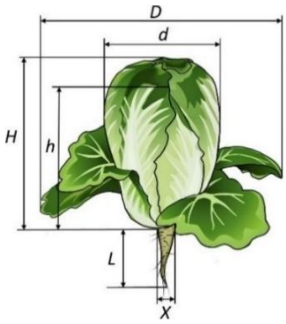

Fig. 2 - Terminology for the determination of basic physical properties of Chinese cabbage

D-Spread; d-Ball Diameter; H-Total Height; h-Nodule Height; X-Root Diameter; L-Root Length

After excluding immature and decayed cabbages from the experimental field, 50 cabbages were selected based on the principles of random sampling, diagonal sampling, and classification. In accordance with the design requirements of the cabbage harvesting equipment, the following parameters were chosen as evaluation indicators for the study of cabbage physical characteristics: total height of the whole cabbage plant (mm), nodule height (mm), spread (mm), nodule diameter (mm), total mass (kg), taproot diameter (mm) and taproot height (mm). The terminology used for determining the basic physical characteristics of cabbage is illustrated in Fig. 2, while the data collection process for these parameters is shown in Fig. 3.

Fig. 3 - The process of collecting basic physical characteristic parameters of Chinese cabbage

- ***Determination of static load compression mechanical properties of Chinese cabbage***

This test was conducted to examine the radial static load compression mechanical properties of cabbage. The extrusion probe was applied to three different sections of the cabbage: the head, waist, and bottom, forming three test groups *(Zhang et al., 2020; Du et al., 2019)*. To ensure test accuracy, the stress relaxation test of the cabbage required minimal deformation. A static measurement method was used, and the extrusion speed of the probe was set to 20 mm/min to apply pressure to the test samples.

The first group of Chinese cabbage samples (a total of 10) was placed horizontally on the fixed plate, and the bottom was fixed with a small amount of hot-melt adhesive, and the extrusion probe of the universal testing machine was placed squarely on the head of the test samples. Then, the test was carried out immediately using the GHS2000 universal testing machine at a lower loading rate of 20 mm/min. After the head-loading test was completed, the same method as described above was used to place the second group of samples (a total of 10). After the completion of the head loading test, the second group of samples (10 in total) was tested by the same method as described above, with the waist facing the extrusion probe of the universal testing machine to complete the test at a lower loading rate of 20 mm/min. Finally, the bottom of the third group of test samples was subjected to static loading compression test in the same way. When the first breakage of the exterior of the cabbage was observed, the loading was stopped, and the extrusion pressure on the test specimens was recorded to investigate the minimum extrusion pressure required for the cabbage to reach the breakage condition. Loading then continued until the cabbage was completely broken, at which point loading was stopped. This process aimed to examine the crack shape and direction in different parts of the cabbage under compression. The static compression mechanical properties test of the cabbage is shown in Fig. 4.

(a) Head Compression (b) Lumbar Compression (c) Bottom Compression

Fig. 4 - Static load compression mechanical characterization of Chinese cabbage plants

Structure and working principle of the whole machine

The current level of mechanization in cabbage harvesting is extremely low, mainly relying on manual labor. Additionally, harvested cabbage must not only meet agronomic production quality requirements but also minimize mechanical damage during the harvesting process to ensure a neat and visually appealing appearance *(Sarkar et al., 2024; Kim et al., 2020)*.

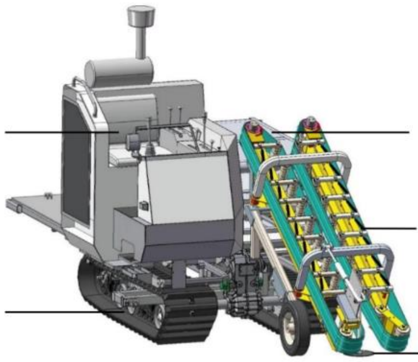

Fig. 5 - Schematic diagram of the single-row crawler-driven Chinese cabbage harvester structure

Based on the demand for mechanized harvesting of Chinese cabbage, the advantages and disadvantages of existing harvesting methods were comprehensively analyzed. The harvesting method selected for this study involves cutting the roots first, followed by clamping and conveying, and finally transporting the cabbage to the collection device. This study combines cabbage planting agronomy and harvesting requirements, developed a self-propelled cabbage harvester equipped with 52 kW engine. Through the design of well-matched root cutting device, clamping and conveying mechanism and lateral conveying device, the cabbage harvesting process can be completed in a single operation. The structure of the self-propelled cabbage harvester is shown in Fig.5.

During the working process of the harvester, the clamping conveyor device is first adjusted to an inclination angle of 20°~30° relative to the ground. The cutting device, driven by a hydraulic motor, completes the cutting of the cabbage roots. After the roots are cut, the cabbages are transferred through the clamping conveyor device to the lateral conveyor device, and finally, they are manually screened and loaded into baskets. The working process of the cabbage harvester is shown in Fig. 6. The main technical parameters of the harvesting machine are presented in Table 2.

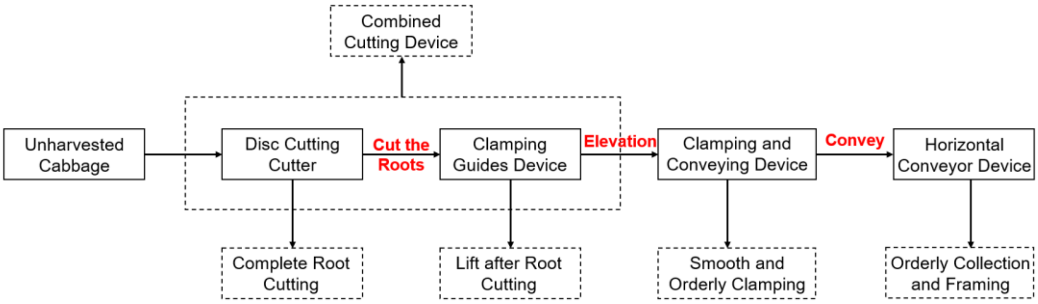

Fig. 6 - The working process of the cabbage harvester

Table 2

Main technical parameters of Chinese cabbage harvester

Technical Parameters	Numerical Value
Structural Form	Crawler-driven
Overall Dimensions /mm	4100×2000×2300
Auxiliary Power/kW	52
Output Speed/(r/min)	2500
Forward Speed/(m/s)	0-2
Number of Rows Harvested	1
Harvest Row Spacing/mm	400-500
Working Width/mm	550
Distance between Plants/mm	350-450
Machine Weight/kg	1520

Design and analysis of clamping conveyor device

Cabbage is transported using a horizontal parallel conveyor belt that clamps the top, which has poor adaptability to the uneven sizes of cabbage. Additionally, compression mechanical properties tests indicate that the radial clamping force on cabbage is relatively small, making it less likely to cause significant deformation or damage. Therefore, this design utilizes a pair of vertically arranged clamping belts, relying on friction to securely clamp the radial surface of the cabbage.

Due to the fragility of cabbage leaves, they are prone to mechanical damage. Therefore, based on the operating environment and the biological characteristics of cabbage. The structure of the clamping and conveying device designed in this program is shown in Fig.7.

The clamping and conveying device mainly consist of clamping belt, active pulley, driven pulley, tensioning pulley and driving hydraulic motor. The two active pulleys are symmetrically installed at the end of the clamping and conveying device. The driving hydraulic motor is installed on the frame above the active pulley and is connected to the driving shaft of the active pulley through a coupling. The driven pulley is suspended and installed at the front of the frame, positioned at the front end of the cutting disk, ensuring that the position of the pulleys remain in the same plane. The tensioning pulleys are installed on both side beams of the frame, with tensioning springs ensuring constant contact with the clamping belt, pushing it outward to maintain proper tension. During operation, two independent hydraulic motors drive the active pulleys, effectively clamping the cabbage between the flexible clamping belts arranged longitudinally. The distance between the clamping belts allows the cabbage head to pass through, while the elastic tensioning wheel ensures that the flexible clamping belt adapts to cabbages of different sizes.

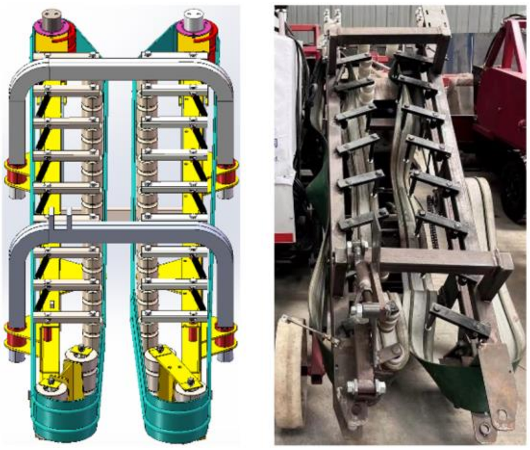

Fig. 7 - The structure of the clamping and conveying device

When the clamping position coincides with the center of gravity, the clamping stability reaches its maximum and the clamping effect is optimal. Therefore, the height of the clamping belt must be appropriately set to ensure compatibility with the cutting disk knife. The drive direction of the clamping belt has an inclination angle relative to the forward direction, which directly affects the accuracy of cabbage clamping and conveying. Based on existing research data, the optimal inclination angle range is determined to be 15° ~ 20°.

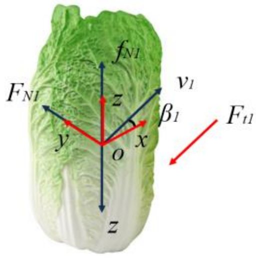

Fig. 8 - Chinese cabbage clamping conveying process force analysis

The force analysis of the cabbage in the clamping and conveying process is shown in Fig. 8. According to Fig. 8, the condition prevents the cabbage from tilting during the clamping and conveying process is:

$$\begin{cases} f_{N1} \geq mg \\ f_{N1} = F_{N1}\mu_{N1} \end{cases} \tag{1}$$

where: f_{N1} is the friction force; F_{N1} is theclamping force; μ_{N1} is the coefficient of static friction between the clamping belt and the cabbage; m is the mass of the cabbage.

The greater the clamping forceand friction force provided by the clamping conveyor belt, the less likely it is to produce tilting and falling. However, excessive clamping force on the conveyor belt is likely to lead to clogging and exacerbate mechanical damage to the cabbage. To prevent excessive clamping force from damaging the outer leaves, the clamping force F_{N1} must remain below the maximum compression damage threshold. Based on the cabbage's external dimensions and weight parameters the average mass of a cabbage is set at m = 2.3 kg, and the static friction coefficient μ_{N1} is 0.57, resulting in a minimum required clamping force F_{N1} of at least 87.20 N.

To avoid slippage of the clamping conveyor belt, the initial tension F_0 after tensioning of the clamping belt is:

$$\begin{cases} F_0 = 500\frac{P_c}{zv_1}(\frac{2.5}{K_\alpha} - 1) + qv_1^2 \\ P_c = (F_{t1} - F_{t2})v_1 \end{cases} \tag{2}$$

where: F_0 is the initial tension of the clamping belt; P_c is the conveying power; z is the number of belt roots; K_α is the correction coefficient of the wrapping angle; v_1 is the linear velocity of the clamping belt; q is the mass of the clamping belt per unit length; F_{t1}, F_{t2} are the tensions of the tight and loose sides of the clamping belt, respectively.

In order to prevent cabbage from piling up and clogging at the feed opening, the clamping belt line speed v_1 should be greater than the forward speed of the harvester v_{m1}:

$$\begin{cases} v_1 \geq \frac{v_{m1}}{\cos\beta_1} \\ v_1 = \frac{\pi n_t D_1}{60} \end{cases} \tag{3}$$

where: v_{m1} is the forward speed of the harvester; β_1 is the angle between the clamping belt and the horizontal plane; D_1 is the diameter of the active pulley, mm; n_t is the rotational speed of the active pulley.

If the forward speed of the harvester v_{m1} is greater than the speed of the clamping conveyor, the cabbage will accumulate due to delayed conveyance, leading to clogging at the feed inlet. Conversely, if the forward speed of the harvester is lower than the speed of the clamping conveyor, clogging will not occur, ensuring smooth operation. As the speed of the active pulley n_t increases, the linear velocity v_1 of the clamping conveyor belt also increases, which enhances the efficiency of the clamping conveyor. However, to prevent cabbage accumulation and clogging at the feed inlet, the forward speed v_m of the harvester can be appropriately reduced and the inclination angle β_1 of the clamping conveyor belt can be adjusted accordingly.

In order to adapt to the main cultivar of cabbage “Si Jin” in Yucheng, Shandong Province, the maximum adjustable center spacing of the clamping and conveying device designed is set to 240 mm. The spacing of the feeding mechanism is set within the range of 140~200 mm, ensuring smooth passage for cabbages of varying ball diameters. Additionally, the following parameters are set: q is 0.25 kg/m, z is 1, K_α is 0.92, and β_1 is 15°, so that under non-blocking conditions, the active roller speed n_t is no less than 282.6 r/min, the linear speed of the clamping belt v_1 is no less than 1.72 m/s, the power of a single belt P_c is about 0.42 kW, and the minimum initial tension of the clamping belt F_0 is 212.76 N. The maximum adjustable center spacing of cabbage is 240 mm, while the feeding mechanism spacing is set within the range of 140~200 mm to ensure the smooth passage of cabbages of varying ball sizes.

Simulation and analysis of EDEM-based clamping conveying device

SolidWorks 3D design software was used to construct and simplify the harvesting component model. The three-dimensional model of Chinese cabbage was imported into EDEM for particle filling to determine the fixation mode of Chinese cabbage plant and soil. Harvesting simulation tests were conducted by modifying structural and working parameters.

The Chinese cabbage was simplified into two parts: the sphere and the rhizome. SolidWorks was used to create a 3D model of the cabbage, with parameter calibration based on real cabbage conditions. According to cabbage planting agronomy, a ridge soil ditch model was established, featuring a ridge top width of 650 mm and a plant spacing of 400 mm.

Table 3

Simulation model material parameters

Materials	Densities/(kg/cm^3)	Poisson's Ratio	Shear Modulus/MPa
Chinese Cabbage	880	0.30	4.06
Soil	1360	0.40	1
Disk Cutting Cutter	7850	0.28	8.20×104
Clamping Conveyor Belt	4000	0.25	1×104

Table 4

Simulation model contact parameters

Contact Type	Coefficient of Restitution	Coefficient of Static Friction	Coefficient of Kinetic Friction
Soil - Soil	0.20	0.40	0.30
Chinese Cabbage - soil	0.40	0.30	0.28
Chinese Cabbage - Chinese Cabbage	0.42	0.46	0.04
Soil - Disk Cutting Cutter	0.30	0.40	0.05
Disk Cutting Cutter - Chinese Cabbage	0.43	0.67	0.05
Clamping Conveyor Belt - Cabbage	0.50	0.50	0.01

The harvester model was simplified, retaining only the disk knife, clamping device, and traveling device. Based on the study of the basic physical parameters and mechanical properties of Chinese cabbage, the material parameters and contact parameters of the model were set. The working parameters of the cabbage harvesting components are shown in Fig. 9 and Table 5. The initial forward speed of the harvester was set to 0.1 m/s, the rotational speed of the disk knife to 100 r/min, and the speed of the conveyor belt to 100 r/min.

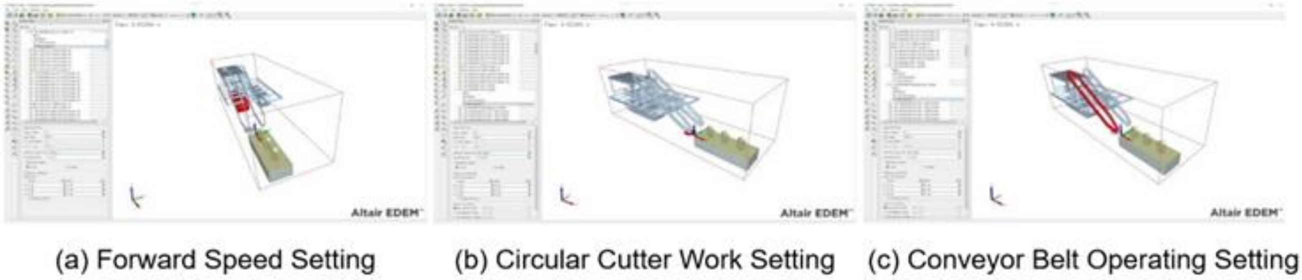

Fig. 9 - Working parameterization of Chinese cabbage harvesting components

Table 5

Simulation model working parameters setting

Experiment No.	Forward Speed (m/s)	Cutter Speed (r/min)	Conveyor Belt Speed (r/min)
1	0.1	100	100
2	1.0	100	100
3	1.5	100	100
4	0.1	200	100
5	0.1	300	100
6	0.1	100	150
7	0.1	100	200

Arrangements for field experiment

- ***Experiment object***

The developed self-propelled Chinese cabbage harvester was field-tested on November 18, 2024, at the planting demonstration base of Yatai Farm in Yucheng City, Dezhou City, Shandong Province. The experimental site followed a monoculture two-row open-field planting pattern. The agronomic parameters for cabbage planting were row spacing of 450 mm, plant spacing of 400 mm, and row top width of about 650 mm. The test subject was the Shandong Yucheng staple cabbage variety "Si Jin", with a total mature cabbage height ranging from 380 to 420 mm. The ball height varied from 270 to 290 mm, the spreading degree from 450 to 480 mm and the ball diameter from 160 to 180 mm. The total weight ranged between 2.1 and 2.5 kg. Additionally, soil firmness was measured at 13.46 MPa and soil moisture content was recorded at 24.75%.

- ***Indicators for the evaluation of experiment results***

The field productivity, clamping and conveying success rate and the harvest damage rate were taken as the evaluation indexes of the performance of cabbage harvesting equipment.

(1) Field productivity

Chinese cabbage field productivity refers to the actual operating area covered by the harvesting equipment per unit time. Measurements should be taken in each test area, and the final value should be calculated as the average.

$$E = 3.6BV \tag{4}$$

where, E represents the field operation rate; B is the operating width of the cabbage harvesting equipment; V is the operating speed of the cabbage harvesting equipment.

(2) Clamping and Conveying Success Rate

The clamping and conveying success rate refers to the proportion of cabbages in the test area that were successfully cut at the roots, smoothly drawn into the clamping and conveying device, and transported without clogging, falling, or root loss due to cutting errors. The number of effectively clamped cabbages should be recorded during the test.

$$Q_p = \frac{N_p}{N} \times 100\% \tag{5}$$

In the formula, Q_P indicates the success rate of cabbage clamping and transportation; N_P is the number of effectively clamped and transported cabbages; N is the total number of harvested cabbages.

(3) Harvest Damage Rate

Harvest damage rate is the number of heavily damaged outer leaves and large deviations in cut root positio n as a proportion of the total harvest.$N_o = \frac{N_s}{N} \times 100\%$ (6)

In the formula, N_O represents the cabbage harvesting damage rate; N_S is the number of damaged cabbages during harvesting; N is the total number of harvested cabbages.

RESULT AND DISCUSSION

Measurement of physical and mechanical properties of Chinese cabbage

The measured soil compactness was (11.16±3.20) kg/cm^2, soil water content was (25.69±4.11)%, and soil bulk weight was (1.41±0.26) g/cm^3. The parameters of soil physical properties are detailed in Table 6. For Chinese cabbage, the total height H was (403.51±22.05) mm, nodule height h was (277.32±9.65) mm, spread d was (481.15±33.10) mm, and nodule diameter d was (169.52±9.05) mm. The total mass was (2.31±0.18) kg, root diameter X was (28.78±4.63) mm, and root length L was (103.76±10.39) mm. The results of the basic physical characteristics of cabbage are presented in Table 7.

Table 6

Parameters of soil physical properties

Test Indicators	Soil Compactness / kg·cm^{-2}	Soil Water Content /%	Soil Bulk Weight / g·cm^{-3}
Maximum Value	14.70	29.82	1.75
Minimum Value	8.30	21.61	1.24
Mean	11.16	25.69	1.41
Standard Deviation	1.63	2.07	0.14
Coefficient of Variation	0.15	0.08	0.10

Table 7

Basic physical characteristic parameters of Chinese cabbage

Test Indicators	Total Height/mm	Nodule Height / mm	Spread / mm	Ball Diameter / mm	Total Mass / kg	Root Diameter/mm	Root Length / mm
Maximum Value	425.6	283.6	523.7	523.7	2.5	32.7	112.5
Minimum Value	381.5	264.3	457.5	457.5	2.1	23.4	91.8
Mean	403.5	277.3	481.2	481.2	2.3	28.8	103.8
Standard Deviation	13.6	5.4	16.7	16.7	0.2	2.6	6.1
Coefficient of Variation	0.03	0.02	0.03	0.03	0.06	0.08	0.06

In the static load compression mechanical properties test, cabbage samples were subjected to compression using an extrusion probe applied to the head, waist, and bottom of the cabbage. The resulting damage is illustrated in Fig. 10. By analyzing the crack direction after compression, the role of the clamping and conveying device in handling the cabbage can be determined, providing a theoretical basis for its design. The characteristic curves of squeezing force and displacement are shown in Fig. 11.

(a) Head Compression Results (b) Lumbar Compression Results (c) Bottom Compression Results

Fig. 10 - Damage diagram for static load compression test of Chinese cabbage plants

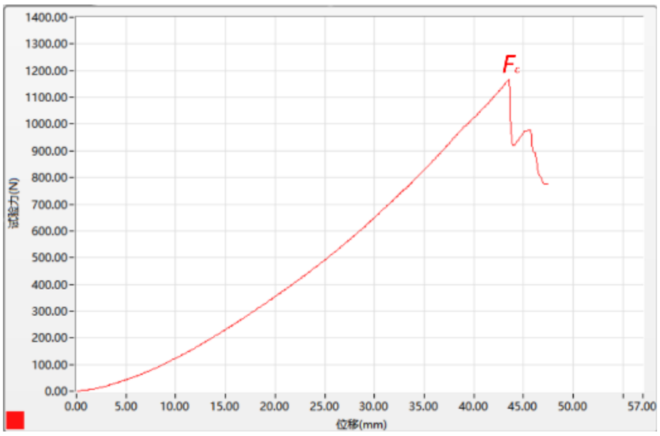

Fig. 11 - Characteristic curves of squeezing force and displacement

From the fitted curve graph, it can be seen that the cabbage strain rupture occurs when the compression displacement reaches 43.6 mm. The maximum compressive breaking force was 1166.1 N. The equation of the fitted curve for the shear characteristic test is:

$$F_p = 0.62x^2$$

where, F_p is the extrusion pressure on the cabbage strain; x is the displacement of the extrusion probe.

Simulation of Chinese cabbage harvesting process

Through the EDEM simulation interface, it can be observed that the disk cutter completes the root-cutting process at the moment when the cabbage is clamped at the front end of the clamping conveyor. The cabbage is then transported upward through the clamping conveyor, completing the entire harvesting process. From the test results, it can be seen that when the forward speed is 0.1~0.3 m/s, the rotational speed of the disk cutter is 100~300 r/min, and the rotational speed of the conveyor belt is 100~200 r/min, the cabbage root-cutting and clamping conveyor process can be successfully completed.

The harvesting process forces are shown in Figure 12. Test groups 1, 3, 5 and 7 were selected as controls. The maximum value of the combined force on the cabbage was 105.7 N. When the forward speed of the harvesting component, the rotational speed of the disk knife and the speed of the conveyor belt changed, the force on the cabbage also changed. The simulation test verified the rationality of the design of the harvesting components of the cabbage harvester. The rationality of the structural design of the device and the actual harvesting effect are further verified through subsequent field tests.

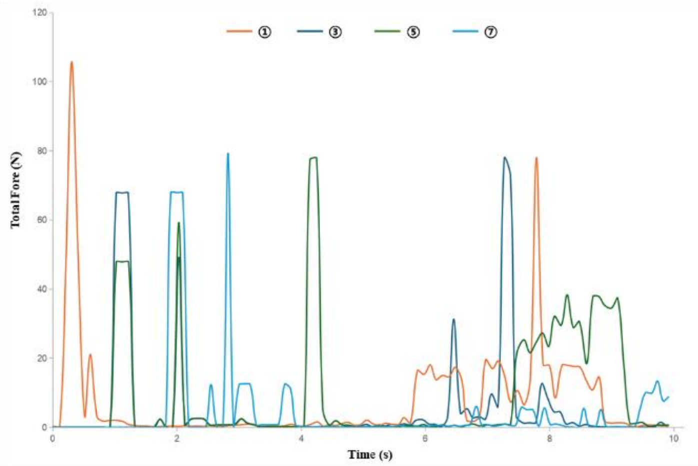

Fig. 12 - Analysis of the force results of the simulation test of Chinese cabbage

Results and analysis of the multifactorial test

Through preliminary theoretical analysis, the main influencing factors on the harvest performance index and their range of values were determined. A three-factor, five-level quadratic regression orthogonal rotary combination test was designed. The cutter speed, forward speed, and clamping belt speed were selected as the influencing factors, while the clamping and conveying pass rate was chosen as the evaluation index. The study aimed to determine the influence of factor interactions on the work performance index.

According to Table 9, the regression model for the clamping and conveying pass rate Q_p has a P-value < 0.0001, indicating that the model is highly significant. The P-value for the lack-of-fit term is 0.2491 > 0.05, and the correlation coefficient R^2 of the multiple regression equation is 0.9872, demonstrating that the fitting accuracy of this regression equation is high. The effects of X_1, X_2, X_3, X_{12}, X_{22} and X_{32} on the clamping qualification rate in the model are highly significant. It can be concluded that the order of influence of each factor on Q_p is: forward speed, cutter speed, and clamping belt speed.

Table 8

Test results

Test Number	Cutter Speed (r/min)	Forward Speed (km/h)	Clamping Belt Speed (r/min)	Clamping and Conveying Pass Rate (%)
1	200	0.2	120	97.62
2	250	0.2	120	91.32
3	200	0.5	120	92.46
4	250	0.5	120	96.73
5	200	0.2	180	95.39
6	250	0.5	180	96.86

Table 9

Variance analysis of clamping and conveying pass rate

Name	Square Sum	Degrees of Freedom	Mean Square	F-value	P-value
Model	436.48	9	46.79	101.79	< 0.0001
X_1	12.34	1	11.96	26.34	0.0002
X_2	17.62	1	16.78	37.46	< 0.0001
X_3	8.77	1	8.72	19.72	0.0006
X_1X_2	4.36	1	3.96	8.96	0.011
X_1X_3	3.43	1	3.72	7.37	0.0159
X_2X_3	12.37	1	12.49	25.49	0.0002
X_{12}	53.16	1	53.71	65.36	< 0.0001
X_{22}	248.46	1	249.25	55.47	< 0.0001
X_{32}	58.72	1	58.66	24.92	0.0002
Residuals	6.46	13	0.4736		
Incoherent	3.15	5	0.5997	1.49	0.2491
Error Term	2.79	8	0.46		
Total Error	419.91	22			

Field harvesting performance experiments

Before conducting the field test, the test area was pre-cleared of dead, immature, and otherwise unsuitable cabbages for harvesting. A laser digital tachometer was used to calibrate key operating parameters of each component. The harvester's cutting device parameters were set as follows: a cutter inclination angle of 11°, a cutter rotational speed of 215 r/min, and a working speed of 0.28 m/s for the cabbage harvesting test. The cabbage harvesting performance test included a total of five groups, with approximately 60 cabbages in each test area. The field test site operation is shown in Fig. 13.

Fig. 13 - Field experiments of Chinese cabbage harvester

During the field performance test of the harvester prototype, the overall performance remained stable. Each component functioned properly, causing minimal mechanical damage to the cabbage. The harvester demonstrated a high harvest integrity rate and met the required harvesting standards. Following the prototype test method, key operational evaluation indexes - including field productivity, clamping and conveying success rate, and harvesting pass rate - were calculated for each test area. The average of five test results was taken. The prototype achieved an average field productivity of 0.12 hm²/h, an average clamping and conveying success rate of 96.38%, and an average harvest breakage rate of 7.43%, meeting the design requirements for the cabbage harvesting model.

Discussion

- ***Experimental analysis of physical and mechanical properties of Chinese cabbage***

The cabbage samples used in this study for physico-mechanical property tests were produced in Shandong Province, located north of the Yangtze River. The cabbage plants were relatively tall, with most leaf bulbs being tightly packed. The overall bulb height ranged from 380 to 425 mm, the mid-diameter ranged from 158 to 177 mm, the average mass distribution was between 2.1 to 2.5 kg, and the plant height exceeded 260 mm. The physical and morphological parameters of cabbage exhibited significant variations in size and quality. Therefore, to enhance the versatility and adaptability of the harvesting machinery, it is essential to incorporate a floating adjustable feeding device and a clamping device structure.

- ***Experimental analysis of Chinese cabbage harvesting process simulation***

During the clamping and conveying process, the clamping belt exerts pressure on the cabbage, leading to deformation of the belt. The combined force exerted on the cabbage during the clamping process fluctuates, indicating that the interaction force between the cabbage and the clamping belt is dynamically changing. This fluctuation is primarily influenced by the flexible deformation of the clamping belt during contact.

- ***Experimental analysis of harvesting performance in the field***

Cabbage harvesting damage is mainly attributed to the following factors: cutting damage caused by variations in individual cabbage sizes and uneven soil conditions, leading to inconsistencies in the cutting position; handling damage - occurring when cabbage collides or is compressed in the collection box after being harvested. To minimize post-harvest losses, efforts should be made to retain 2-3 outer leaves of the cabbage during harvesting. Minor root and surface damage has minimal impact on subsequent sales. Therefore, the cabbage loss rate during harvesting is acceptable within a certain range.

CONCLUSIONS

This study focused on the structural design and analysis of the clamping and conveying device of a cabbage harvester, considering the basic physical properties of cabbage and the mechanical properties of static load compression. The discrete element method (DEM) was employed to simulate and analyze the clamping and conveying process. Additionally, field harvesting performance tests and practical feasibility analyses were conducted to verify the rationality and accuracy of the clamping and conveying device design. The main conclusions are as follows

1) To enhance the versatility and adaptability of cabbage harvesting machinery, a floating adjustable feeding device and a clamping conveyor structure were implemented to improve the harvester’s adaptability.

2) The clamping and conveying device adopts a longitudinal arrangement, utilizing flexible feeding and flexible clamping to achieve low-loss conveying, thereby improving its adaptability to cabbages with different ball diameters.

3) A dynamic coupling simulation model of cabbage harvesting components was established, allowing for the analysis of kinematic and dynamic characteristics through cabbage harvesting process simulations.

4) The cabbage harvester developed in this study underwent field performance tests, and the results confirmed that the harvester meets the design requirements for the mechanized harvesting of Chinese cabbage.

ACKNOWLEDGEMENT

The work was sponsored by the National Key R&D Program Project of China (2022YFD2001502).

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