DESIGN AND TESTING OF SMALL ELECTRIC DOUBLE-ROW LEEK HARVESTER
/
小型电动双行韭菜收获机设计与试验

Yuxin SHAN[1)], Yinping ZHANG*[1)], Hua ZHOU[1)], Jiasheng WANG[2)], Qun MA[3)]
[1)] College of Agricultural Engineering and Food Science, Shandong University of Technology, Zibo, 255000/China;
[2)] College of Mechanical and Electrical Engineering, Qingdao Agricultural University, Qingdao, 266109/China;
[3)] Shandong Dayi General Purpose Machinery Limited Company, Linyi, 276002/China.
Tel: +86-15165333108, Email: zhangyinping@sdut.edu.cn
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ABSTRACT
Aiming to address the limited space and the inapplicability of large harvesting equipment in Chinese greenhouses, a small electric double-row leek harvester was designed. This machine is capable of cutting, clamping, transporting, and collecting leeks simultaneously. A reciprocating cutting device was employed to accommodate varying row spacings. To make the machine suitable for small greenhouse environments, the parameters of the torsion clamping conveyor belt were optimized to reduce the overall size. Through theoretical analysis of the clamping and conveying system, the cutting mechanism, and the parameters for coordinated clamping-cutting operations, the structural design and working parameters were determined. A prototype was developed, and field experiments were conducted. The results showed that when the machine's forward speed was 0.3 m/s, the linear speed of the cutting knife was 0.66 m/s, and the conveyor belt speed was 0.42 m/s, the average damage rate was 4.87%, meeting the requirements for mechanized leek harvesting. This study provides a reference for the design of leek harvesters.

摘要
针对中国设施温室空间小、大型收获设备不适应等问题，设计了小型电动双行韭菜收获机，可一次性完成韭菜切割、夹持、输送、装框作业。采用往复式切割装置适应不同行距韭菜切割，优化扭转夹持输送带参数，减小整机尺寸，适应温室小空间作业。通过对夹持输送装置、切割装置以及夹持-切割协同作业参数进行理论分析，确定了夹持输送装置、切割装置的结构、工作参数。试制样机并进行了田间试验，试验结果表明，当机器前进速度为0.3 m/s，割刀线速度为0.66 m/s、输送带速度为0.42 m/s 时，平均作业损失率为4.87%，满足韭菜机械化收获要求。本研究旨为韭菜收获机的设计提供参考。

INTRODUCTION
Leek is native to China, with a perennial planting area of about 400,000 hm^2 and an annual output of about 2 million tons. Due to its special planting methods and different growth methods, it can be harvested at least 4~5 times a year *(Gong et al., 2018)*, but the mechanization level of leek harvest is low, mainly relying on manual sorting and boxing, which not only has low work efficiency, high labor intensity and high operating costs, but it is also difficult to guarantee the quality and efficiency of artificial harvest, affecting the development of leek industry *(Zou et al., 2022)*.

At present, the mechanical harvesting technology of leeks and other slender stalk leafy vegetables in foreign countries has been relatively mature *(Wang et al., 2021)*, such as the SLIDE TRAX SMALL parsley orderly harvesting machine from Hortech in Italy and the PO-335A leek harvester from ASA-LIFT in Denmark, which adopts a vertical clamping conveyor device with adjustable lifting and small clamping damage. However, the conveying device has a large structure and is not suitable for facility greenhouses *(Liu et al., 2019)*. The 4G-200 leek harvester of Korea Plant Company uses a twist clamping conveying belt to make leeks orderly spread in the same direction. The model is small and suitable for facility greenhouse operations, but it needs manual secondary sorting and boxing *(Xu et al., 2020)*. The mechanical harvesting technology of leek and other slender stalks of leafy vegetables in China is in the research stage. Some authors designed a leek harvesting machine with a two-stage conveying device *(Feng et al., 2023; Zhang et al., 2022a; Liu et al., 2023; Xin et al., 2024; Xu et al.,2024)*. The first-stage conveying device will transfer leek from vertical posture to horizontal posture, and the second-stage conveying device will transfer leek with horizontal posture to the collection device, which makes the leeks harvested this way more orderly. However, the overall length of the model is too long and the flexibility is poor.

Other researchers designed a small single-row leek harvester, which used a disc cutting knife and a twisting conveying belt to directly transport the cut leek to the ground behind the machine and lay it on the ground. The leek was manually picked up into the box *(Zhao et al., 2021; Zhang., 2024a)*. *Su et al. (2020)* extended the conveying distance of the conveyor belt and placed a collection box behind the machine to allow the leeks fall directly into the box. However, due to the significant height difference between the leeks and the box, the leeks tended to become disorganized after falling in.

Due to the long stems and leaves of leeks and the variation in row spacing, current leek harvesters primarily operate in a single row, using disc cutting knives and semi-cross torsion clamping conveyor belts, which result in low efficiency. Multi-row harvesters with high operation efficiency tend to be large in size and unsuitable for small plots in greenhouse facilities *(Zhang et al., 2024b)*. In this study, a small electric double-row leek harvester was designed. A reciprocating cutting knife was used, and the layout of the twisting clamping belt was optimized to shorten the clamping and conveying distance, thereby enabling double-row harvesting. The model is compact and offers high harvesting efficiency, making it suitable for greenhouse operations. The optimal structural parameters were determined through theoretical calculations of the clamping conveying device, cutting mechanism, and coordinated clamp-cutting operation. A prototype was developed, and field experiments were conducted to verify the rationality of the design parameters. This study provides a technical reference for the design of mechanized leek harvesters.

MATERIALS AND METHODS

Structure and Working Principle of the Harvester

The structure of the whole machine is shown in Fig. 1. It is mainly composed of a divider, a cutting device, a clamping conveying device, a collecting device, a travel device and a rack which can complete the cutting, clamping, conveying and boxing of leek at one time. The height of the reciprocating cutting knife can be adjusted up and down to meet the requirements of different cutting heights. Clamping conveying mechanism adopts double-row twisting clamping conveying mode to improve harvesting efficiency and orderliness. Conveying belt with sponge rubber strip is selected to reduce damage to leek. The main technical parameters of the machine are shown in Table 1.

Table 1

Main technical parameters of double-row electric leek harvester

Parameters	Unit	Values
Size of whole machine	mm	1800×900×880
Matched power	kW	0.5
Output Speed	r/min	330
Machine forward speed	m/s	0～0.75
Conveyor belt line speed	m/s	0～1.04
Working width	mm	660
Harvest height	mm	10～30

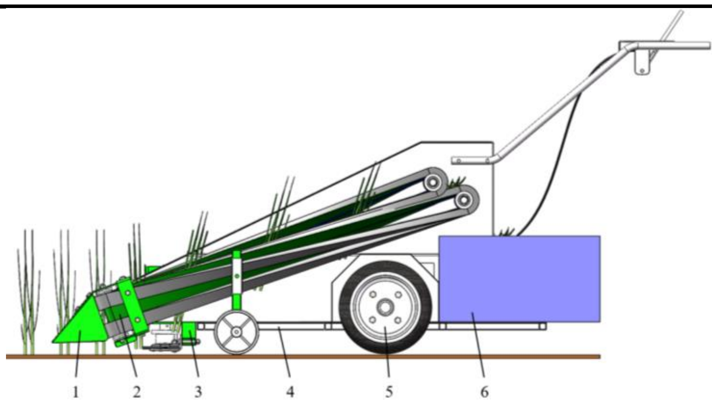


Fig. 1 - Structure diagram of double-row leek harvester

1 - Divider; 2 - Clamping conveying device; 3 - Reciprocating cutting device; 4 - Rack; 5 - Travel device; 6 - Collecting device

When the double-row leek harvester operates, the limiting wheel is first adjusted to align the divider of the harvester with the leek row, ensuring that the reciprocating cutting knife is parallel to the ground. During the machine's forward movement, the clamping conveyor first clamps the leek plant, and then the reciprocating cutting knife cuts the leek from the stem, and the clamping conveyor is transported backwards.

In the conveying process, to ensure the stability of the conveying and facilitate the subsequent collection, the clamping conveying belt is twisted, so that the state of the leek plant changes from vertical to horizontal, and the leek plants fall horizontally into the collection box in an orderly manner when it is transported to the end of the clamping conveying device.

Key component design

Clamping conveying device design

The clamping conveying device consists of two sets of torsion conveying mechanisms. Each mechanism is supported by two sets of belt rollers arranged at a 90-degree angle to each other, enabling the transition of the conveying direction from vertical to horizontal. Power is transmitted between the drive shaft and the driven shaft through a pair of spur gears with identical indexing diameters, ensuring synchronized rotation. The driven roller mounting rack can move forward and backward to adjust the tension of the conveyor belt, and left and right to adjust the belt gap. The structure of the clamping conveying device is shown in Fig. 2.

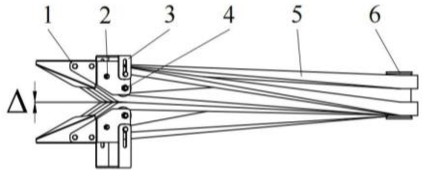


Fig. 2 - Structure diagram of clamping conveying device

1 - Driven roller guide roller holder; 2 - Guide roller; 3 - Fixed frame support frame; 4 - Driven roller; 5 - Conveying belt; 6 - Drive roller

During the conveying process, the gap between the upper and lower conveyor belts determines the size of the clamping force. Too large gap and too small clamping force will lead to misalignment or even dropping of the leeks during transport. Conversely, too small gap and too large clamping force will potentially cause damage to the leeks at the clamping point. To ensure orderly collection with minimal damage, the conveyor belt clearance was carefully designed. Experimental results on the physical characteristics of leeks showed that the diameter at the cutting position ranges from 5.09 to 7.76 mm. Mechanical property tests revealed that the critical compression force at which leeks become damaged is between 12.5 N and 18.95 N *(Liu et al., 2022)*. Based on this, the initial gap between the upper and lower conveyor belts Δ was set to 3 mm, adjustable according to the planting density in a single row and stem diameter of the leeks during operation.

As shown in Fig. 3, to ensure reliable clamping and transportation of leek plants, the driving roller, driven roller, guide roller, and conveyor belt form a torsional clamping transport channel. Before the leeks enter the clamping conveying device, the gap between the upper and lower belts is small. As the leek plants enter the device, the sponges on the upper and lower conveyor belts are compressed and deformed by the leeks, causing the gap to widen. The leeks become "wrapped" by the sponge layers of the belts, which increases the number of contact points and improves clamping stability. This design effectively reduces damage to the leek plants.

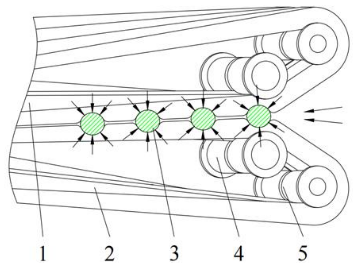


Fig. 3 - Schematic diagram of the transport process of the clamped part of leek plant

1 - Upper conveying belt; 2 - Lower conveying belt; 3 - Leek plant; 4 - Driven roller; 5 - Guide roller

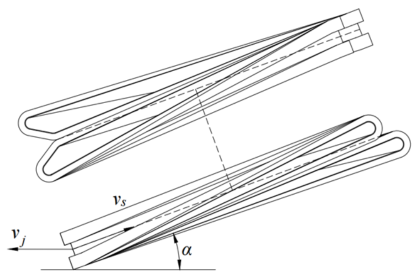


Fig. 4 - Speed analysis of transport process

To ensure smooth backward transmission of leeks and to prevent them from being pushed forward by the conveyor belt during harvesting, the belt speed must exceed the forward speed of the harvester *(Li et al., 2023)*. Therefore, the conveyor belt speed and the machine's forward speed must satisfy the following condition:

$$v_s \cos\alpha > v_j \tag{1}$$

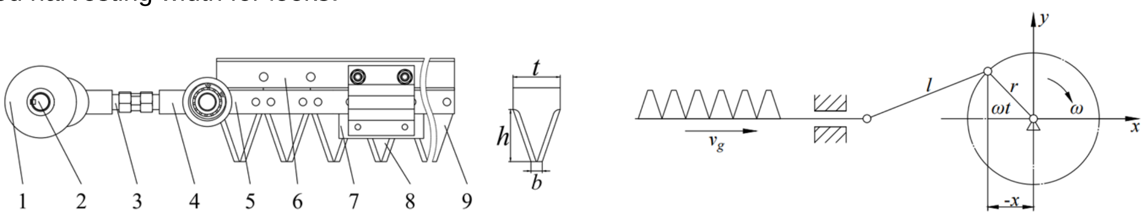
where:

α is the angle between the conveyor belt and the horizontal plane, (°), α=20° *(Zhang et al., 2016)*; v_s is the conveyor belt speed, m/s; v_j is the machine's forward speed, m/s.

The minimum forward speed requirement for leek harvesting machinery is 0.2 m/s. According to equation (1), the speed of the driving roller must exceed 64 r/min. The designed speed range of the driving roller is 0~4495 r/min, corresponding to a conveyor belt speed range of 0~1.04 m/s. The design speed of the wheels is 0~55 r/min, corresponding to a forward machine speed of 0~0.75 m/s.

Cutting device design

Since the moisture content of the leek stem is as high as 84.5%, and considering the soft and easily damaged characteristics of the leek itself, this design selects a single-acting reciprocating cutting device, as shown in Fig. 5 (a). The cutting stroke S=50 mm, with a moving blade spacing c=50 mm, fixed blade spacing c0=50 mm, top width d=10 mm, and edge height h=55 mm. The cutting knife length is 550 mm to meet the required harvesting width for leeks.



(a) Structure diagram **(b) Motion analysis**

Fig. 5 - Cutting device

(a) *1 - Eccentric wheel; 2 - Power input shaft; 3 - Threaded connecting rod. 4 - Crank sleeve; 5 - Tool bar; 6 - Tool holder; 7 - Pressing edge plate; 8 - Moving blade; 9 - Fixed blade*

Research indicates that as the angle *θ* increases, the cutting resistance will decrease, but if the angle *θ* exceeds a certain limit, the crop stems will slide out of the mouth of the moving and fixed blade, resulting in missed cutting or uneven stubbles *(Shi et al., 2017)*. To reduce the above phenomenon and ensure that the reciprocating cutting device can cut normally at the moment of contact with the leek stem, the cutting process of the leek stem is analyzed, as shown in Fig. 6.

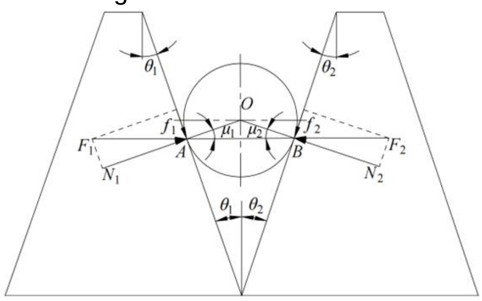


Fig. 6 - Force analysis diagram of blade clamping stem

As can be seen from Fig. 6., when the stems are clamped to maintain balance, the forces F_1 and F_2 must be equal in magnitude, opposite in direction, and on the same straight line:

$$\begin{cases} F_1 = N_1 \tan\frac{\theta_1+\theta_2}{2} \le N_1 \tan\mu_1 \\ F_2 = N_2 \tan\frac{\theta_1+\theta_2}{2} \le N_2 \tan\mu_2 \end{cases} \tag{2}$$

where: θ_1- the cutting angle of the moving blade, (°); θ_2- the cutting angle of the fixed blade, (°); μ_1- the friction angle of the fixed blade to the stem, (°); μ_2- the friction angle of the moving blade to the stem, (°); F_1- the resultant force of the moving blade acting on the stem, N; F_2- the resultant force of the fixed blade on the stems, N; N_1- the normal force of the moving blade on the stems, N; N_2- the normal force of the fixed blade on the stems, N;

After analysis, the following condition is obtained:

$$\theta_1+\theta_2\leq\mu_1+\mu_2 \tag{3}$$

This inequality ensures the limiting condition for the clamping of the stem between the moving and fixed blades. Specifically, it means that the sum of the cutting angles θ_1 and θ_2 of the moving and fixed blade must not exceed the sum of the friction angles μ_1 and μ_2 between the blades and the stem. In this study, the values used were θ_1 =19°, θ_2 =18°.

During the operation of the cutting knife in the reciprocating cutting device, its absolute motion is a combination of reciprocating motion (as shown in Fig. 5. (b)) and linear motion:

$$\begin{cases} y = v_j t \\ x = r\,(1\text{-}\cos\omega t) \end{cases} \tag{4}$$

where:

t is the time, s; y is the distance the machine travels in t time, mm; r is the crank radius, mm; x is the displacement of the moving blade in t time, mm.

The formula for calculating the forward distance of the moving blade is:

$$H=\frac{60v_j}{2n}=\frac{\pi}{\omega}v_j \tag{5}$$

where:

n is the rotational speed of the crank, r/min; H is the feed per revolution of the cutter, mm.

Based on geometric relations, the following equation can be derived:

$$y=\frac{H}{\pi}\arccos\frac{r\text{-}x}{r} \tag{6}$$

For leafy and stem vegetables like leeks, which require high cutting quality, a clean and smooth cut surface helps reduce damage and decay, extends shelf life, and enhances market value *(Shan et al., 2024)*. The cutting diagram, drawn according to eq. (5), is shown in Fig. 7. Ⅰ is the primary cutting area; Ⅲ is the recutting area; b_1 is the average width of the fixed blade. The cutting device has no missed cutting zones and the repeated cutting area is relatively large, resulting in a neater and smoother cutting surface.

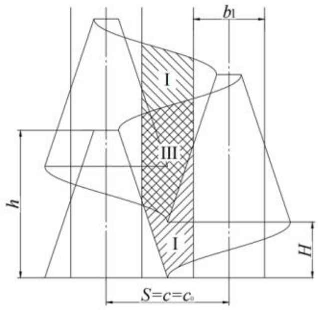


Fig. 7 - Cutting diagram of reciprocating cutting device

Clamping-cutting collaborative operation parameter design

Cutting leek plants while they are clamped is essential to ensure their orderly conveyance. After clamping and cutting, due to the combined effects of the machine's forward motion, the separation function of the divider, and the pulling action of the clamping conveyor belt, the leek plants may adopt unstable postures, such as leaning forward or backward in the direction of movement *(Xin et al., 2023)*. To ensure smooth clamping and transport after cutting, the relative positions of the clamping conveying device and the cutting device were carefully designed. Additionally, the postural changes of the leek plants in the forward direction of the machine were analyzed during the clamping-cutting process.

As the machine moves forward, the cutting knife contacts the clamped leek stems and performs a double-supported cutting action. For ease of analysis, a Cartesian coordinate system is established with the contact point *O* between the leek plant and the ground, at the clamping-uncut stage, as the origin. It is assumed that the clamping conveying device remains stationary relative to the ground, while the leek plant moves relative to the clamping conveying device at a speed v_j. The geometric relationship is illustrated in Fig. 8. Let the distance between the clamping point *A* and the front end of the cutting knife be l_g, the height of the cutting knife from the ground be h_1, the height of the clamping point *A* from the ground be h_2, the clamping-cutting time be t_1, and the angles between the leek plant and the horizontal ground during clamping and cutting be β_1 and β_2 respectively.

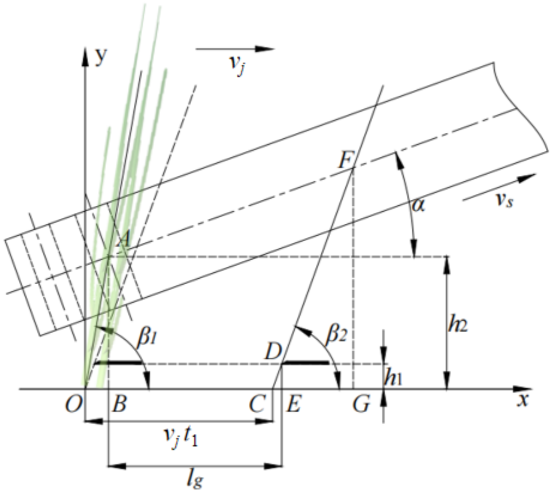


Fig. 8 - Analysis of the clamping-cutting process of leek plants

Since the motion of leek plant is the result of the combined movement of the harvester's forward speed v_j, and the clamping conveying speed v_s, the displacement equation of the clamping point *F*, during the clamping-cutting stage, relative to the clamping point *A*, in the clamping-uncut stage, is as follows:

$$\begin{cases} x_F = v_s t_1 \cos\alpha \\ y_F = v_s t_1 \sin\alpha \end{cases} \tag{7}$$

The clamping conveyor belt holds the leek stem at point A. To ensure the stem is securely clamped before cutting, it is necessary to determine the appropriate installation position of the cutting knife:

$$h_2 \cot\beta_1 \le l_g \tag{8}$$

As shown in Fig. 9, during the clamping-cutting stage, the angle between leek plants and the ground satisfies the following trigonometric relationships in △CDE and △CFG:

$$\begin{cases} \tan\beta_2 = \dfrac{h_1}{l_g + h_2 \cot\beta_1 - v_j t_1} \\ \tan\beta_2 = \dfrac{h_2 + v_s t_1 \sin\alpha}{h_2 \cot\beta_1 + v_s t_1 \cos\alpha - v_j t_1} \end{cases} \tag{9}$$

According to eq. (9), the angle between the leek plant and the ground in the clamping-cutting stage is:

$$\beta_2 = \arctan \frac{v_s t_1 \sin\alpha + h_2 - h_1}{v_s t_1 \cos\alpha - l_g} \tag{10}$$

According to eq. (10), the main parameters affecting the posture of leek plants during the clamping-cutting process are the linear speed of clamping conveying belt v_s, the height of cutting knife from the ground h_1, the distance between clamping point A and the front end of the cutting knife l_g, and the angle between clamping conveying belt and horizontal plane α. Among them, the smaller the angle α between the clamping conveying belt and the horizontal plane. The smaller the inclination angle β_2, the more inclined the clamping position of the clamping conveying belt relative to plant stems, the more unstable the clamping, and the greater the possibility of the clamping stem and leaf damage. If the angle α is too large, it may affect the overall height of the machine and interfere with the harvesting process *(Hou et al., 2023)*. Research on the direction of stalk cutting showed that the cutting resistance and power consumption of skew cutting were reduced by 60% and 30% compared with perpendicular cutting. Using the skew cutting method at small angle to harvest vegetables with high water content such as leek can reduce damage to plants. In this study, the angle between the clamping conveying belt and the horizontal plane α =20°, and the cutting knife installation position l_g =10 mm, so as to ensure that clamping precedes cutting during harvester operation.

Field experiment

The prototype of double-row electric leek harvester was field-tested on July 22, 2024 at Shandong University of Technology in Zibo City, Shandong Province. The experiment equipment included the harvester, tape measure, stopwatch and other tools. The field experiment process is shown in Fig. 9.

Fig. 9 - Process of field experiment

This paper refers to the "Technical Specification for Quality Evaluation of Hand-held Stem and Leafy Vegetable Harvesters" *(Ministry, 2020)* and "Leafy Vegetable Harvesters" *(Ministry, 2024)*, and related literature *(Zhang et al., 2022b; Kang et al., 2020).* Operation damage rate Z_s were used as performance evaluation experiment indexes of double-row electric leek harvester. The calculation formula is as follows:

$$Z_s = \frac{S_s}{S_j} \times 100\% \tag{11}$$

where: Z_s is the operation damage rate, %; S_s is the number of damaged leek plants; S_j is the number of effective clamping conveying leek plants.

According to preliminary experiments and theoretical analysis, machine's forward speed v_j, cutting speed v_g and conveying belt speed v_s, which affect operation damage rate, are selected as experimental factors. The experimental factors and levels are shown in Table 2.

Table 2

Experimental factors and levels

Level	Machine's forward speed v_j (m/s)	Cutting speed v_g (m/s)	Conveying belt speed v_s (m/s)
1	0.35	0.77	0.49
0	0.3	0.66	0.42
-1	0.25	0.55	0.35

RESULTS

Design-Expert software was used to conduct a secondary rotary combination design experiment on the experimental data. The experimental schemes and results are shown in Table 3.

Table 3

Experimental schemes and results

Number	v_j (m/s)	v_g (m/s)	v_s (m/s)	Z_s (%)
1	0.25	0.55	0.42	4.93
2	0.35	0.55	0.42	5.07
3	0.25	0.77	0.42	4.92
4	0.35	0.77	0.42	5.1
5	0.25	0.66	0.35	4.94
6	0.35	0.66	0.35	5.07
7	0.25	0.66	0.49	4.93
8	0.35	0.66	0.49	5.11
9	0.3	0.55	0.35	4.98
10	0.3	0.77	0.35	5.02
11	0.3	0.55	0.49	5.01
12	0.3	0.77	0.49	5.05
13	0.3	0.66	0.42	4.86
14	0.3	0.66	0.42	4.84
15	0.3	0.66	0.42	4.85
16	0.3	0.66	0.42	4.89
17	0.3	0.66	0.42	4.9

The experimental results were analyzed using Design-Expert software. The significance of the regression equation model was verified through analysis of variance and regression coefficient experiments. The results are presented in Table 4.

Table 4

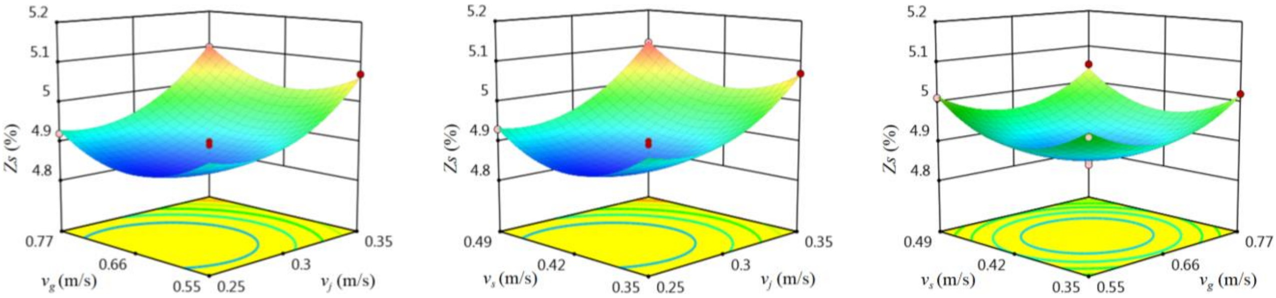
Variance analysis of damage rate

Source	Sum of Squares	Degree of freedom	Mean Square	F-value	p-value
Model	0.1251	9	0.0139	29.9	< 0.0001
v_j	0.0496	1	0.0496	106.69	< 0.0001
v_g	0.0013	1	0.0013	2.69	0.1451
v_s	0.001	1	0.001	2.18	0.1836
v_jv_g	0.0004	1	0.0004	0.8602	0.3845
v_jv_s	0.0006	1	0.0006	1.34	0.2843
v_gv_s	0	1	0	0	1
v_j^2	0.019	1	0.019	40.95	0.0004
v_g^2	0.0205	1	0.0205	44.05	0.0003
v_s^2	0.0251	1	0.0251	54.04	0.0002
Residual	0.0033	7	0.0005		
Lack of Fit	0.0006	3	0.0002	0.2861	0.8341
Pure Error	0.0027	4	0.0007		
Cor Total	0.1284	16			

According to Table 4, the regression equation for the damage rate Z_s was obtained by excluding the insignificant terms from the regression equation.

$$Z_s=12.776-17.265v_j+26.9v_j^2+5.764v_g^2+15.765v_s^2 \quad (12)$$

The interaction between any two factors and their effect on Z_s was analyzed by fitting the response surface, with any factor in eq. (12) set to the zero level, as shown in Figure 8.



(a) (b) (c)

Fig. 8 - Response surfaces effect of factor interaction on experiment indicators

As shown in the response surface in Fig. 8, the factors affecting the operation damage rate from the largest to the smallest are machine's forward speed, cutting speed and conveying belt speed.

The Design-Expert software regression equation model was used to find the optimal parameters for the experiment impact factors: v_j at 0.3 m/s, v_g at 0.66 m/s, and v_s at 0.42 m/s. Under the optimal combination of parameters, the minimum operation damage rate Z_s was 4.84%.

The average operating damage rate was 4.87%, less than 5%, which meets the design requirements. The damage was mainly due to the tearing and breakage of the stubble, and the crushing damage caused by the plants detaching from the clamping conveying device at the end of the clamping conveying.

CONCLUSIONS

(1) Based on the agronomic and mechanized harvesting requirements of leek cultivation, a double-row electric leek harvester was developed. The machine primarily consists of travel, cutting, dividing, clamping, and conveying devices. It is capable of performing cutting, conveying, and collecting operations in a single pass, thereby reducing labor intensity and significantly improving harvesting efficiency.

(2) A clamping conveying device was designed, and the working conditions required to prevent leek plants from falling, clogging, or being crushed during the clamping and conveying process were analyzed. Based on this analysis, the structural parameters and conveying speed of the device were determined.

(3) A kinematic model of the single-acting reciprocating cutting device was established, and the structural parameters of the cutting mechanism were determined. The critical conditions required for smooth and complete cutting without omissions were analyzed, leading to the determination of the optimal working parameters for the cutting device.

(4) A field experiment and performance testing method were proposed, and the field experiment was successfully conducted. During both the harvesting operation and transfer process, the harvester met the operational and mobility requirements, demonstrating good power performance and passing ability. The results of the field experiment showed that the average operational damage rate was 4.87%, meeting the actual production and mechanized harvesting requirements for leek crops.

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