EXPERIMENTAL STUDY ON TWO-SIDED LOOSENING SHOVEL OF DIGGING-PULLING CASSAVA HARVESTER

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挖拔式木薯收获机两侧式松土铲的试验研究

Wang YANG[1)], Xu WAN[1)], Junhui XI[1)], Debang ZHANG[1)], Yu HUANG[1)], Xian ZHENG[1)], Zhiheng LU[1*)], Ganran DENG[2)], Zhende CUI[2)]

[1)]College of Mechanical Engineering, Guangxi University, Nanning, 530004, China

[2)]Institute of Agricultural Machinery, Chinese Academy of Tropical Agricultural Sciences, Zhanjiang, 524091, China

Tel: +86 13552574667; E-mail: 8812316@163.com

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ABSTRACT

Cassava is one of the world's top three tuber crops, and its harvesting mechanization level is low. Digging-pulling cassava harvester is the main research direction of cassava harvesters. However, the soil-loosening components of the existing digging-pulling harvesters have poor loosening effect, high tuber damage rate, and large pulling force of cassava tubers after loosening. The two-sided loosening shovel that digs and loosens the soil on both sides of the tubers has low working resistance and is not easy to damage the tubers, but there are few reports on the impact of its operating performance. Therefore, this study focuses on three common types of two-sided soil-loosening shovels: the offset-wing shovel (OWS), L shovel (LS), and double-wing shovel (DWS). A two-factor, three-level orthogonal experiment is conducted, taking tillage depth (h) and shovel distance (b) as variables, then range analysis and factor impact analysis are carried out. Finally, through comprehensive comparison and optimization, a shovel type with best operational effects and its optimal working conditions are identified. The results show the LS demonstrated optimal performance when the breakage rate and pulling force were minimized. At the optimal combination of h of 0.25 m and b of 0.6 m, the LS has a breakage rate of 7.576% and a pulling force of 291.608 N. This study can provide basis for optimizing the design of loosening parts of digging-pulling cassava harvester.

摘要

木薯是世界三大薯类作物之一，其机械化收获水平低。挖拔式木薯收获机是木薯收获机的主要研究方向。但现有挖拔式木薯收获机的挖掘松土部件松土效果较差，伤薯率高，且松土后木薯块根拔起力大。而挖松块根两侧土壤的两侧式松土铲工作阻力小，不易伤薯，但目前其作业性能影响研究鲜有报道。因此，本文以偏翼铲、L 铲、双翼铲三种常用的两侧式松土铲为对象，以耕深 h 和铲距 b 作为因素，分别进行两因素三水平正交试验，并对试验因素及结果进行极差分析和因素影响分析，最后通过综合比较和优化获得一种作业效果相对好的铲型及其较优的耕作条件。结果表明当断薯率和最大拔起力小时，L 铲作业效果最优。该铲在耕深为 0.25m 和铲距为 0.6m 的较优组合时，断薯率为 7.576%，最大拔起力为 291.608N。本文可为挖拔式木薯收获机松土部件的优化设计提供依据。

INTRODUCTION

Harvesting is one of the most difficult and expensive operations worldwide *(Awad, et al., 2022, Khater, et al., 2023)*. Cassava (*Manihot esculenta*) is widely cultivated in tropical and subtropical regions, and is one of the world's three major tuber crops along with potatoes and sweet potatoes. Its tuberous roots are rich in starch, known as the "king of starch" and "underground granary" *(Wang, et al., 2019)*. Ranked sixth in terms of yield among food crops, cassava serves as a staple food for about six hundred million people worldwide *(Jansson, et al., 2009, Vandegeer, et al., 2013).* Moreover, it is a key component in industrial raw materials and a prominent source of biofuel energy *(Li, et al., 2017, Parmar, et al., 2017, Sivamani, et al., 2018).* However, primarily manual labor is still employed in cassava harvesting *(Amponsah, et al., 2014, Chalachai, et al., 2013),* which is labor-intensive and hampers the expansion of the cassava industry. Therefore, research of cassava harvesting machinery is important to the progress of the cassava industry.

Cassava harvesters are categorized into digging and loosening type, digging and shaking separation type, and digging-pulling type *(Yang, et al., 2012)*. The digging and loosening type cassava harvester uses a digging shovel to separate cassava roots from the soil, then manually picks up the tubers after arching them out. This harvester has a simple structure, low manufacturing cost, and has been adaptable to various soil types. However, its working efficiency is low. The representative machines include the Ⅱ type single-row cassava harvester developed by Cuba *(Odigboh, 1991)*, the P-900 type double-row cassava tuber harvester (Fig. 1a) developed by Brazil *(Chen, et al., 2022, Ospina, et al., 2002)*, the TEK mechanical harvester developed in Ghana *(Amponsah, et al., 2018)*, and the 4UMS-390II cassava harvester designed by Xue et al. *(Xue, et al., 2010)*. The digging and shaking separation type cassava harvester uses a digging shovel to lift the clods containing tubers and roots, which is then elevated and shaken along lifting chain to separate the soil from the cassava tubers. This cassava harvester is highly efficient but consumes a lot of power and is not adaptable to the various types of soil where cassava is planted. In sandy soils, the loss and damage rate of tuber is relatively low, while in clayey soil is higher. The representative machines include the API cassava tuber excavator from Malaysia *(*Akhir and Sukra, 2002*)*, the vibrating cassava harvester developed by Gupta et al. in Thailand *(Gupta, et al., 1999)*, the 4U-160 cassava harvester (Fig. 1b) produced by Henan Kunda Agricultural Machinery and Equipment Co. (*Zhang, et al., 2012)*, and the 4UM-160 cassava harvester developed by Mo and Huang *(Mo and Huang, 2012)*. The digging-pulling type cassava harvester first passes under the tubers to loosen the soil with its loosening shovels, then uses the clamping and uprooting device to pull out the tubers. Its representative machines include the cassava tuber digging and uprooting harvester developed by Cuba (Chalachai, et al., 2013*)*, CHM-3407 digging and pulling cassava harvester developed by Estonian scientists *(Thasontea and Chansiri, 2015)*, the Leipzig mechanical cassava harvester developed by the Leipzig University, Germany *(Gupta, et al., 1999)*, the clamping strap pulling cassava harvester (Fig. 1c) developed by Hainan University *(Liao, et al., 2012)*, and the clamping and pulling cassava (Fig. 1d) harvester developed by Guangxi University (*Qi, et al., 2018)*. Compared with the previous two types of harvesters, the digging-pulling type cassava harvester can achieve fully mechanized harvesting of tuber roots. It has high operating efficiency, low power consumption, and strong adaptability to various cassava planting soils. This type of cassava harvester represents the primary focus of current study on cassava harvesting technology.

(a) Digging and loosening cassava harvester (b) Digging and shaking separation cassava harvester

(c) Digging-clamping strap pulling cassava harvester (d) Loosening-clamping pulling cassava harvester

Fig. 1 - Cassava Harvester

The loosening shovel is a crucial component of the digging-pulling cassava harvester. Its loosening performance significantly affects the harvest effect and traction resistance of the harvester. Currently, the loosening shovel exhibits poor loosening effectiveness, high traction resistance, and other issues. Therefore, it is essential to conduct a comprehensive study on the loosening components.

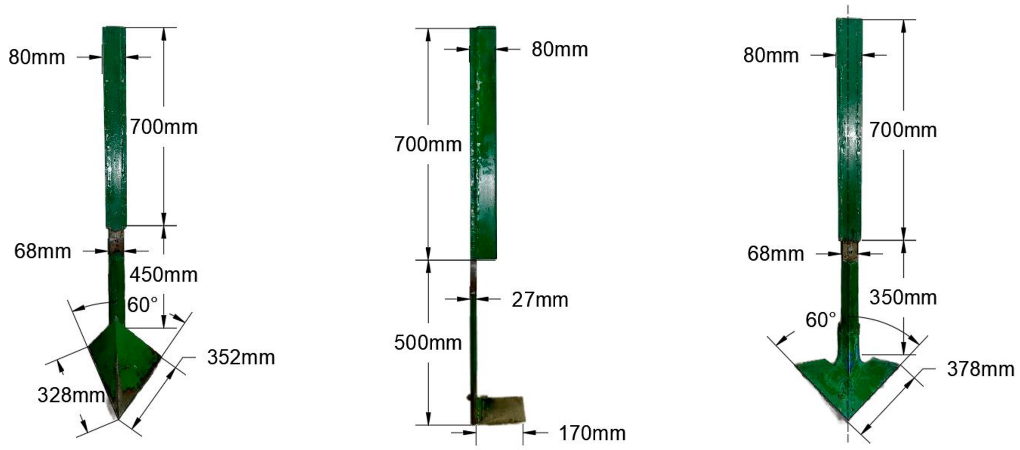
Agbetoye et al. *(Agbetoye, et al., 1998)* studied the effects on soil traction resistance and disturbance by varying the tillage depth using three types of bilateral loosening device: an L-tine, an A-blade, and a combination of a curved chisel tine. The results showed that the L-tine shovel had a better loosening effect, was simple to manufacture, and easy to adjust the working width. The effects of the L-tine shovel on the disturbance of the soil around the cassava tubers were later investigated through indoor soil trench tests and an orthogonal test in the field *(Agbetoye and Ilevbare, 2012)*. Liao et al. developed an integral fence loosening shovel, a combined shovel and a bionic loosening shovel for digging-pulling cassava harvesters *(Li, et al., 2022, Liao, et al., 2012, Liu, et al., 2014, Wang, et al., 2015)*. However, it has a high traction resistance and a high injury rate for cassava tuber. A two-sided offset-wing loosening shovel was designed by Liu *(Liu, 2020)*. And a loosening shovel-stalk-tuber-root-soil system dynamics simulation model was established to conduct a quadratic regression generalized rotary combination design simulation test, so as to optimize operating conditions of the loosening shovel. The results indicated that the loosening effect was better at a tillage depth of 0.25 m and a shovel distance of 0.7 m. However, the maximum traction resistance of a single side shovel was high, reaching 4609 N. And the optimization results were not validated in the field yet. Moreover, in order to study the loosening mechanism of the shovel and the deformation process of tubers from a microscopic perspective, *Yang et al. (Yang, et al., 2013a, Yang, et al., 2013b)* established a biplane loosening shovel-stalk-tuber-root-soil system dynamics simulation model to numerically simulate and analyze the digging and loosening process of tubers.

The aforementioned studies indicate that the integral digging shovel, which excavates from the bottom of the tubers, experiences high traction resistance and a high cassava tuber injury rate. In contrast, the two-sided loosening shovel, which loosens the soil on both sides of the tubers, encounters low traction resistance and is less likely to cause tuber injuries. However, there is limited research on the impact of its operational performance. Therefore, this study focuses on three common types of double-sided soil-loosening shovels: the offset-wing shovel (OWS), the L shovel (LS), and the double-wing shovel (DWS). Using tillage depth and shovel distance as factors, a two-factor, three-level orthogonal test is conducted, range analysis and factor impact analysis are performed on the test factors and results. Finally, a relatively optimal shovel type and its improved operating conditions are identified through comprehensive comparison and optimization. This study provides a basis for optimizing the design of loosening components in digging-pulling cassava harvester.

MATERIALS AND METHODS

Two-sided loosening shovel

The double-wing shovel (DWS) used in the test was adapted from a two-sided deep loosening shovel with wings of equal size on both sides. The offset-wing shovel (OWS) had wings of different sizes on each side. These two shovels were designed with reference to the articles by Liu et al. *(Liu, et al., 2017)* and Liu *(Liu, 2020)* respectively. The L-shaped shovel was identified as the most effective loosening shovel in the Agbetoye's test *(Agbetoye, et al., 1998)*. In this experiment, the L shovel (LS) was customized to match its dimensions, and a cutting edge was incorporated into the arm of the loosening shovel to enhance its breaking capability once it penetrates the soil. The three types of shovels are shown in Fig. 2.



(a) OWS (b) LS (c) DWS

Fig. 2 - Three types of loosening shovels

Test site and equipment

The test site was Wei Zhou Village, Liangjiang Town, Wuming District, Nanning City, Guangxi, China (108°33'E, longitude; 23°51'N, latitude; and 171.6 m height). The cassava variety was Nanzhi 199, and it was planted in single rows with mulching film inserted obliquely, spaced 1 m between rows and 0.8 m apart. The soil's physical properties were measured using the five-point sampling method, as detailed in Table 1, with the values presented on a wet basis. In order to be consistent with a manual cassava harvesting scenario, only cassava stalks with a vertical distance of 30 cm from the ground were retained before the start of the test.

Table 1

Parameters of physical properties of soil

Depth	Soil hardness on ridge	Soil hardness on furrow	Soil density	Soil moisture content
[cm]	[kg/cm^2]	[kg/cm^2]	[kg/m^3]	[%]
0-10	3.3	9.7	1547.2	22.83
10-20	12.9	12.6	1686.3	26.5
20-30	11.5	11.7	1653.3	29.19

Main instruments and equipment included the LOVOL-AUPAX 704 wheeled tractor (Weichai Lovol Intelligent Agricultural Technology Co., Ltd., China), three types of loosening shovels, the attachments for mounting the loosening shovels (Fig. 3), a custom-made device for testing the pulling force of cassava tuber roots (Fig. 4), and a custom-made instrument for measuring soil disturbance. Both the traction resistance of the loosening shovel and the force required to uproot cassava tubers were measured using a strain measurement method. Strain gauges were connected in a full bridge configuration, and DH5902 and DH5981 data acquisition systems (Jiangsu Donghua Testing Technology Co., Ltd., China) were utilized for the measurements.

Fig. 3 - Loosening shovel resistance test system

1 - Ground wheel; 2 - Resistance sensor; 3 - Loosening shovel; 4 - Three-point suspension hinge; 5 – Crossbeam

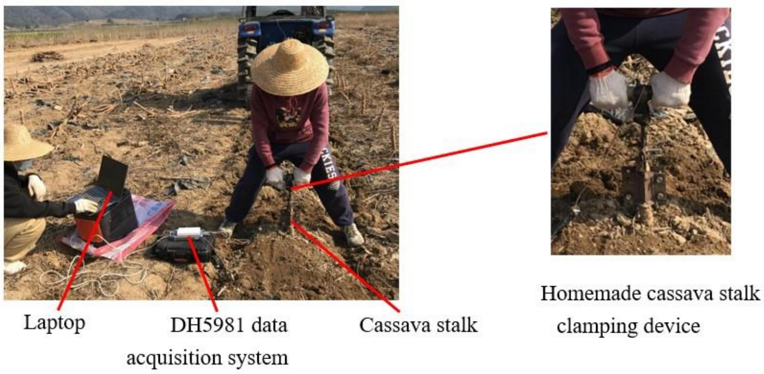


Fig. 4 - Cassava tuber pulling force test system

Test methods

Experimental design for loosening shovel operations

The position of the loosening shovel relative to the tuber has a significant impact on operational performance. Different types of loosening shovels have varying effects and different levels of soil disturbance on cassava tubers.

In this study, the tillage depth (h) and the installed shovel distance (b) – (the distance between the center of the two loosening shovel columns) – were considered as the experimental factors. The range of values for tillage depth and shovel distance were determined based on the depth of planting and the row distance of cassava. Each shovel type underwent a two-factor, three-level orthogonal test, and each trial of tests was repeated three times, with the results averaged.

Fig. 5 - Field test

Traction resistance and maximum pulling force test

Each trial started with adjusting the loosening shovel tillage depth and shovel distance. The tractor advanced at a speed of 0.9 km/h for 20 m at a constant speed, and the traction resistance (F_q) of the loosening shovel was determined using the traction resistance test system. The field test was shown in Fig. 5. After each trial loosening operation, three cassava plants were randomly selected in the operation area. The cassava stalks were clamped using a homemade cassava stalk clamping device, and the cassava was slowly pulled out vertically with both hands. The maximum cassava tuber pulling force (F_b) was determined using the pulling force test system (Fig. 4).

Soil fluffiness and soil disturbance coefficient test

Soil fluffiness (B) and soil disturbance coefficient (y) are indicators of the quality of loosened soil. According to Li's article *(Li, et al., 2015)*, the pre-tillage soil surface curve was measured first between two cassava stalks, followed by the post-tillage soil surface curve and furrow bottom curve. The measurement process was illustrated in Fig. 6. Soil fluffiness and soil disturbance coefficient were calculated using Eq. (1) and (2), respectively.

(a) Pre-tillage surface profile measurement (b) Measurement of furrow bottom curve after tillage

Fig. 6 - Soil disturbance measurement

$$B = \frac{A_h - A_q}{A_q} \times 100\% \tag{1}$$

$$y = \frac{A_s}{A_q} \times 100\% \tag{2}$$

where:

A_h is area bounded by the ground surface after loosening operation and the theoretical furrow bottom (cm^2);

A_q is area bounded by the ground surface before loosening operation and the theoretical furrow bottom (cm^2),

A_s is area bounded by the ground surface before loosening operation and the actual furrow bottom (cm^2)

Breakage rate of cassava tuber test

Tuber breakage refers to the noticeable fracturing of cassava tubers caused by mechanical action during harvester operations, this study specifically examined the fracturing of cassava tubers that occurs during the loosening shovel operation. After the loosening shovel operation, the cassava tubers from each trial were manually dug out. Tubers with a length of less than 5 cm at the end were not counted as broken. The total number of tubers and the number of broken tubers were counted. According to Yang's article *(Yang, et al., 2016)*, the breakage rate of cassava tuber (*s*) was derived from Eq. (3). In the formula, "*n*" represents the total number of tubers in one trial, and "*a*" represents the number of broken cassava tubers.

$$s = \frac{a}{n} \times 100\% \tag{3}$$

Factor impact analysis and optimization methods

(1) Range analysis: Based on the orthogonal test results of each loosening shovel, a range analysis was conducted to determine the effect size of the factors and the optimal combination of levels.

(2) Factor impact analysis: According to the test methods and results, the average values of the test indexes for the same tillage depth but different shovel distance was calculated, as well as for the same shovel distance but different tillage depth. Subsequently, a line graph illustrating the relationship between tillage depth, shovel distance, and the changes in the test indexes respectively was created. Finally, the impact pattern was analyzed by using the line graph.

(3) Comprehensive comparison and optimization: This study gave priority to small breakage rate of cassava tuber and optimal maximum pulling force. To achieve this, line graphs were used to compare the operational effectiveness of each shovel type based on the average maximum pulling force and average cassava tuber breakage rate data. Subsequently, the analysis identified the type of shovel that led to a relatively low breakage rate and pulling force. By analyzing the factors influencing these indicators, the study determined the most effective combinations. Finally, a comprehensive balancing method was used to identify the optimal combination with a relatively small breakage rate and maximum pulling force.

RESULTS

Test results of loosening shovel operation

A table of factor levels for loosening shovel operations is shown in Table 2, and the three loosening shovels test program and results are presented in Table 3.

Table 2

Table of factor levels

Levels	Factors	
	Tillage depth *h*	Shovel distance *b*
	[m]	[m]
1	0.2	0.6
2	0.25	0.7
3	0.3	0.8

Table 3

Orthogonal test program and results

Test number		Level of factors		Test indicators				
		Tillage depth *h*	Shovel distance *b*	Traction resistance F_q	Maximum pulling force F_b	Soil fluffiness *B*	Soil disturbance coefficient *y*	Breakage rate of cassava tuber *s*
		[m]	[m]	[N]	[N]	[%]	[%]	[%]
OWS	1	0.2	0.6	2523.160	375.463	25.995	21.198	13.402
	2	0.2	0.7	3638.887	531.259	18.494	18.529	4.587
	3	0.2	0.8	4250.371	629.584	11.201	12.707	9.790
	4	0.25	0.6	6094.149	251.879	15.747	23.462	4.587
	5	0.25	0.7	6332.209	468.624	14.360	26.046	11.034
	6	0.25	0.8	7167.747	434.775	10.027	18.243	10.000
	7	0.3	0.6	7727.880	436.194	16.170	26.300	17.105
	8	0.3	0.7	8199.327	333.535	14.222	32.075	19.403
	9	0.3	0.8	8642.769	346.363	7.586	11.896	33.793
LS	10	0.2	0.6	1465.699	435.754	16.092	15.905	7.237
	11	0.2	0.7	1800.573	385.229	22.229	16.590	7.914
	12	0.2	0.8	2116.673	567.920	17.490	9.728	6.202

	13	0.25	0.6	2626.817	291.608	16.036	17.669	7.576
	14	0.25	0.7	3102.530	315.218	10.331	16.998	9.286
	15	0.25	0.8	3863.050	338.540	10.173	16.337	4.348
	16	0.3	0.6	4936.538	278.263	12.151	17.516	15.108
	17	0.3	0.7	6031.200	402.959	7.752	19.618	19.841
	18	0.3	0.8	6504.520	351.904	6.250	17.561	20.313
DWS	**19**	0.2	0.6	1208.154	305.848	19.919	21.658	15.789
	20	0.2	0.7	1556.319	388.936	19.090	24.070	13.483
	21	0.2	0.8	2018.091	246.651	19.057	12.097	25.806
	22	0.25	0.6	3156.697	281.318	17.613	22.209	16.867
	23	0.25	0.7	3611.550	327.796	16.066	24.176	25.974
	24	0.25	0.8	4420.176	402.582	14.631	12.561	12.791
	25	0.3	0.6	5436.548	216.471	9.284	23.630	22.892
	26	0.3	0.7	6430.480	275.962	14.643	25.482	15.315
	27	0.3	0.8	6554.018	364.649	12.807	13.111	25.352

Range analysis

The results of the range analysis for each type of shovels are presented in Table 4. In the table, "*k*" represents the statistical mean, while subscripts 1, 2, and 3 denote the levels of the three factors, and "*R*" signifies the extreme variance of the statistical mean.

Table 4

Range analysis for three types of loosening shovels

Test indicators	**Statistical averages**	**OWS**		**LS**		**DWS**	
		Tillage depth *h* [m]	**Shovel distance *b* [m]**	**Tillage depth *h* [m]**	**Shovel distance *b* [m]**	**Tillage depth *h* [m]**	**Shovel distance *b* [m]**
Traction resistance F_q	k_1	3470.806	5448.396	1794.315	3009.685	1594.188	3267.133
	k_2	6531.369	6056.808	3197.466	3644.768	3729.474	3866.116
	k_3	8189.992	6686.962	5824.086	4161.415	6140.348	4330.761
Maximum pulling force F_b	k_1	512.102	354.512	462.968	335.208	313.812	267.879
	k_2	385.093	444.473	315.122	367.802	337.232	330.898
	k_3	372.031	470.241	344.375	419.455	285.694	337.961
Soil fluffiness *B*	k_1	18.563	19.304	18.604	14.760	19.355	15.605
	k_2	13.378	15.692	12.180	13.437	16.103	16.600
	k_3	12.659	9.604	8.718	11.304	12.245	15.498
Soil disturbance coefficient *y*	k_1	17.478	23.653	14.075	17.030	19.275	22.499
	k_2	22.584	25.550	17.002	17.735	19.649	24.576
	k_3	23.424	14.282	18.232	14.542	20.741	12.590
Breakage rate of cassava tuber *s*	k_1	9.260	11.698	7.117	9.974	18.360	18.516
	k_2	8.541	11.675	7.070	12.347	18.544	18.257
	k_3	23.434	17.861	18.421	10.287	21.186	21.316
R	$R\ (F_q)$	4719.186	1238.566	4029.771	1151.730	4546.160	1063.629
	$R\ (F_b)$	140.071	115.729	147.846	84.246	51.538	70.082
	$R\ (B)$	5.904	9.699	9.886	3.455	7.111	1.101
	$R\ (y)$	5.945	11.268	4.157	3.193	1.466	11.986
	$R\ (s)$	14.893	6.186	11.351	2.373	2.827	3.059

As seen from the results of the range analysis of the OWS in Table 4, the extreme variance in the traction resistance of factor *h* is significantly larger than that of factor *b*. Therefore, the effect on the traction resistance is $h > b$. In terms of the effect of the maximum pulling force, $h > b$. Regarding the effect of soil fluffiness, $h < b$. With respect to the effect of the soil disturbance coefficient, $b > h$. In relation to the breakage rate of cassava tuber, $h > b$.

For the LS, the effect of the soil fluffiness is $h > b$. The magnitude of the extreme variance between *h* and *b* on the soil disturbance coefficient does not differ significantly. The main factors affecting the other test indicators of the LS, such as traction resistance, maximum pulling force, and breakage rate of cassava tubers, all have values where $h > b$.

The main relationship among the factors influencing the test indexes of the DWS, such as maximum pulling force, soil disturbance coefficient, and breakage rate of cassava tuber, is that $h < b$. Conversely, the factors of traction resistance and soil fluffiness exhibit the relationship $h > b$.

The optimal combinations of factors for each test index for the three types of shovels are determined from the results of the range analysis, as presented in Table 5.

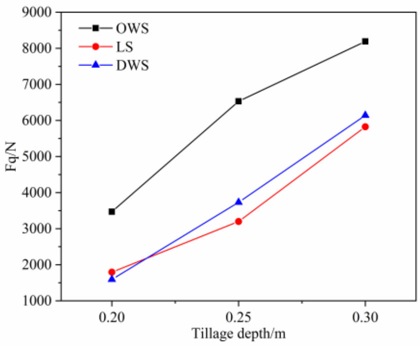
Table 5

Optimal combinations of the three shovel factors

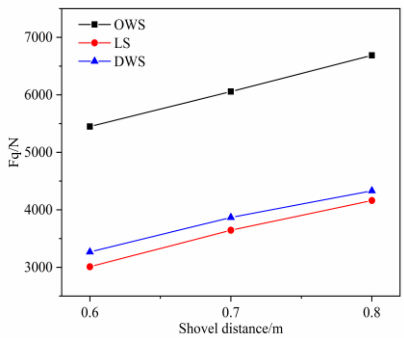
Test indicators	OWS	LS	DWS
Traction resistance F_q	$h_1\ b_1$	$h_1\ b_1$	$h_1\ b_1$
Maximum pulling force F_b	$h_3\ b_1$	$h_2\ b_1$	$b_1\ h_3$
Soil fluffiness B	$b_1\ h_1$	$h_1\ b_1$	$h_1\ b_2$
Soil disturbance coefficient y	$b_2\ h_3$	$h_3\ b_2$	$b_2\ h_3$
Breakage rate of cassava tuber s	$h_2\ b_2$	$h_2\ b_1$	$b_2\ h_1$

Factor impact analysis

The factor change impact diagrams are shown in Figs. 7-11. The three types of shovels are represented by different colors in the diagram. The black color represents the OWS, the red color represents the LS, and the blue color represents the DWS.



(a) Impact of tillage depth



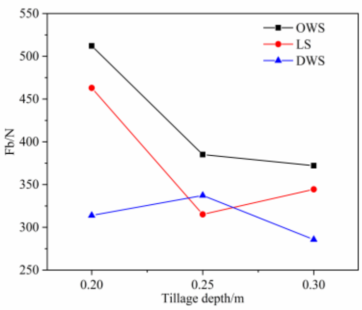
(b) Impact of shovel distance

Fig. 7 - Effect of three shovels on traction resistance

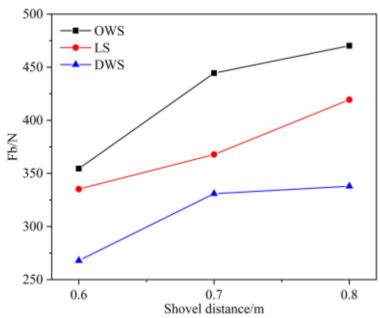
According to Fig. 7(a), the traction resistances of the three types of shovels rise as the tillage depths increase. This is due to the loosening shovels plowed deeper, the positive pressure exerted by the soil above the shovel wings also increases, resulting in an increase in traction resistance.

Fig. 7(b) demonstrates that the traction resistances of the three shovels rise as the shovel distances increase. This is attributed to a large shovel distance, wide operating width, and the gradual contact of the loosening shovel's wings with the furrows. Additionally, the first layer of soil hardness in the furrows is greater than that of the ridges, thereby contributing to the increase in traction resistance.

Furthermore, Fig. 7 illustrates that the OWS exhibits significantly higher traction resistance compared to the other two shovels when the tillage depth and shovel distance are altered. On the other hand, the traction resistances of the LS and the DWS are closer.



(a) Impact of tillage depth



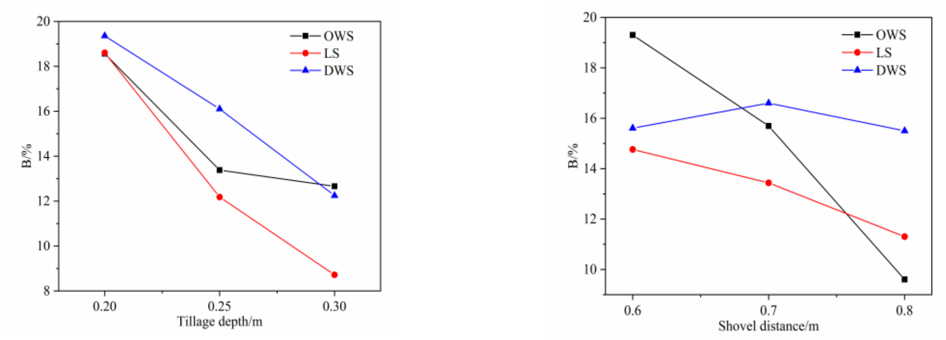
(b) Impact of shovel distance

Fig. 8 - Effect of three shovels on maximum pulling force

As could be seen from Fig. 8(a), with the tillage depths increase, the maximum pulling force of the OWS decrease, while the maximum pulling force of the LS initially decreases and then increases. Both forces decrease by the same amount, and both of them have a relatively large decrease. The maximum pulling force of the DWS initially increases and then decreases with the increase in tillage depth, but the magnitudes of the increase and decrease are not significantly different.

From Fig. 8(b), it can be seen that with the increase in shovel distances, the maximum pulling forces of the three shovels increase. This is because the wider the shovel distance, the less the loosening shovel affects the cassava tubers in the middle. In addition, the trends of the OWS and DWS are essentially the same.

As shown in Fig. 8, when the tillage depth and shovel distance are varied, the maximum pulling force of the OWS is greater than that of the other two shovels.

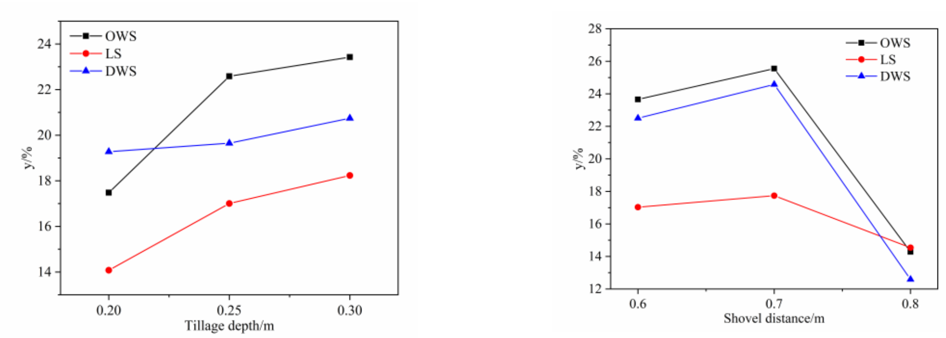


(a) Impact of tillage depth (b) Impact of shovel distance

Fig. 9 - Effect of three shovels on soil fluffiness

As shown in Fig. 9(a), with the increase in tillage depths, the soil fluffiness of the three types of shovels decrease. This is due to the increase of tillage depth, the loosening shovel penetrates the soil to a greater depth, resulting in a decrease in soil surface elevation after tillage. This is consistent with the result that "soil fluffiness gradually decreases with the increase of deep loosening depth" obtained in the test by Li et al. *(Li, et al., 2017)*. However, when the tillage depth of the DWS increases from 0.25 m to 0.3 m, the soil fluffiness does not change significantly, whereas the soil fluffiness of the LS decreases rapidly.

From Fig. 9(b), the soil fluffiness of the OWS and LS decrease with the increase of shovel distance, which is consistent with Shi's result *(Shi, et al., 2021)*. However, the soil fluffiness of the OWS decreases rapidly. In addition, the soil fluffiness of the DWS is not significantly affected by the shovel distance.

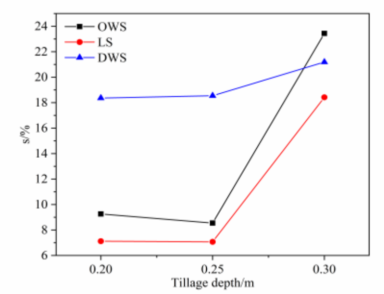


(a) Impact of tillage depth (b) Impact of shovel distance

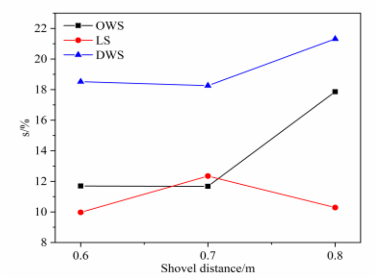
Fig. 10 - Effect of three shovels on soil disturbance coefficient

As shown in Fig. 10(a), the soil disturbance coefficients of the three types of shovels increase with the increase in tillage depth. This trend is associated with the rise of tillage depth and the subsequent decrease of soil surface elevation after tillage. Among them, the soil disturbance coefficients of the OWS and LS show more consistent trends. While the soil disturbance coefficient of the DWS does not vary significantly. And those of the LS are the smallest.

As depicted in Fig. 10(b), the soil disturbance coefficients of the OWS and DWS initially increase with the rise of shovel distance, followed by a sharp decrease. When the shovel distance is 0.8 m, the soil disturbance coefficient is significantly smaller compared to the other two shovel distance conditions. Furthermore, even though it also increases and then decreases with the increase of shovel distance, the soil disturbance coefficient of the LS does not change significantly.



(a) Impact of tillage depth



(b) Impact of shovel distance

Fig. 11 - Effect of three shovels on breakage rate of cassava tuber

From Fig. 11(a), the cassava tuber breakage rates of the OWS and LS exhibit an initial slight decrease followed by a rapid increase as the tillage depths increase, displaying the same pattern. Conversely, the cassava tuber breakage rate linked to the DWS consistently maintains a relatively high level, demonstrating a gradual rise with the increase of tillage depth.

In Fig. 11(b), as the shovel distances increase, the cassava tuber breakage rates of the OWS and DWS show a gentle decrease followed by an increase. In contrast, the cassava tuber breakage rate of the LS increases initially and then decreases with the expansion of shovel distance.

Comprehensive comparison and optimization

The fluctuations in the average values of maximum pulling force and breakage rate of cassava tuber across various tillage depths and shovel distances for each type of shovel are illustrated in Figs. 8 and 11.

As shown in Fig. 8(a), the maximum pulling force exerted by the OWS diminishes as the tillage depth increases. The LS initially experiences a decrease followed by a slight increase, whereas the DWS demonstrates an initial increase followed by a decrease. The OWS exhibits the highest maximum pulling force, and the LS and DWS show similar maximum pulling forces at tillage depths of 0.25 m and 0.3 m. Analysis of Fig. 11(a) reveals that at tillage depths of 0.2 m and 0.25 m, the cassava tuber breakage rates are significantly lower for the LS and OWS compared to the DWS. Notably, the LS exhibits the lowest cassava tuber breakage rate among three shovels.

From Fig. 8(b), the maximum pulling forces exhibited by the three types of shovels increase with the extension of shovel distance. And the OWS demonstrates a higher maximum pulling force compared to the LS, which in turn surpasses the DWS. Analysis of Fig. 11(b) reveals a similar trend in cassava tuber breakage rate between the OWS and DWS, while the breakage rate of the LS initially increases and then decreases in relation to a rising shovel distance. Moreover, the DWS incurs a higher cassava tuber breakage rate compared to the other two shovel types. And the LS shows a relatively low breakage rate among the three.

Based on the aforementioned analysis, the OWS exhibits a low breakage rate but possesses the highest maximum pulling force. Conversely, the DWS demonstrates a small maximum pulling force but a high breakage rate. The LS shows the lowest breakage rate among the three shovel types and a maximum pulling force smaller than that of the OWS. In a comprehensive comparison, the LS emerges as the optimal shovel type due to its lowest breakage rate, relatively small pulling force, and low cost-effectiveness.

Finally, utilizing Table 5 and employing a comprehensive balance method, the optimal combination of the LS type is identified as (h_2, b_1), indicating a tillage depth of 0.25 m and a shovel distance of 0.6 m.

CONCLUSIONS

(1) The order of factors affecting the traction resistance, maximum pulling force, and cassava tuber breakage rate of the OWS was $h > b$, and vice versa for other test indicators. The order of factors affecting the five test indexes of the LS was $h > b$. The order of factors affecting the maximum pulling force, soil disturbance coefficient, and cassava tuber breakage rate of the DWS was $b > h$, and the opposing order for other test indicators.

(2) The traction resistance and soil disturbance coefficient of the OWS, LS, and DWS increased with deeper tillage depths, while the soil fluffiness decreased. The maximum pulling force of the OWS decreased as tillage depth increased, while the LS initially decreased and then increased. The DWS's maximum pulling force initially mildly increased and then decreased. The cassava tuber breakage rate of the OWS and LS decreased slightly before rapidly increasing with deeper depth, while the DWS maintained a relatively high breakage rate that increased gradually. Additionally, the traction resistance and maximum pulling force of three

shovels increased with increasing shovel distance. The soil fluffiness of the OWS and LS decreased with increasing shovel distance, while the DWS initially increased and then decreased. The soil disturbance coefficient of three shovels gently increased and then decreased with increasing shovel distance. The breakage rate of the OWS and DWS increased after a slight decrease with increasing shovel distance, while the LS's breakage rate increased and then decreased. When it came to adjusting the tillage depth and shovel distance, the OWS exhibited higher traction resistance and maximum pulling force compared to the other two shovels.

(3) Between maintaining a low cassava tuber breakage rate and minimizing the maximum pull force, the LS was identified as the optimal shovel type When operating at an optimal tillage depth of 0.25 m and shovel distance of 0.6 m, the breakage rate of cassava tuber was 7.576 %, and the maximum pulling force was 291.608 N.

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REFERENCES

[1] Agbetoye L.A.S, Ilevbare I., (2012), Evaluation of L-tines for soil disturbance during mechanised cassava harvesting, *2012 ASABE Annual International Meeting Sponsored by ASABE*, vol.12;

[2] Agbetoye L.A.S., Kilgour J., Dyson J., (1998), Performance evaluation of three pre-lift soil loosening devices for cassava root harvesting, *Soil & Tillage Research*, vol.48, no.4, pp.297-302;

[3] Akhir H.M., Sukra A.B., (2002), Mechanization possibilities for cassava production in Malaysia, *Cassava Research and Development in Asia: Exploring New Opportunities for an Ancient Crop, International Center for Tropical Agriculture(CIAT)*, pp.271-276;

[4] Amponsah S.K., Addo A., Gangadharan B., (2018), *Review of Various Harvesting Options for Cassava*, Chapter 16, pp.291-304;

[5] Amponsah S.K., Sheriff J.T., Byju G., (2014), Comparative evaluation of manual cassava harvesting techniques in Kerala, India, *Agricultural Engineering International : The CIGR e-journa*, vol.16, no.2;

[6] Awad M., Fouda O., Fathy W., El Balkemy W., Egela M., El-Fakhrany W., Okasha M., (2022), *A combined machine for collecting and chopping rice straw*, *Heliyon*, vol.8, no.8;

[7] Chalachai S., Soni P., Chamsing A., Salokhe V.M., (2013), A critical review of mechanization in cassava harvesting inThailand, *International Agricultural Engineering Journal*, vol.22, no.4, pp.81-93;

[8] Chen L., Mou X., Xue J., Peng Z., Liu W., (2022), Research status and prospect of cassava mechanize planting and harvesting equipment at home and abroad (国内外木薯机械化种收装备研究现状与展望), *Agricultural Engineering*, vol.12, no.2, pp.10-16;

[9] Gupta C.P., Paul S.C., Stevens W.F., (1999), Development of a vibrating cassava root harvester, *Agricultural Mechanization in Asia, Africa and Latin America*, vol.30, no.1, pp.1-55;

[10] Jansson C., Westerbergh A., Zhang J., Hu X., Sun C., (2009), Cassava, a potential biofuel crop in (the) People's Republic of China, *Applied Energy*, vol.86, pp.S95-S99;

[11] Khater A., Fouda O., El-Termezy G., Hamid S.A., El-Tantawy M., El-Beba A., Sabry H., Okasha M., (2023), Modification of the rice combine harvester for cutting and binding wheat crop, *Journal of Agriculture and Food Research*, vol.14;

[12] Li D., Peng X., Liao Y., Guo D., Shi T., (2022), Design and experiment of bionic shovel for single row cassava root harvester (单行木薯块根收获机仿生铲的设计与试验), *Journal of Agricultural Mechanization Research*, vol.44, no.1, pp.174-182;

[13] Li S., Cui Y., Zhou Y., Luo Z., Liu J., Zhao M, (2017), The industrial applications of cassava: current status, opportunities and prospects, *Journal of the Science of Food and Agriculture*, 97, 8, 2282-2290;

[14] Li W., Zhang S., Huang Y., Zhu R., (2017), Distinct element method simulation and experimental research of subsoiling depth on soil disturbance (深松深度对土壤扰动影响的仿真与试验研究), *Journal of Agricultural Mechanization Research*, vol.39, no.11, pp.153-157;

[15] Li X., Zhang D, Wang W., Cui T., (2015), Performance parameter optimization and experiment of forced-vibration subsoiler (受迫振动深松机性能参数优化与试验), *Transactions of the Chinese Society of Agricultural Engineering*, vol.31, no.21, pp.17-24;

[16] Liao Y., Sun Y., Liu S., Cheng D., Wang G., (2012), Development and prototype trial of digging-pulling style cassava harvester, *Transactions of the Chinese Society of Agricultural Engineering*, 28, 2, 29-35;
[17] Liu C., (2020), *Optimization study on operation parameters of cassava shovel (木薯松土铲作业参数优化研究)*, MSc Thesis, Guangxi University, Guangxi Zhuang Autonomous Region/China;
[18] Liu J., Wang X., Li H., He J., (2017), Optimization of structural parameters of subsoiler based on soil disturbance and traction resistance (基于土壤扰动与牵引阻力的深松铲结构参数优化), *Transactions of the Chinese Society for Agricultural Machinery*, vol.48, no.2, pp.60-67;
[19] Liu S., Weng S., Liao Y., Zhu D., (2014), Structural bionic design for digging shovel of cassava harvester considering soil mechanics, *Applied Bionics and Biomechanics*, vol.11, pp.1-11;
[20] Mo Q., Huang M., (2012), Development and application of 4UM-160 cassava harvester (4UM-160 型木薯收获机的研发应用), *Guang Xi Agricultural Mechanization*, vol.3, pp.20-22+25;
[21] Odigboh E.U., (1991), Single-row model Ⅱ cassava harvester, *Agriculture Mechanization In Asia, Africa and Latin America*, vol.22, no.3, pp.63-66;
[22] Ospina B., Cadavid L.F., Garcia M., (2002), Mechanization of cassava production in Colombia, *Cassava Research and Development in Asia. Centro International de Agricultura Tropical*, pp.277-287;
[23] Parmar A., Sturm B., Hensel O., (2017), Crops that feed the world: Production and improvement of cassava for food, feed, and industrial uses, *Food Security*, vol.9, no.5, pp.907-927;
[24] Qi P., Wang J., Yuan J., (2018), Design and experiment of digging and pulling harvester (挖拔式木薯收获机的设计与试验), *Guang Xi Agricultural Mechanization*, vol.14, pp.23-25;
[25] Shi Z., Yu Z., Yang L., Yang M., (2021), On simulation and experiment of soil disturbance caused by airfoil subsoil shovel spacing (翼型深松铲铲间距对土壤扰动的仿真与试验), *Journal of Southwest China Normal University (Natural Science Edition)*, vol.41, no.4, pp.38-44;
[26] Sivamani S., Chandrasekaran A.P., Balajii M., Shanmugaprakash M., Hosseini-Bandegharaei A., Baskar R., (2018), Evaluation of the potential of cassava-based residues for biofuels production, *Reviews in Environmental Science and Bio-Technology*, vol.17, no.3, pp.553-570;
[27] Thasontea M., Chansiri C., (2015), The potential on development of cassava combine harvester in Thailand, *Farm engineering and automation technology journal*, vol.1, no.2, pp.107-116;
[28] Vandegeer R., Miller R.E., Bain M., Gleadow R.M., Cavagnaro T.R., (2013), Drought adversely affects tuber development and nutritional quality of the staple crop cassava (Crantz), *Functional Plant Biology*, vol.40, no.2, pp.195-200;
[29] Wang T., Liao Y., Yang Y., Zheng M., Yuan C., (2015), The design and mechanical analysis of digging shovel of cassava harvest machine (木薯收获机多阶挖掘铲设计及其力学特性分析), *Journal of Agricultural Mechanization Research*, vol.37, no.10, pp.50-54;
[30] Wang Z., Zhou J., Yang X., Liu Y., Liu F., (2019), Research progress of cassava tuber harvesting technology and machine (木薯块根收获技术与机具研究进展), *Agricultural Engineering*, 9, 1, pp.1-8;
[31] Xue Z., Huang H., Li M., Qiu Z., Gao W. ,Cui Z., (2010), Study on 4UMS-390II cassava harvester (4UMS-390Ⅱ型木薯收获机的研制), *Journal of Agricultural Mechanization Research*, vol.32, no.8, pp.78-81+85;
[32] Yang W., Jia F., Yang J., (2013a), Numerical simulation of digging processes of cassava root (木薯块根挖掘作业过程的数值模拟), *Engineering Mechanics*, vol.30, no.6, pp.301-307;
[33] Yang W., Li X., Wang R., Yang J., Pan Q., Li J., (2016), Numerical simulation test of maximum stress of tuber in cassava lifting (木薯块根拔起的最大应力数值模拟及试验), *Transactions of the Chinese Society of Agricultural Engineering*, vol.32, no.6, pp.58-64;
[34] Yang W., Yang J., Jia F., Wang Q., Huang Y., (2013b), Numerical simulation of digging operation of cassava root planted in red clay (种植于红粘土的木薯块根挖掘作业数值模拟), *Journal of Mechanical Engineering*, vol.49, no.09;
[35] Yang W., Yang J., Zheng X., Jia F., (2012), Current research and development trends of cassava root harvest machinery and technology (木薯块根收获机械与技术研究现状及发展趋势), *Journal of Agricultural Mechanization Research*, vol.32, no.12, pp.230-235;
[36] Zhang Y., Huang H., Cui Z., (2012), Harvesting principle and structure design of cassava harvester (国内木薯收获机采挖原理和结构设计), *Tropical Agricultural Engineering*, vol.36, no.5, pp.17-20;