SWEET POTATO VINE CUTTING MACHINE: KEY COMPONENTS DESIGN AND EXPERIMENTAL RESEARCH
/
甘薯切蔓机关键部件设计及试验研究

Biao MA[1)], Tianchan LI[2)], Weiqiang LIN[1)], Yongsheng CHEN[3)], Run ZHAO*[1)], Yanyan SHI*[1)]
[1)]Nanjing Institute of Agricultural Mechanization, Ministry of Agriculture and Rural Affairs, Jiangsu/China;
[2)] Jiangsu Academy of Agricultural Sciences, Jiangsu /China; [3)] Institute of Western Agriculture, CAAS, Xinjiang/China
Tel:+8615366092802,E-mail: 949704383@qq.com ; Tel:+8615366092810,E-mail: nriamyan@163.com
Correspondent authors: Run Zhao, Yanyan Shi
DOI: https://doi.org/10.35633/inmateh-74-39

Keywords: *Sweet potato, Vine, Straw crushing, Flail knife*

ABSTRACT
In response to technical challenges such as the difficulty in cutting long sweet potato vines in ridge furrows, low stem crushing rate, long stubble residues, and sweet high potato damage rate with the direct shredding and returning machine for sweet potato vines, this study conducted research on ridge furrow long vine removal and crushing technology, as well as optimization experiments on operating parameters. A ridge furrow boot-type vine picking knife structure, a "dynamic embedding static" shaft end anti-entanglement mechanism, and a ridge-like crushing chamber structure were designed. A high-efficiency sweet potato vine shredding and returning machine was developed, with ridge surface vine length qualification rate and ridge top stubble height as the main control indicators. The study conducted a 3-factor, 3-level orthogonal experiment in typical regions to analyze the factors of machine forward speed, knife roller speed, and ground clearance height, which significantly influence the performance. The results indicate that the optimal working parameters for the sweet potato vine cutting machine are a knife roller speed of 2000 r/min, a forward speed of 0.6 m s^{-1}, and a ground clearance height of 10 mm. The vine crushing length qualification rate reached 94%, and the stubble height of 5.3 cm exceeded the various indicators, meeting the agricultural requirements for sweet potato harvesting.

摘要
针对甘薯秧蔓直接粉碎还田机械垄沟秧难切断、茎秆粉碎率低、留茬长、伤薯率高等技术难题，本文开展了垄沟长蔓清除粉碎技术研究、作业参数最优化试验研究，设计了垄沟靴型挑秧刀结构，"动嵌静"轴端防缠绕机构和仿垄形粉碎仓机构，研制了一款高清除性甘薯秧蔓粉碎还田机，以垄面薯蔓长度合格率和垄顶留茬高度为主控指标，将机具前进速度、刀辊转速和离地高度这三个显著影响指标的因素在典型地区进行 3 因素 3 水平正交试验。结果表明甘薯切蔓机的最优工作参数：刀辊转速为2000r/min，前进速度为0.6m s^{-1}，离地高度为10mm。薯蔓粉碎长度合格率 94%，留茬高度 5.3cm 高于各项指标，满足了甘薯收获农艺要求。

INTRODUCTION
Sweet potatoes have been cultivated in China for over 400 years. In 2022, China's total sweet potato planting area was 2.25 million hectares, accounting for 30% of the world's planting area, with a total production of 49.196 million tons, representing 55% of the world's production *(Mu et al., 2019).*

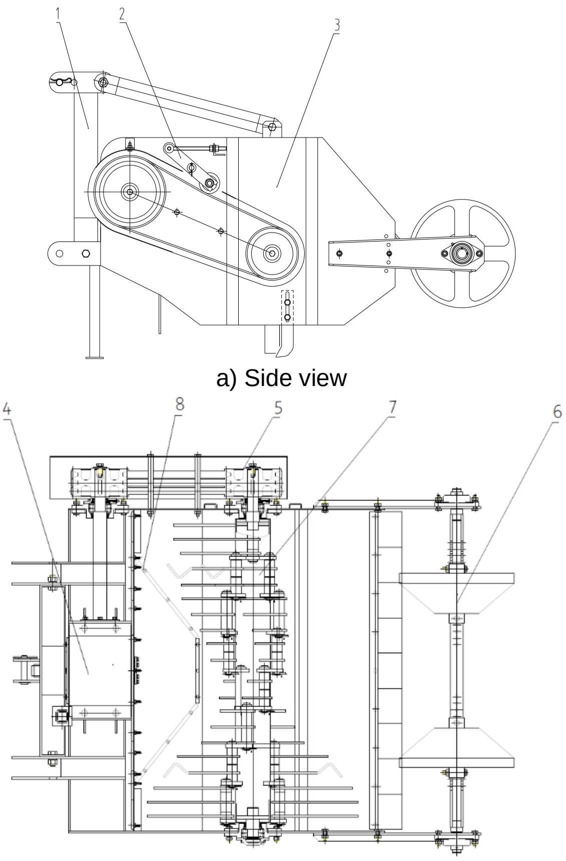
The crushing of sweet potato vines is a crucial step in sweet potato harvesting, directly affecting the efficiency and effectiveness of the harvest. Developed countries have conducted early and relatively mature research on vine shredders *(Amer et al., 2014)*. Countries like the UK and the US mainly use large-scale equipment, including large multi-row vine shredding and returning machines, as well as large combined harvesters that can complete digging, conveying, forced separation of vines, cleaning, sweet potato collection, and vine throwing operations in one go. These machines require significant power, close coordination between agricultural machinery and practices, and are designed for shorter varieties of sweet potato vines. For example, the TSP1900 large tractor-mounted sweet potato harvester produced by the Stanton company in the UK is currently not applicable in China due to its vine removal and harvesting mode. Countries like Japan and South Korea, where the field sizes are relatively small, mostly adopt the direct vine shredding and returning mode before sweet potato harvesting, using small single-row machines. The technology of small-scale vine shredding has certain reference value for China.

In recent years, with the emergence of large-scale sweet potato plantations and severe shortage of rural labor, the market demand for sweet potato machinery has been increasing. The development of sweet potato cutting and vine removal devices in China has entered a new stage, with the successive development of some sweet potato vine cutting machines *(Mu et al., 2018).* Currently, most domestically developed sweet potato vine cutting machines are improved and designed based on rice, wheat, corn, and potato shredding and returning machines. Sweet potato vines mostly grow horizontally, and aside from vine removal, it is essential to prevent long vines from entangling or blocking during subsequent digging and harvesting. The different physical and growth characteristics, as well as agricultural practices of sweet potatoes, lead to poor adaptability of other machinery used for vine cutting. Therefore, existing sweet potato vine cutting machines still have significant limitations, including high resistance, high energy consumption, low crushing qualification rates, long stubble residue lengths, low ridge furrow vine removal rates, and high sweet potato damage rates *(Ma et al., 2014; Zheng et al., 2019).* After operations, manual or mechanical secondary cleaning in the ridges is often required, restricting their widespread promotion and application. Aiming at the above problems, this paper, through structural design and experimental research, overcame the difficulty in cutting long sweet potato vines in ridge furrows, low stem crushing rate, long stubble residues, and sweet high potato damage rate with the direct shredding and returning machine for sweet potato vines, and developed an efficient and high-clearance vine crushing and returning machine to provide a good working environment for sweet potato harvesting.

MATERIALS AND METHODS

Sweet Potato Vine Cutting Machine Structure and Working Principle

The sweet potato vine cutting machine is mainly composed of the hood assembly, camshaft roller assembly, suspension mechanism, gearbox assembly, transmission mechanism, tensioning components, and ridge-like depth wheel components. Its basic structure is shown in Figure 1. The power transmission path during operation is as follows: the power output shaft at the rear of the tractor transmits power to the gearbox assembly through the universal joint drive shaft *(Ma et al., 2015; Lv et al., 2016; Zhou et al., 2022).* The gearbox assembly increases the speed and changes direction, then transfers the power to the camshaft roller assembly through pulleys and V-belts.



a) Side view

b) - Top view

Fig. 1 - The structure diagram of sweet potato vine-cutting machine

1. Traction frame; 2. Tensioning gear; 3. Casing assembly; 4. Gearbox assembly; 5. Transmission mechanism; 6. Ridge-like deep limit wheel assembly; 7. Profile cutter roll assembly; 8. Ridge-like hood

Sweet Potato Vine Cutting Machine Working Principle

During operation, the vine cutting machine is suspended behind the tractor through the suspension mechanism. It connects the power output shaft at the rear of the tractor and the input shaft of the cutting machine gearbox through universal joints. After opening, the power output controls the speed at the rated speed. Then, the ridge-like depth wheel is mounted on the ridge, and the tractor moves forward at a constant speed *(Mu et al., 2021).* The knife roller is driven to rotate at high speed through the transmission system to cut and directly crush the vine. The high-speed rotation of the knife roller creates negative pressure in the semi-enclosed crushing chamber. The vine is sucked into the crushing chamber under the negative pressure at the feed inlet, and after multiple impacts, cutting, tearing, and kneading actions, it forms crushed segments that are scattered and returned to the field. When completing a turn at the end of each ridge operation, the power output is closed, the rear suspension is lifted, and then the machine is turned around.

Key Component Parameter Determination

Length of the Vine-cutting knife

If the clearance between the vine-cutting knife and the ground is too large, it may miss cutting the vines that grow close to the ground. If the vine-cutting knife enters the soil, it will impact the tool, knife holder, and knife roller, causing strong vibration of the machine, which will greatly affect the service life, stability, and reliability of the machine. Additionally, it may cause damage to the sweet potatoes, so it should be avoided as much as possible to prevent the vine-cutting knife from entering the soil. The determination of the vine-cutting knife length should vary according to the changes in the ridge shape, gradually increasing from the ridge top to the ridge furrow, with the vine-cutting knife tip about 4 cm away from the ridge surface. Furthermore, to ensure the proper coordination of the vine-cutting knife with the ridge-like hood for vine cutting, the distance between the vine-cutting knife and the upper hood should be controlled at 23 mm.

The number of blades is 40 pieces, using double helix staggered symmetrical arrangement, each pair of blades in the rotation process of the centrifugal force generated in the same plane, opposite direction, the same size, good balance, small vibration.

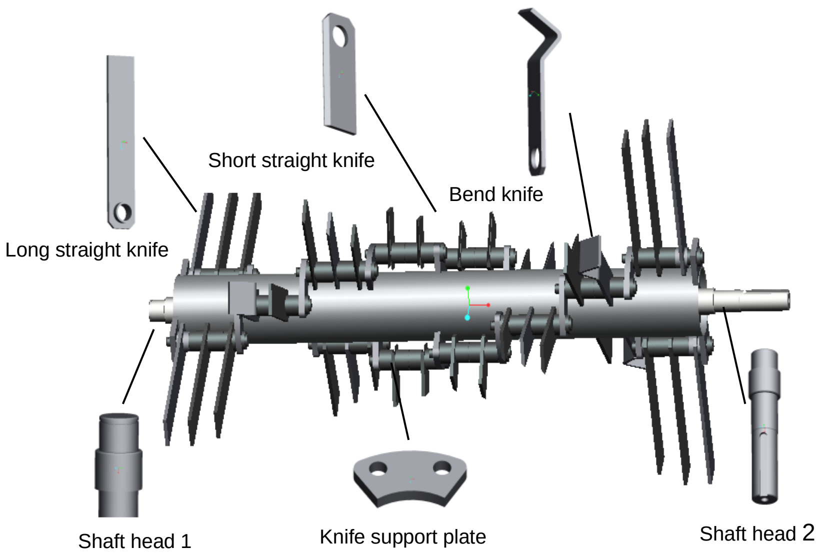


Fig. 2 - The structure diagram of cutter roller combination mechanism

Design of boot-shaped knife for raising vine

In order to solve the phenomenon of insufficient cleaning of ridge and vine, a pair of picking knife is added to the bottom of both sides of the vine cutting machine. By using the combination of boot-type ridge lifting knife with self-sliding angle and the long cutter outside the cutter roll, the broken vine will automatically slide down along the boot angle to realize automatic cleaning, and effectively solve the entanglement and blocking problem of ridge and long vine on subsequent harvesting machinery, improving the operation smoothness. The inclination Angle β of the blade tip of the seedling picking knife should be satisfied, and the friction angle of the soil on the blade is 23° - 26 °, so 60° is taken here. In order to facilitate the upward slippage of the vine being picked, the knife tip is designed at a 55° angle. The 65Mn material is used, the blade is double-sided, and the tip needs heat treatment.

Determination of Knife Roller Speed

If the knife roller speed is too low, the vine may not be crushed sufficiently. On the other hand, if the speed is too high, it will increase power consumption and exacerbate the wear and tear of the machine. Therefore, the speed should be determined within a reasonable range, ideally lower to ensure the vines are fully crushed. During machine operation, the absolute speed of the vine-cutting knife is the composite of the forward speed of the whole machine and the rotation speed of the knife roller. To avoid vine pushing during operation, the vine-cutting knife's motion trajectory needs to be a cycloidal curve, as shown in Figure 3.

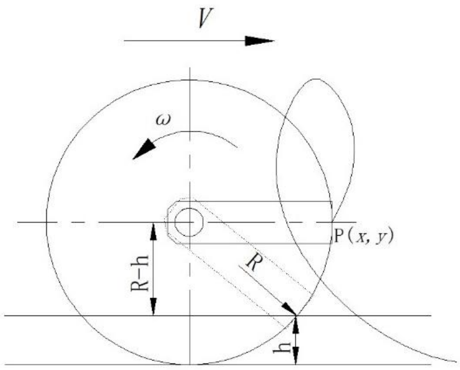


Fig. 3 - The trajectory of the vine-cutting knife

Let P (x, y) be a point on the tip of the vine-cutting knife for vine cutting, assuming the coordinates of the origin are at position O(0,0) at the initial time of 0.

It can be seen that:

$$\begin{cases} x = Vt - R\cos\omega t \\ y = R\sin\omega t \end{cases} \quad (1)$$

where: V is the forward speed of the vine cutting machine, (m s-1);

t is the duration of the knife roller movement, (s);

R is the maximum radius of rotation for the vine-cutting knife in vine cutting, (m);

ω is the angular speed of the knife roller for vine cutting, (rad/s);

h is the distance from the ground on the tip of the knife, (m);

Differentiating equation (1) with respect to t as the independent variable:

$$\begin{cases} V_x = V + R\sin\omega t \\ V_y = R\cos\omega t \end{cases} \quad (2)$$

In equation (1):

V_x is the horizontal component velocity (m s-1)

V_y is the vertical component velocity (m s-1)

In a stable operating state of the sweet potato vine cutting machine, with V_p=0.48m s^{-1}, effective cutting height h=0.15m, maximum vine-cutting knife rotation radius R=0.326m, and based on “Agricultural machinery design manual”, V_c=30m s^{-1}. As shown in Figure 3, in order to ensure that the sweet potato vines are fully crushed, the absolute value of the horizontal component velocity of the vine-cutting knife must not be lower than the linear speed V_c required for vine cutting. From the given condition, $sin\omega t=(R-h)/R$, combining the above formulas, the speed of the knife roller can be determined.

$$n \geq 30\ (Vc\text{-}V)\ /\ [\pi\ (R\text{-}h)\ ] \quad (3)$$

Substituting the above data into formula (3), the rotational speed n of the sweet potato vine cutting knife roller should not be less than 1602 r/min.

Ridge-like Depth Wheel Assembly

When the vine cutting machine is too low, the vine-cutting knife may enter the soil, causing damage to the sweet potatoes, generating strong vibrations in the machine, leading to damage and increased energy consumption. On the other hand, if the vine cutting machine is too high, it may result in insufficient crushing of the vine. The main components of the depth wheel assembly include: width adjustment tube, height adjustment support arm, dumbbell-shaped ground wheel, support shaft, and bearing seat. Due to different ridge specifications in different regions, the depth wheel can adjust the machine's operating state according to different specifications.

The adjustable width range is 190 mm to 430 mm, and the adjustable height range is 290 mm. Additionally, the depth wheel is designed with a conical surface to clamp the side of the ridge, preventing the machine from swaying from side to side, facilitating smooth operation, and improving work quality *(Wu et al., 2021).* The structural diagram of the depth wheel assembly is shown in Figure 4.

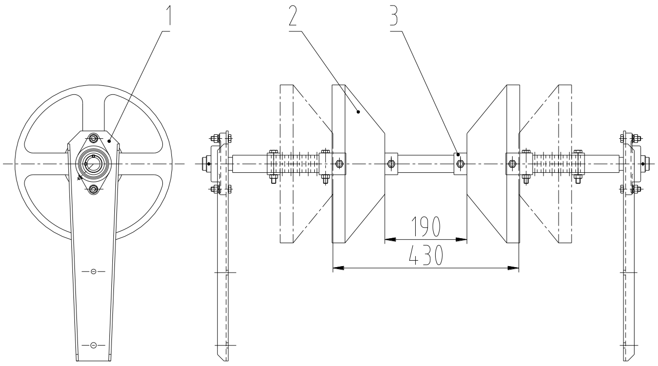


Fig. 4 - The basic structure of depth-control wheel combination
1. Height adjustment arm; 2. Land wheel; 3. Width regulating tube

Solutions for anti-winding device

The root cause of the winding is found that the gap between the end of the knife roll and the bearing seat is too large. Therefore, reducing or even eliminating the gap is the design idea of the anti-winding technology of the shaft end. It is found that the diameter of the bearing seat is less than the diameter of the cutter roller barrel, and the idea of extending the bearing seat into the shaft barrel is put forward. Translate the side plate of the cutter roll inward to leave space, and then extend the bearing seat into the shaft barrel, as shown in Figure 5. The experiment proved that the anti-entanglement had a good effect, and almost no entanglement problem occurred.

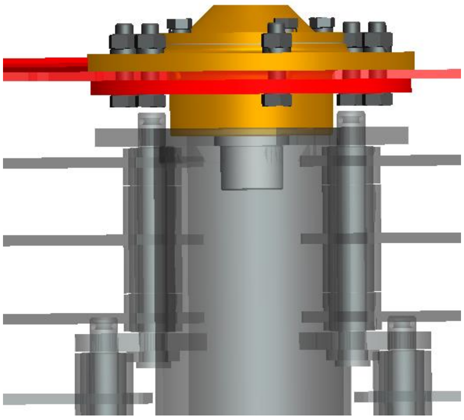


Fig. 5 - The technology of winging preventing at the shaft end

Sweet Potato Vine Cutting Machine Field Test

Test Conditions

The test site selected is the Sweet Potato Base of the Commercial Crop Research Institute in Shangqiu City. The terrain of the site is flat, free of obstacles, with sandy loam soil, measuring 60 meters long and 22 meters wide. The average soil moisture content is 7.3%. The average soil compaction is 120.3 kPa. The average plant spacing is 22.2 cm, ridge height is 20.4 cm, ridge top width is 30.8 cm, ridge base width is 64.6 cm, and ridge spacing is 89.5 cm.

Physical Characteristics of Sweet Potatoes in the Test Site

(1) Variety Selection

The selected variety for the experiment is Shangshu 19, which has a large planting area in China and is highly representative. The vine length ranges from 1 to 3.5 meters, with around 8 branches at the base and no trichomes at the top of the stem.

(2) Vine Length, Diameter, and Moisture Content

At ten random locations in the test site, measurements were taken for the vine length, vine diameter, and stem moisture content. The average values obtained through measurements are 259.4 cm for length, 0.57 cm for diameter, and 89.4% for moisture content.

(3) The tensile and shear tests of sweet potato stem were carried out by universal testing machine. The average tensile force was 110 N and the average cutting force was 106 N.

Field Test and Analysis

In order to determine the optimal combination of machine operating parameters, field tests were conducted at the Sweet Potato Experimental Base of the Commercial Crop Research Institute in Liangyuan District, Shangqiu City. The weather conditions were sunny, with an environmental temperature of 23.5°C and humidity of 43.6%. The sweet potato variety used was Shangshu 19.

Factors Affecting Experimental Indicators

Field tests and equipment inspections refer to the "Draft Regulations for Sweet Potato Vine Crushing and Returning Machine Tests and Inspections" and the "Technical Regulations for Mechanized Ridge Harvesting Operations of Sweet Potatoes."

There are many factors that influence the indicators of sweet potato vine crushing and returning machines (such as the qualification rate of vine crushing length on ridge surface and the average height of stubble left at the top of the ridge), including design factors, processing and manufacturing factors, planting mode factors, crop growth conditions, field conditions, and machine operating parameter factors. The following experiments will focus on the impact of machine operating parameters on the indicators. Among the operating parameters, the factors that have a significant impact on the operational indicators are the forward speed of the machine (v), the rotational speed of the knife roller (ω), and the height of the knife roller above the ground (h).

Single-factor Experiments Affecting the Quality of Sweet Potato Vine Crushing and Returning Machine Operation

Through single-factor experiments, analyze the impact of each influencing factor on the quality of sweet potato vine crushing and returning machine operation, observe the trend of each factor's impact on the qualification rate of vine crushing length (The qualified length of potato vine crushing is not more than 150 mm) and a significant effect on the height of stubble left at the top of the ridge, determine the range of values for each factor, conduct orthogonal experimental research on each factor and its levels, determine the primary and secondary factors affecting vine crushing, and identify the optimal parameter combination for each factor.

(I) Impact of Forward Speed on Operational Quality

(1) Experimental Plan

To study the effect of machine forward speed on the sweet potato vine crushing effect, with the knife roller speed set at 1800 rpm and the lifting height of the vine-cutting knife set at 20 mm, the tractor drives the vine cutting machine to advance at five different speeds of 0.7 m s-1, 0.65 m s-1, 0.6 m s-1, 0.55 m s-1, and 0.5 m s-1. The qualified rate of sweet potato vine length and stubble height at ridge top were used as the main control index. During the experiment, the machine worked for 20 meters per row, excluding the first and last 5 meters. Measurements of various indicators of sweet potato vine crushing will be taken at three points within a stable 10-meter working area in the middle, to study the relationship between machine forward speed and crushing effect.

(2) Experimental Results and Analysis

Field experiments were conducted according to the experimental plan, and the qualification rate of vine crushing length on the ridge surface and the average height of stubble left at the top of the ridge were obtained under different forward speeds of the machine. Single-factor analysis of variance on the impact of different forward speeds on operational quality was conducted using SPSS and Excel software, with results shown in Figure 6.

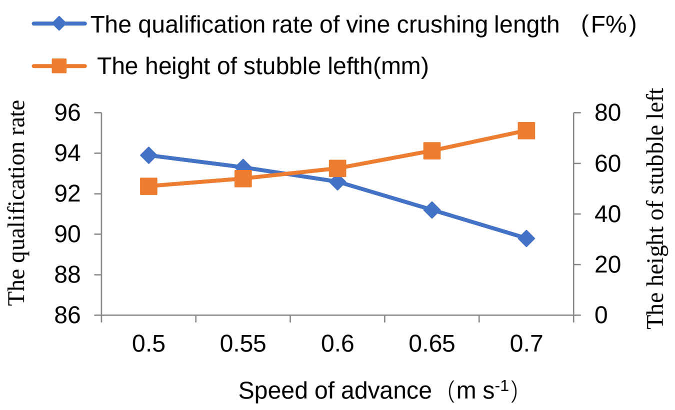


Fig. 6 - The influence of forward speed on indexes

The analysis results indicate that the machine's forward speed has a significant impact on the qualification rate of vine crushing length on the ridge surface and a significant effect on the height of stubble left at the top of the ridge. From a comprehensive analysis of the experimental results, it can be concluded that the qualification rate of sweet potato vine crushing decreases with increasing machine forward speed, while the height of stubble left at the top of the ridge increases with the machine's forward speed.

(II) Impact of Knife Roller Speed on Operational Quality

(1) Experimental Plan

To study the effect of the cutting knife roller speed on the quality of sweet potato vine crushing and returning machine operation, the forward speed of the machine was set at 0.6 m s-1, the lifting height was set at 20 mm, and the knife roller speed was set at 1600 rpm, 1700 rpm, 1800 rpm, 1900 rpm, and 2000 rpm. Since the parameter values when the speed is set to 1800 rpm were repeated in the third group of the experiment on the impact of knife roller speed on operational quality, this group was omitted in this round of experiments. The qualified rate of sweet potato vine length and stubble height at ridge top were used as the main control index. During the experiment, the machine worked for 20 meters per row, excluding the first and last 5 meters. Measurements of various indicators of sweet potato vine crushing were taken at three points within a stable 10-meter working area in the middle to study the relationship between the cutting machine's knife roller speed and crushing effect.

(2) Experimental Results and Analysis

Field experiments were conducted according to the experimental plan, obtaining the qualification rate of vine crushing length on the ridge surface and the average height of stubble left at the top of the ridge under different roller speeds. Single-factor analysis of variance on the impact of knife roller speed on operational quality was conducted using SPSS and Excel software, with results shown in Figure 7. The analysis results indicate that the roller speed has a highly significant impact on the qualification rate of vine crushing length on the ridge surface and a significant effect on the height of stubble left at the top of the ridge.

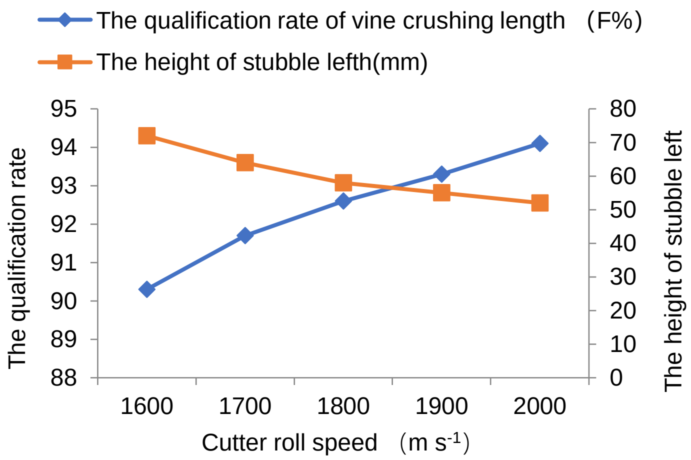


Fig. 7 - The influence of cutter roller speed

From a comprehensive analysis of the experimental results, it can be concluded that the qualification rate of sweet potato vine crushing increases with the increase in roller speed, while the height of stubble left at the top of the ridge decreases with the increase in roller speed.

(III) Impact of Knife Roller Lifting Height on Operational Quality

(1) Experimental Plan

To study the effect of the knife roller lifting height on the quality of sweet potato vine crushing and returning machine operation, the forward speed of the machine was set at 0.6 m s-1, the knife roller speed was set at 1800 m s-1, and the knife roller lifting height was set at 10 mm, 15 mm, 20 mm, 25 mm, and 30 mm. The qualified rate of sweet potato vine length and stubble height at ridge top were used as the main control index. During the experiment, the machine worked for 20 meters per row, excluding the first and last 5 meters. Measurements of various indicators of sweet potato vine crushing were taken at three points within a stable 10-meter working area in the middle to study the relationship between the knife roller lifting height and the crushing effect.

(2) Experimental Results and Analysis

Field experiments were conducted according to the experimental plan, obtaining the qualification rate of vine crushing length on the ridge surface and the average height of stubble left at the top of the ridge under different lifting heights of the knife roller. Single-factor analysis of variance on the impact of the knife roller at different lifting heights on operational quality was conducted using SPSS and Excel software, with results shown in Figure 8. The analysis results indicate that the knife roller lifting height has a highly significant impact on the qualification rate of vine crushing length on the ridge surface and the height of stubble left at the top of the ridge.

From a comprehensive analysis of the experimental results, it can be concluded that the qualification rate of sweet potato vine crushing increases with decreasing lifting height, while the height of stubble left at the top of the ridge decreases with decreasing lifting height.

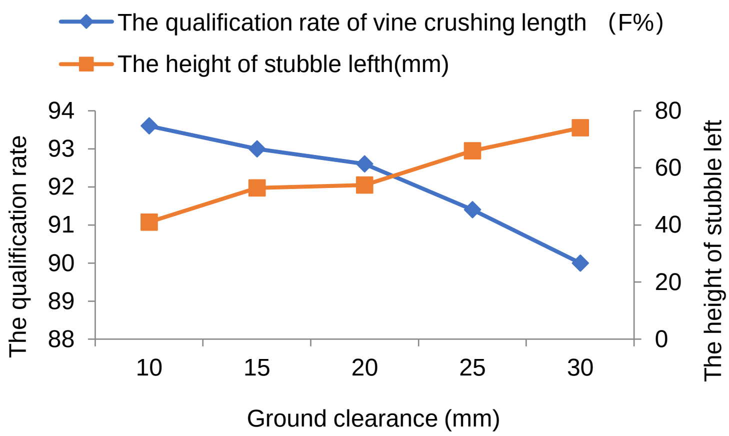


Fig. 8 - The influence of the height from the ground

Orthogonal Experiment Affecting Operational Quality

Through single-factor experiments, it is known that the machine's forward speed, knife roller speed, and knife roller lifting height in the working parameters of the sweet potato vine crushing and returning machine all play significant roles in the operational quality of the machine. The following orthogonal experiment will be conducted to determine the primary and secondary factors affecting the qualification rate of vine crushing length on the ridge surface and the average height of stubble left at the top of the ridge, as well as the optimal combination of working parameters.

Fig. 9 - Working conditions of vine-cutting machine

(1) Experimental Plan and Results

In this round of experiments, based on the single-factor experiments, with the qualification rate of vine length on the ridge surface (The qualified length of potato vine crushing is not more than 150 mm) and the height of stubble left at the top of the ridge as the main control indicators, a 3-factor 3-level orthogonal experiment was conducted on the three significant influencing factors of machine forward speed, knife roller speed, and lifting height. The levels of each factor are shown in Table 1, taking into account the primary interactions between the factors. The experimental design was based on the L27 orthogonal table. The plan and results are shown in Table 2.

Table 1

Orthogonal test factors and levels

Factor	Level		
	-1	0	1
A Speed of advance (m s^{-1})	0.7	0.6	0.5
B Cutter roll speed (rpm)	1600	1800	2000
C Ground clearance (mm)	10	20	30

Table 2

Test plan and experimental data

Test number	Factor													The qualification rate of vine crushing length F (%)	The height of stubble left H (mm)
	A	B	A×B		C	A×C		B×C		Empty list					
1	1	1	1	1	1	1	1	1	1	1	1	1	1	89.5	66
2	1	1	1	1	2	2	2	2	2	2	2	2	2	88.9	72
3	1	1	1	1	3	3	3	3	3	3	3	3	3	87.4	74
4	1	2	2	2	1	1	1	2	3	2	2	3	3	91.1	63
5	1	2	2	2	2	2	2	3	1	3	3	1	1	89.8	73
6	1	2	2	2	3	3	3	1	2	1	1	2	2	89.6	74
7	1	3	3	3	1	1	1	3	2	3	3	2	2	92.9	52
8	1	3	3	3	2	2	2	1	3	1	1	3	3	92.5	59
9	1	3	3	3	3	3	3	2	1	2	2	1	1	91.2	67
10	2	1	2	3	1	2	3	1	1	2	3	2	3	90.8	68
11	2	1	2	3	2	3	1	2	2	3	1	3	1	90.3	72
12	2	1	2	3	3	1	2	3	3	1	2	1	2	89.2	75
13	2	2	3	1	1	2	3	2	3	3	1	1	2	91.6	41
14	2	2	3	1	2	3	1	3	1	1	2	2	3	92.6	58
15	2	2	3	1	3	1	2	1	2	2	3	3	1	88.0	74
16	2	3	1	2	1	2	3	3	2	1	2	3	1	94.4	49
17	2	3	1	2	2	3	1	1	3	2	3	1	2	94.1	52
18	2	3	1	2	3	1	2	2	1	3	1	2	3	92.9	59
19	3	1	3	2	1	3	2	1	1	3	2	3	2	93.2	49
20	3	1	3	2	2	1	3	2	2	1	3	1	3	93.0	57
21	3	1	3	2	3	2	1	3	3	2	1	2	1	91.7	68
22	3	2	1	3	1	3	2	2	3	1	3	2	1	94.8	47
23	3	2	1	3	2	1	3	3	1	2	1	3	2	93.9	51
24	3	2	1	3	3	2	1	1	2	3	2	1	3	90.2	63
25	3	3	2	1	1	3	2	3	2	2	1	1	3	95.8	48
26	3	3	2	1	2	1	3	1	3	3	2	2	1	94.1	50
27	3	3	2	1	3	2	1	2	1	1	3	3	2	93.3	59

(2) Analysis of Variance of Experimental Results

The results obtained from the orthogonal experiment were subjected to variance analysis using SPSS software to determine the primary and secondary factors affecting the qualification rate of vine length on the ridge surface and the height of stubble left at the top of the ridge, as well as the significance of these factors. With a given significance level of 0.05, the results are shown in Table 3.

Table 3

The result of analysis variance

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig·
Calibration Model	F	132.171a	18	7.343	4.002	.026
	H	2748.667c	18	152.704	6.048	.007
Intercept	F	227553.840	1	227553.840	124020.058	.000
	H	101200.333	1	101200.333	4007.934	.000
A	F	37.254	2	18.627	10.152	.006
	H	679.556	2	348.778	13.813	.003
B	F	44.827	2	22.414	12.216	.004
	H	709.556	2	354.778	14.051	.002
C	F	41.956	2	20.978	11.433	.005
	H	1028.222	2	514.111	20.361	.001
A×B	F	4.095	4	1.024	.558	.700
	H	151.556	4	37.889	1.501	.289
A×C	F	.559	4	.140	.076	.987
	H	80.889	4	20.222	.801	.557
B×C	F	3.479	4	.870	.474	.754
	H	80.889	4	20.222	.801	.557
Error Total	F	14.679	8	1.835	/	/
	H	202.000	8	25.250	/	/
Total	F	227700.690	27	/	/	/
	H	104151.000	27	/	/	/
Corrected Total	F	146.850	26	/	/	/
	H	2950.667	26	/	/	/

a. R-squared = 0.900 (Adjusted R-squared = 0.675); b. The calculation result using alpha = 0.05
c. R-squared = 0.932 (Adjusted R-squared = 0.778)

From the analysis in Table 7, the primary and secondary factors affecting the qualification rate of vine length on the ridge surface and the height of stubble left at the top of the ridge are as follows:

(1) Significance Analysis

Factors A, B, and C have a very significant impact on the qualification rate of vine length on the ridge surface and the height of stubble left at the top of the ridge. Other interactions do not significantly affect the qualification rate of vine length on the ridge surface and the height of stubble left at the top of the ridge.

(2) Primary and Secondary Factors Analysis

The ranking of primary and secondary factors affecting the qualification rate of vine length on the ridge surface is as follows: B > C > A, meaning that knife roller speed > lifting height > forward speed. The ranking of primary and secondary factors affecting the height of stubble left at the top of the ridge is as follows: C > B > A, meaning that lifting height > knife roller speed > forward speed.

(3) Weighted Comprehensive Scoring Method to Determine the Optimal Parameter Combination

From the results of the analysis of variance, it is evident that the significance and primary-secondary relationships of each factor on each indicator are different. In order to comprehensively assess various indicators and determine the optimal parameter combination to achieve the best crushing effect, a weighted comprehensive scoring method is used to analyze the experimental results. The cleaning of sweet potato vines is to facilitate the work of the sweet potato harvester in the following steps. Leaving too many long vines will cause the sweet potato harvester to become entangled or even blocked, affecting the efficiency of the sweet potato harvester and potentially causing damage to the harvester. In addition, work efficiency needs to be taken into account as well. Work efficiency increases with the increase in the machine's forward speed. The time required for the machine to travel 10 m in a stable working state, denoted as T, is added as an evaluation indicator to the comprehensive index. Considering the importance of each indicator, with a total weight of 100 points, the qualification rate of vine length on the ridge surface (F') is assigned 40 points, the height of stubble left at the top of the ridge (H) is assigned 30 points, and the time to pass 10 m (T) is assigned 30 points. Additionally, to calculate the weighted comprehensive index, the qualification rate of vine length is converted to the non-qualification rate to ensure that all indicators have the same trend. The weighted comprehensive index Z can be calculated using the following formula:

$$Z_i = \sum_{j=1}^{r} W_j \frac{y_{ij}}{y_{j\max}} \tag{4}$$

Z_i represents the calculated weighted evaluation index of the i-th experiment group, where i = 1, 2, 3, ..., 27;
W_j represents the "weight" value of the j-th indicator, where j = 1, 2, 3, with $W1$ = 40, $W2$ = 30, $W3$= 30;
y_{ij} represents the j-th indicator in the first experiment group, where y_{1j} is the non-qualification rate of vine length on the ridge surface, y_{2j} is the height of stubble left at the top of the ridge, and y_{3j} is the time to pass 10 m;
y_{jmax} represents the maximum value of the j-th indicator among all 27 experiment groups.

The results of calculating the weighted comprehensive index Z by inputting the data of each parameter into the formula are shown in Table 4.

Table 4

Test results of the comprehensive index

Test number	Factor													Composite indicator Z
	A	B	A×B		C	A×C		B×C		Empty list				
1	1	1	1	1	1	1	1	1	1	1	1	1	1	80.2
2	1	1	1	1	2	2	2	2	2	2	2	2	2	85.9
3	1	1	1	1	3	3	3	3	3	3	3	3	3	91.5
4	1	2	2	2	1	1	1	2	3	2	2	3	3	73.9
5	1	2	2	2	2	2	2	3	1	3	3	1	1	81.9
6	1	2	2	2	3	3	3	1	2	1	1	2	2	82.9
7	1	3	3	3	1	1	1	3	2	3	3	2	2	64.0
8	1	3	3	3	2	2	2	1	3	1	1	3	3	68.0
9	1	3	3	3	3	3	3	2	1	2	2	1	1	75.2
10	2	1	2	3	1	2	3	1	1	2	3	2	3	80.4
11	2	1	2	3	2	3	1	2	2	3	1	3	1	83.5
12	2	1	2	3	3	1	2	3	3	1	2	1	2	87.4
13	2	2	3	1	1	2	3	2	3	3	1	1	2	67.5
14	2	2	3	1	2	3	1	3	1	1	2	2	3	70.8
15	2	2	3	1	3	1	2	1	2	2	3	3	1	91.6
16	2	3	1	2	1	2	3	3	2	1	2	3	1	61.7
17	2	3	1	2	2	3	1	1	3	2	3	1	2	63.8
18	2	3	1	2	3	1	2	2	1	3	1	2	3	70.3
19	3	1	3	2	1	3	2	1	1	3	2	3	2	70.4
20	3	1	3	2	2	1	3	2	2	1	3	1	3	74.1
21	3	1	3	2	3	2	1	3	3	2	1	2	1	82.5
22	3	2	1	3	1	3	2	2	3	1	3	2	1	64.6
23	3	2	1	3	2	1	3	3	1	2	1	3	2	69.0
24	3	2	1	3	3	2	1	1	2	3	2	1	3	85.3
25	3	3	2	1	1	3	2	3	2	2	1	1	3	61.8
26	3	3	2	1	2	1	3	1	3	3	2	2	1	68.0
27	3	3	2	1	3	2	1	2	1	1	3	3	2	74.0

Performing variance analysis on the comprehensive scoring results, the results are shown in Table 5.

Table 5

The result of comprehensive score analysis variance

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Calibration Model	Z	2084.287[a]	18	115.794	9.666	.001
Intercept	Z	152656.001	1	152656.001	12743.655	.000
A	Z	160.814	2	80.407	6.712	.019
B	Z	945.254	2	472.627	39.455	.000
C	Z	773.081	2	386.540	32.268	.000
A×B	Z	101.690	4	25.423	2.122	.170
A×C	Z	36.890	4	9.223	.770	.574
B×C	Z	66.557	4	16.639	1.389	.320
Error	Z	95.832	8	11.979	/	/
Total	Z	154836.120	27	/	/	/
Corrected Total	Z	2180.119	26	/	//	

a. R-squared = 0.956 (Adjusted R-squared = 0.857); b. The calculation result using alpha = 0.05

From the table, it is evident that factors A, B, and C have a very significant impact on the comprehensive index. The primary and secondary factors affecting the comprehensive index of the operation of the vine shredder and returning machine are B = C > A, meaning that the knife roller speed = lifting height > forward speed. Through visual analysis of the comprehensive index, it is determined that the optimal parameter combination is the 16th group A2B3C1, with a forward speed of 0.6m s^{-1}, knife roller speed of 2000r/min, and lifting height of 10mm.

Operational Index Testing

The machine parameters are set as follows: forward speed of 0.6 m s-1, knife roller speed of 2000 r/min, lifting height of 10 mm. The vine shredder is tested by the Mechanical Industry Agricultural Machinery Product Quality Testing Center. The test results show a vine length qualification rate of 94% and a stubble height of 5.3 cm, which are much higher than the standards in "JB/T6678-2001 Straw Shredder for Returning to the Field," the "Sweet Potato Vine Shredder Test and Inspection Method (Draft)," and the "Technical Regulations for Sweet Potato Mechanized Ridge Harvesting Operations." The machine has achieved high efficiency in vine removal.

CONCLUSIONS

This article introduces the structure and working principle of the vine cutting machine, determines the operating parameters of key components, measures the soil conditions, ridge conditions, and physical characteristics of sweet potato vines at the experimental site. By conducting field performance tests on the sweet potato vine shredder, the technical performance, vine shredding quality, and operational efficiency of the machine are determined. The study verifies whether the developed sweet potato high-efficiency vine cutting machine meets the design requirements and inspection standards, assesses its operational reliability and performance stability, and evaluates its operational quality. Through orthogonal experiments, it is revealed that the primary and secondary factors affecting the qualification rate of vine shredding length on the ridge surface are ranked as B>C>A, indicating that the knife roller speed > ground clearance height > forward speed. The primary and secondary factors affecting the height of the ridge top stubble are ranked as C>B>A, meaning that the ground clearance height > knife roller speed > forward speed. Using a weighted comprehensive analysis and scoring method, the optimal working parameter combination for the sweet potato vine cutting machine is determined to be a forward speed of 0.6 m s^{-1}, a knife roller speed of 2000 r/min, and a ground clearance height of 10 mm.

ACKNOWLEDGEMENT

This research was supported by Chinese Academy of Sciences foresight strategic science and technology pilot project (XDA0440404), National key research and development plan project(2022YF200210203), Major scientific and technological tasks of the Chinese Academy of Agricultural Sciences(CAAS-ZDRW202407).

The authors wish to thank the useful comments of the anonymous reviewers of this paper.

REFERENCES

[1] Mu Guizhi, Xin Qingqing, Xuan Guantao, Lv Zhaoqin, Wang Haining, Xin Qingsong. (2019). Design and experiment of Ridge Cutting crushing and Throwing Device for sweet potato vine Recovery Machine (甘薯秧蔓回收机仿垄切割粉碎抛送装置设计与试验). *Transactions of the Chinese Society for Agricultural Machinery*, 50 (12), pp.53-62, Shandong/China.

[2] Amer N.N. Kakahy, Ahmad D., Akhir M.D., Sulaiman S., Ishak A. (2014). Effects of rotary mower blade cutting angles on the pulverization of sweet potato vine[J]. *Agriculture and Agricultural Science Procedia*, 30(2), pp. 95－101, Iraq.

[3] Mu Guizhi, Zhang Xianguang, Lv Zhaoqin, Guo Zimeng. (2018). Design and simulation analysis of the knife roller of the profiling sweet potato seedling killing machine (仿形甘薯杀秧机刀辊的设计与仿真分析). *Journal of Chinese Agricultural Mechanization*, 39(5), pp. 21-26, Shandong /China.

[4] Ma Biao. (2014). *The research and optimized design on the high performance of cutting vine technology and mechanism of sweet potato (甘薯高清除性切蔓技术及其装置研究与优化设计).* Hefei: Anhui Agricultural University, Jiangsu/China.

[5] Zheng Wenxiu, Lv Zhaoqin, Zhang Wanzhi, Liu Zhengyi, Lu Yao, Li Yudao. (2019). Design and test of single row sweet potato vine recycling machine (单行甘薯秧蔓回收机设计与试验). *Transactions of the CSAE*, 35(6), pp. 1 − 9, Shandong/China.

[6] Ma Biao, Hu Lianglong, Xu Liangyuan, Tian Lijia, JI Fulai, Wang Bing. (2015). Design and Dynamic balance analysis of cutter roll of sweet potato vine crushing machine (甘薯秧蔓粉碎还田机刀辊设计与动平衡分析). *Journal of Chinese Agricultural Mechanization*, 36 (4), pp. 18 ~ 21, Jiangsu/China.

[7] Lv Jinqing, Shang Qinqin,Yang Ying, Li Zihui, Li Jicheng, Liu Zhongyuan. (2016). Design and experimental on potato haulm cutter (马铃薯杀秧机设计优化与试验). *Transactions of the Chinese Society for Agricultural Machinery*, 47(5), pp. 106 − 114, Heilongjiang/China.

[8] Zhou Zihan, Shang Shuqi, Wang Dongwei, He Xiaoning, Tan Ying, Dong Cheng. (2022). Sweet potato seedling special cut harvest machines, design and test (甘薯秧蔓收获机专用割台设计与试验). *Journal of Chinese agricultural mechanization, lancet*, (12), pp. 26-32, Shandong /China.

[9] Mu Guizhi, Qi Xieteng, Zhang Wanzhi, Lv Zhaoqing, Zhang Tingting, Wang Shuwen, Wang Gongpu. (2021). Chopped sweet potato seedling discrete element simulation parameters measurement and calibration (碎甘薯秧离散元仿真参数测量与标定). *Journal of Chinese agricultural mechanization*, vol.(11), pp. 72-79, Shandong/China.

[10] Wu Teng, Hu Lianglong, Wang Gongpu, Hu Zhichao, Yan Wei,Wang Bing. (2017). Design and experiment of Walking Machine for returning shredded sweet potato to field (步行式甘薯碎蔓还田机的设计与试验). *Transactions of the Chinese Society of Agricultural Engineering*, 33(16), pp. 8-17, Jiangsu/China.