DESIGN AND EXPERIMENTAL TESTING OF A FLIP-TYPE PEANUT DIGGING AND SPREADING HARVESTER
/
翻转式花生挖掘铺放收获机设计与试验

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ABSTRACT
At present, peanuts are predominantly harvested using a two-stage harvesting method. During the digging and laying stage, peanut plants are generally laid sideways for drying. Owing to differences in light exposure and air permeability, the moisture content of the pods becomes non-uniform, which adversely affects subsequent picking and harvesting operations. To address these issues, a two-ridge, four-row directional inversion peanut digging and spreading harvester was designed based on the plant directional inversion mechanism. Field experiments demonstrated that the primary operating parameters influencing peanut inversion and laying performance were clamping height, conveying speed, and the horizontal inclination angle of the clamping chain. Using peanut inversion degree and pod loss rate as evaluation indicators, an orthogonal experimental design was employed to determine the optimal parameter combination: clamping height of 170 mm, conveying speed of 1.5 m/s, and clamping chain inclination angle of 15°. Field test results showed that, after clamping, conveying, and inversion operations, the peanut inversion degree reached 94.4%, while the pod loss rate was limited to 3.5%.

摘要
现阶段花生主要采取两段式收获方式，挖掘铺放环节多采取植株侧向铺放晾晒，由于光照和透气性等因素造成荚果含水率不一致，进而影响后续捡拾收获作业。针对上述问题，基于植株定向翻转机理，设计了一种两垄四行定向翻转式花生挖掘铺放收获机。通过田间试验明确影响花生翻转放铺的主要作业参数为夹持高度、输送速度及链条水平倾角。以花生倒置度和掉果率为试验指标，通过开展正交试验确定最优组合参数为：夹持高度 170 mm、输送速度 1.5 m/s、夹持链条倾角 15°。田间试验结果表明，经过夹持输送翻转放铺后的花生倒置度为 94.4%，花生掉果率为 3.5%。

INTRODUCTION
Peanuts are an important oil crop in China *(Shen et al., 2024)*. Mechanized peanut harvesting methods are generally classified into two types: combined harvesting and two-stage harvesting. Compared with combined harvesting, two-stage harvesting has become the predominant approach due to its lower pod damage rate and improved separation performance *(Chen et al., 2016; Chang et al., 2023)*. At present, digging and laying operations mainly adopt orderly lateral laying methods, which result in pronounced moisture stratification of peanut plants during the drying process. The substantial moisture differences between the upper and lower plant layers directly affect the quality and efficiency of subsequent picking operations. Therefore, modifying the laying pattern of peanut plants during the digging and laying stage is of significant importance for improving the overall quality and performance of mechanized peanut harvesting *(Xu et al., 2023; Gao et al., 2016; Cuan et al., 2014)*.

Researchers both domestically and internationally have made notable progress in the development of peanut digging and laying equipment. *Bader (2009)* employed horizontal root-cutting combined with inclined conveying technology to achieve inverted plant placement. The rod-type combined conveyor system developed by AMADAS effectively enhances impurity removal; however, it is limited by high cost and insufficient adaptability *(Amadas Industries, 2022)*.

Pearman's multi-row shovel–clamp harvester utilizes clamping-chain extraction and inertial laying, but suffers from limited adaptability across operating conditions *(Pearman Corporation, 2022)*. In China, the research team led by Gao Lianxing proposed a "flip-slide grid" laying method to achieve orderly plant arrangement. Although the vibration-type inverted spreader developed by Zheng Jinsong provides a high inversion rate, it is prone to impurity accumulation and clogging *(Li, 2018)*. Overall, existing technologies still require further improvement in terms of impurity removal efficiency, adaptability, and operational stability.

Most existing studies focus on digging resistance modeling and the optimization of separation and conveying parameters. However, relatively limited attention has been paid to the mechanisms governing the influencing factors during the plant turnover process, which constitutes the core control stage for placement quality *(Wang, 2023; Jiang, 2021; Liu, 2020)*. This mechanism directly determines the timing and effective action range of the inversion device, thereby dominating the key performance index of peanut inversion. Consequently, analyzing the factors affecting peanut inversion during the inversion and landing process represents a critical theoretical foundation for improving inversion performance and achieving low-loss, high-efficiency harvesting operations *(Liu et al., 2020; Chen et al., 2017)*.

Therefore, based on the post-excavation laying patterns of peanut plants and pods, this study designed a directional inversion peanut digging and laying harvester. Considering the physical characteristics of peanut plants and the moisture content requirements after drying, the key factors influencing peanut inversion and their governing mechanisms were investigated. Field experiments were conducted to evaluate the optimal operating performance of the developed machine, with the aim of providing technical references for peanut digging, laying, and harvesting technologies and equipment.

OVERALL DESIGN OF THE DIRECTIONAL INVERSION PEANUT HARVESTER

Overall structure and working principle

There are two main peanut plant growth types: creeping and upright. In countries such as the United States, Brazil, and Argentina, creeping peanut varieties are predominantly cultivated. These plants develop numerous lateral branches and grow close to the ground, with pods widely distributed in the soil. This growth habit facilitates plant inversion and orderly laying during mechanical harvesting, which is beneficial for field drying and subsequent picking operations *(Chen et al., 2020; Ma et al., 2021)*. In contrast, upright peanut varieties are mainly cultivated in China. These plants typically have fewer branches and upright main stems, with pods concentrated near the root zone. As a result, it is difficult to form a neat, upward-facing plant arrangement during harvesting, which limits ventilation and drying efficiency and negatively affects the effectiveness of ground picking operations *(Zhou et al., 2022)*.

In response to the requirements of domestic upright peanut cultivation, a directional plant-inversion peanut harvester designed for two ridges and four rows was developed. The machine mainly consists of a profiling device, digging device, clamping and conveying device, plant-inversion laying device, depth-limiting adjustment device, and frame, as shown in Fig. 1.

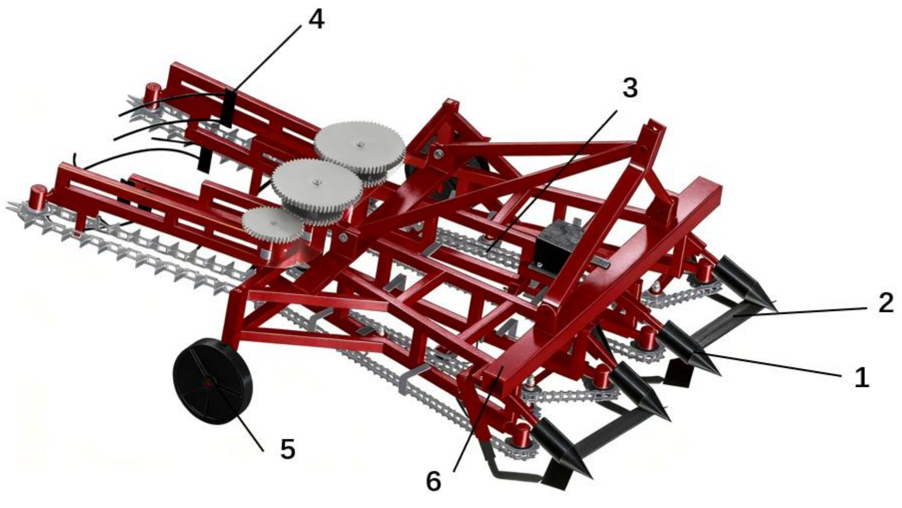


Fig. 1 - Structural diagram of the directional plant-inversion peanut harvester

1. Profiling device; 2. Digging device; 3. Clamping and conveying device; 4. Plant-inversion laying device; 5. Depth-limiting adjustment device; 6. Frame

Working principle

The workflow of the directional plant-inversion peanut harvester is illustrated in Fig. 2. During operation, the harvester is connected to the tractor via a three-point hitch, which provides the forward traction force. Simultaneously, power is transmitted from the tractor power take-off (PTO) shaft to the gearbox and then, via a belt drive, to the clamping conveyor drive gears. Through power distribution, two harvesting units are driven, comprising a total of two front clamping conveyor chains and two rear conveying chains. During operation, the digging shovel penetrates the soil at a predetermined entry angle, uniformly digging the peanut plants from the soil. The plants are subsequently stably clamped by the double-chain clamping device and lifted upward into the conveying section. During this process, the machine simultaneously performs soil-shaking and patting actions, effectively dislodging soil from the root system and reducing entrained impurities.

When the peanut plants are conveyed to the rear frame, the plant-inversion laying device is activated, turning the plants over and laying them in an orderly manner. This process forms a continuous and neat windrow structure, with pods facing upward and vines oriented downward. The laying method utilizes the plant vines as natural supports, thereby minimizing direct contact between the pods and the soil. This arrangement enhances ventilation and light penetration between plants, accelerates field drying, and improves drying uniformity and efficiency. Furthermore, it creates favorable conditions for subsequent mechanical picking and collection operations, thereby improving overall harvesting quality and operational efficiency. The working state of the machine is shown in Fig. 3.

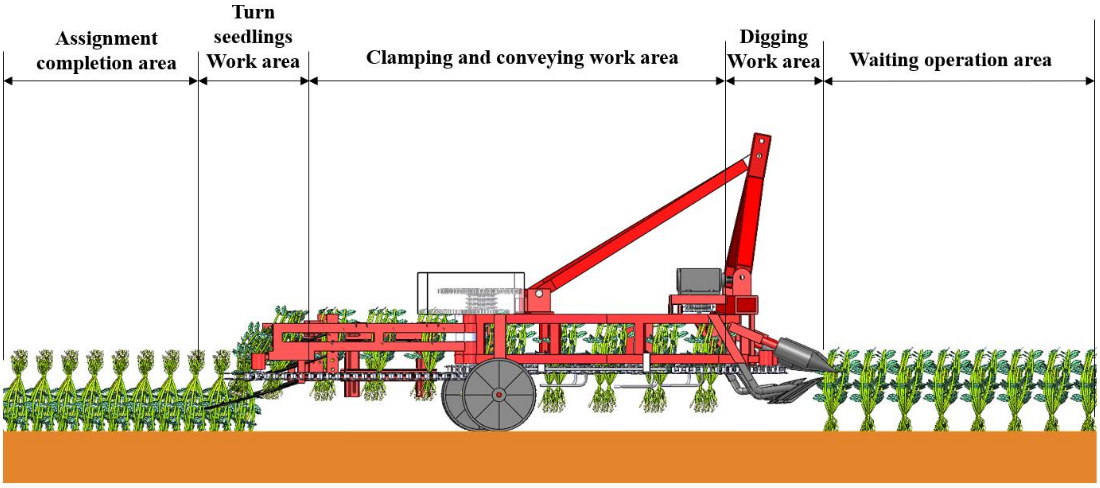


Fig. 2 - Workflow diagram

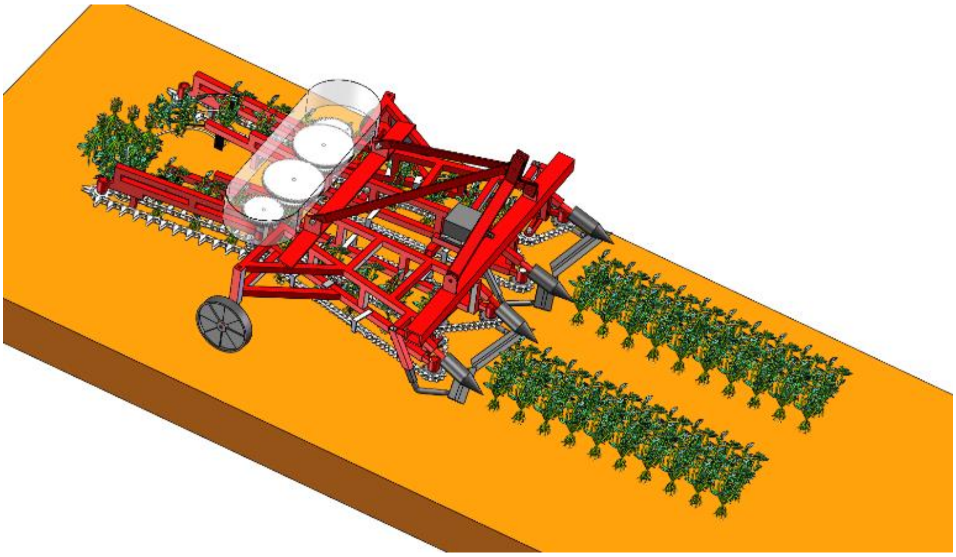


Fig. 3 - Working status diagram

Main technical parameters

Table 1 shows the main technical parameters of the seedling-turning peanut harvester: it mainly includes working width, dimensions, machine quality, travel speed, etc.

Table 1 presents the main technical parameters of the directional plant-inversion peanut harvester, including working width, overall dimensions, machine mass, and harvesting configuration.

Table 1

Main technical parameters of the directional plant-inversion peanut harvester

Project	Parameter
Overall dimensions (L × W × H), mm	2600×1900×1300
Working width/mm	1600
Machine mass/kg	600
Harvesting configuration	2 ridges, 4 rows

Digging shovel design and analysis

Based on a review of relevant literature and market research on peanut harvesting machinery, three main types of digging shovels are currently used for peanut harvesting: fixed, active, and combined (hybrid). Fixed digging devices are rigidly connected to the machine frame, either directly or indirectly. Common shovel forms include flat shovels, curved shovels, and grooved shovels, which primarily perform soil cutting through static penetration during operation. Active digging devices, in addition to moving with the machine, utilize an auxiliary power source to drive the digging shovels in reciprocating or rotary motion. According to their kinematic characteristics, these devices can be classified into rotary digging shovels and vibrating digging shovels. Among them, vibrating digging shovels are particularly effective in reducing digging resistance and overall energy consumption. Combined digging devices integrate two or more digging components in a modular configuration to accommodate varying operating conditions. Typical examples include composite structures combining a fixed flat shovel with a vibrating side shovel, as well as disc–clamp combined designs. These configurations are intended to enhance soil disturbance efficiency and improve adaptability under diverse field conditions.

Considering that peanuts in China are predominantly cultivated in sandy loam soils and are mainly upright-growing varieties, the root systems are relatively complex, which can easily lead to pod detachment during harvesting. To address this issue, a V-shaped flat double-shovel structure was adopted. This design effectively reduces the width of the main shovel while maintaining good soil-sliding performance (i.e., reduced soil adhesion) and high harvesting efficiency. The digging shovel is rigidly connected to the machine frame by bolts, which enhances structural stiffness, facilitates disassembly and maintenance, and eliminates the need for an independent power source. As a result, the overall structure is simple and energy consumption is low. At crop maturity, peanut pods are located below the soil surface, while the vines grow upright above ground. During operation, the digging shovel severs the main root of the peanut plant without directly impacting the pods. The shovel surface then lifts the soil containing the pods and guides the plants into the subsequent clamping and conveying device. The structure of the digging shovel is shown in Fig. 4.

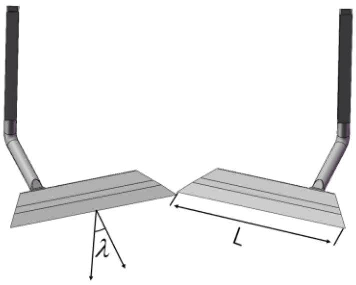


Fig. 4 - Structure diagram of digging shovel

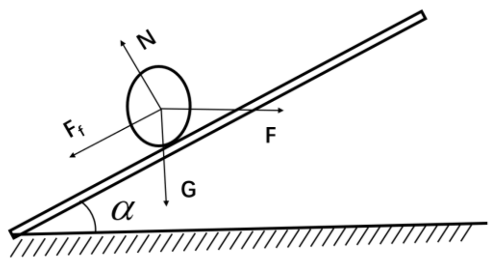


Fig. 5 - Soil force analysis chart

The soil entry angle of the digging shovel is a key design parameter, as it directly affects shovel length, soil penetration performance, soil fragmentation, and operating resistance. A smaller soil entry angle reduces soil penetration difficulty and digging resistance; however, it requires an increased shovel length to achieve the necessary lifting height and results in limited soil-breaking capability. Conversely, increasing the soil entry angle shortens the shovel length and enhances soil fragmentation, but may hinder soil penetration, increase operating resistance, and even lead to blockage or slippage.

Optimizing the soil entry angle enables a balance between these competing factors, thereby improving operational efficiency, stability, and harvesting quality. The force analysis of the soil–shovel interaction is presented in Fig. 5.

To ensure that the digging shovel can effectively lift and convey soil, a force balance equation was established based on the forces acting on the shovel surface of the digging unit:

$$\begin{cases} \mathrm{F}\cos\alpha - f - G\sin\alpha \geq 0 \\ N - G\cos\alpha - F\sin\alpha = 0 \\ f = \mu N \end{cases} \tag{1}$$

where: α is the soil entry angle of the digging shovel, F is the force required by the shovel surface to lift the soil-plant mixture, G is the gravitational force acting on the soil-plant mixture borne by the shovel, N is the normal reaction force exerted by the shovel on the soil-plant mixture, F_f is the friction force between the soil-plant mixture and the shovel surface, μ is the friction coefficient between the soil and the shovel surface.

From Eq. (1), Eq. (2) can be derived as follows:

$$\alpha \leq \arctan\frac{F-\mu G}{\mu F+G} \tag{2}$$

As indicated by Eq. (2), when the soil entry angle exceeds the critical range, excessive accumulation of excavated material occurs on the shovel surface, which significantly degrades the operating performance of the machine. To ensure optimal performance of the digging shovel, commonly recommended soil entry angle ranges reported in the literature were considered, and the design value was ultimately set to 22°.

For digging shovels, the blade tip angle θ has a significant influence on the cutting efficiency of peanut seedlings and vines. When θ is excessively large, the risk of rhizome entanglement increases markedly; conversely, when θ is too small, cutting efficiency decreases and the frequency of slippage increases significantly. Within the optimal range of θ, a trade-off relationship exists: reducing the blade tip angle enhances sliding-cutting performance, but results in a linear increase in blade length. This increase in blade size enlarges the longitudinal space occupied by the machine, which conflicts with the design objectives of lightweight construction and compact layout in agricultural machinery. The force analysis of blade sliding and cutting is illustrated in Fig. 6.

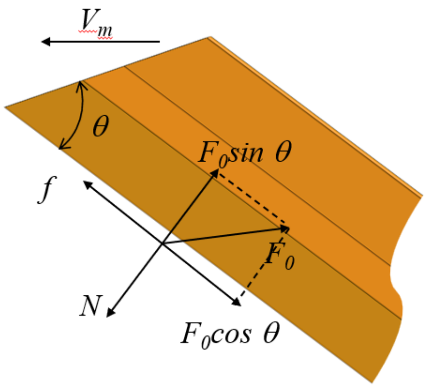


Fig. 6 - Sliding–cutting force analysis of the shovel blade

To balance operational performance and structural optimization, the blade tip angle must satisfy the following constraint:

$$\begin{cases} M = F_0\sin\theta \\ N = F_0\cos\theta \\ f = N\tan\alpha \end{cases} \tag{3}$$

where:

θ is the blade tip angle, F_0 is the digging resistance acting on the shovel surface, f is the sliding friction force, N is the normal force exerted by the shovel blade on the contact material.

The conditions for slippage can be expressed as:

$$F_0 \cos\theta > N \tan\alpha = F_0 \sin\theta \tan\alpha \quad (4)$$

which can be simplified to:

$$\theta < 90° - \alpha \quad (5)$$

Considering that the friction coefficient between soil and steel generally falls within the range tan ω = 0.4~0.8, field tests indicated that selecting ω = 50° effectively reduces soil congestion and mitigates impact effects during operation.

Field test

Field testing of the complete machine is a critical step in evaluating the operational performance of harvesting machinery and an effective means of verifying the coordination and rationality of the individual components within the mechanized peanut harvesting system. Based on the key parameters influencing peanut plant inversion performance, a three-factor, three-level Box–Behnken experimental design was employed to optimize the operating parameters of the directional plant-inversion conveying device of the peanut harvester. By analyzing the effects of clamping height, conveying speed, and the horizontal inclination angle of the clamping chain on peanut inversion degree and pod loss rate, the study aimed to identify an optimal combination of operating parameters to enhance conveying performance and overall harvesting quality.

Test conditions and test plan

The field tests were conducted at the Jiaozhou Test Base. The peanut variety cultivated at the test site was Huayu No. 25. The planting pattern consisted of one ridge with two rows, with ridge spacing of 750~900 mm, ridge surface widths of 550~600 mm, and row spacing between peanut plants of 250~350 mm. Based on theoretical predictions and actual operating conditions, the selected test parameters were a clamping height of 170 mm, a conveying speed of 1.5 m/s, and a clamping chain inclination angle of 15°. A stable operating area was selected along the forward direction of the harvester, with a test length of 50 m and a width equal to the effective harvesting width. Each test was repeated three times, and the average values were used for analysis. The field test operation is shown in Fig. 7.

(a) Field test process

(b) Field test results

Fig. 7 - Field trial

Test evaluation indicators and measurement methods

The field tests were conducted in accordance with the relevant provisions of NY/T 502-2016 (Peanut Harvester Operation Quality) and NY/T 7502-2002 (Agricultural Industry Standard of the People's Republic of China - Peanut Harvester Operation Quality). Peanut inversion degree, pod loss rate, and pod moisture content were selected as the performance indicators for evaluating the directional plant-inversion conveying device. Following each test, the peanut inversion degree and pod loss rate of the laid peanut plants were measured and calculated to assess the operational performance of the device.

Determination of peanut inversion

After 50 m of stable operation of the directional plant-inversion peanut digging and laying harvester, the number of peanut plants with pods facing upward and the total number of laid peanut plants were recorded. The peanut inversion degree was calculated as follows:

$$A = \frac{x_0}{X} \times 100\% \tag{6}$$

where: A is the peanut inversion degree, x_0 is the number of peanut plants with pods facing upward, X is the total number of peanut plants laid on the ground.

Determination of peanut pod loss rate

During the harvesting operation of the directional plant-inversion peanut digging and laying harvester, the mass of pods lost to the ground and the total pod mass were measured. The peanut pod loss rate was calculated as follows:

$$\begin{cases} P = \dfrac{p_0}{p_z} \times 100\% \\ p_z = p_0 + p_1 \end{cases} \tag{7}$$

where: P is the pod loss rate, p_0 is the mass of peanut pods lost to the ground, p_1 is the mass of peanut pods retained on the peanut plants, p_z is the total mass of all peanut pods.

Orthogonal test

The clamping height X_1, clamping chain inclination angle X_2, and conveying speed X_3 of the directional plant-inversion conveying device were selected as test factors. The peanut inversion degree Y_1 and pod loss rate Y_2 were used as evaluation indicators. An orthogonal experimental design was established using the $L_9(3^4)$ orthogonal array. The factor levels are presented in Table 2, and the orthogonal test results are shown in Table 3.

Table 2

Test factor coding and levels

Level	Factor		
	X_1 / (mm)	X_2 / (°)	X_3 / (m·s^{-1})
-1	160	10	1.3
0	170	15	1.5
1	180	20	1.7

Table 2

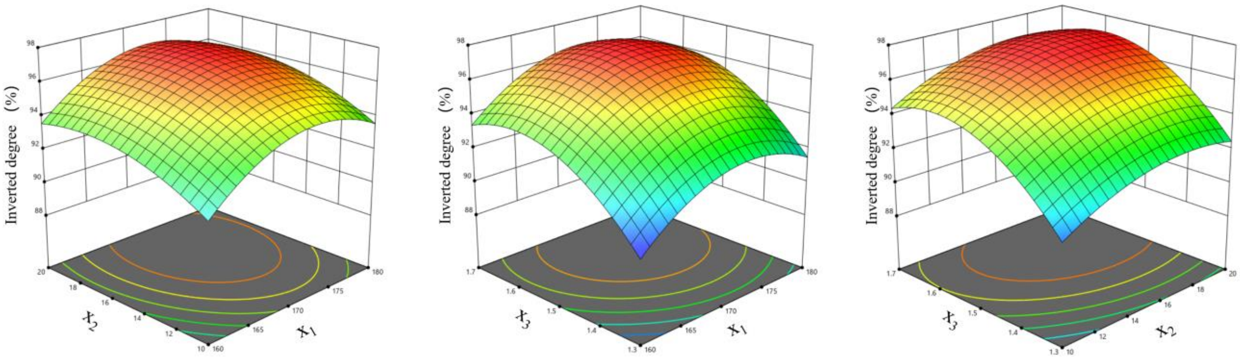
Orthogonal test plan and results

Test serial number	X_1	X_2	X_3	Inversion degree / %	Pod loss rate / %
1	160	10	1.5	93.1	2.8
2	180	10	1.5	91.5	2.9
3	160	20	1.5	93.3	3.2
4	180	20	1.5	90.1	3.8
5	160	15	1.3	92.1	2.6
6	180	15	1.3	88.1	2.4
7	160	15	1.7	89.0	3.4
8	180	15	1.7	88.3	4.3
9	170	10	1.3	94.9	2.7
10	170	20	1.3	95.1	3.1
11	170	10	1.7	94.4	3.6
12	170	20	1.7	93.2	4.5
13	170	15	1.5	97.4	3.4
14	170	15	1.5	97.5	3.5
15	170	15	1.5	97.7	3.5
16	170	15	1.5	97.2	3.6
17	170	15	1.5	97.8	3.5

Response surface analysis of test results

1) Influence of test factors on peanut inversion degree

As shown in Fig. 8, the maximum peanut inversion degree of 97.33% was obtained when the clamping height was 173.99 mm, the conveying speed was 1.6 m/s, and the horizontal inclination angle of the clamping chain was 17.9°. Experimental observations indicated that when the inclination angle of the clamping chain was small, peanut plants were released from the inversion device at a relatively low height above the ground. Under these conditions, some plants were unable to complete posture adjustment during free fall, resulting in a reduced inversion degree. As the inclination angle increased, the release height of the plants gradually increased, allowing sufficient time for posture adjustment and leading to an improvement in inversion degree. However, when the inclination angle was further increased, the combined effects of plant gravity and soil extraction resistance generated a downward force along the chain direction, causing plant slippage and sinking within the chain. This phenomenon led to a subsequent decrease in inversion degree. A positive correlation between inversion degree and conveying speed was observed within a certain range. At low conveying speeds, peanut plants tended to interact and interfere with one another after entering the inversion device, preventing timely posture adjustment and resulting in an inversion degree of approximately 90%. As the conveying speed increased, inversion performance improved; however, excessive conveying speed caused an excessive number of plants to enter the inversion device simultaneously, limiting posture adjustment time and leading to a reduction in inversion degree. The effect of clamping height on inversion degree followed a trend of initial increase followed by decrease. When the clamping height was too low, the number of plants entering the conveying device was insufficient, resulting in reduced inversion performance. Conversely, an excessively high clamping height produced a similar effect, as plant posture control became unstable, again leading to a decrease in inversion degree.

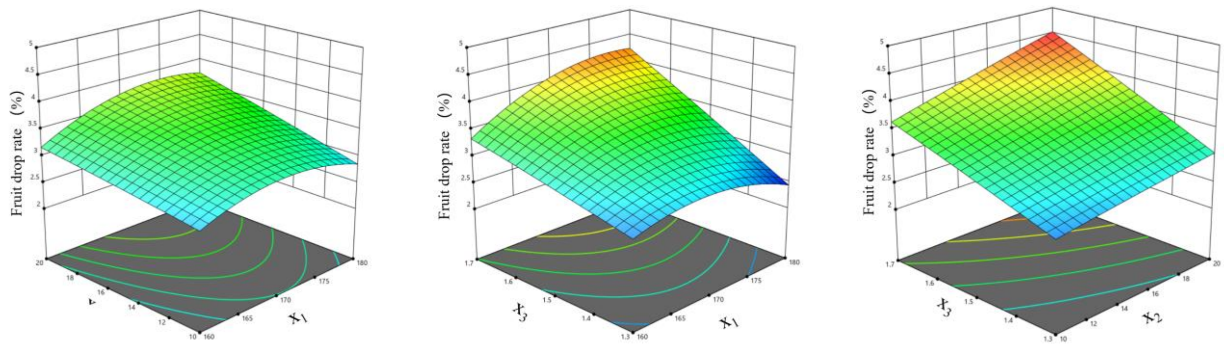


(a) Interaction between factors A and B (b) Interaction between factors A and C (c) Interaction between factors B and C

Fig. 8 - Effects of test factor interactions on peanut inversion

2) Influence of test factors on pod loss rate

As shown in Fig. 9, the minimum peanut pod loss rate of 4.51% was obtained when the clamping height was 173.1 mm, the conveying speed was 1.65 m/s, and the horizontal inclination angle of the clamping chain was 19.84°. Experimental observations indicated that, as the inclination angle of the clamping chain increased, peanut plants experienced greater gravitational effects during conveying, which increased the risk of fruit stalk fracture and consequently led to a higher pod loss rate. A positive correlation was also observed between pod loss rate and conveying speed. As the conveying speed increased, the inertial forces and vibration acting on the peanut plants intensified, resulting in increased pod loss. The effect of clamping height on pod loss rate exhibited a decreasing-increasing trend. When the clamping height was either too low or too high, interference and collisions occurred between the peanut plants, the conveying chains, and the clamping sprockets, leading to an increase in pod loss rate.



(a) Interaction between factors A and B (b) Interaction between factors A and C (c) Interaction between factors B and C

Fig. 9 - Effects of experimental factor interactions on peanut pod loss rate

Parameter optimization

Using Design-Expert software, maximization of the peanut inversion degree Y_1 and minimization of the pod loss rate Y_2 were set as the optimization objectives. Based on the boundary conditions, the constraint equation (8) was established. The optimized parameter combination obtained was a clamping height of 175.54 mm, a clamping conveying speed of 1.43 m/s, and a clamping chain inclination angle of 13.74°. Under these conditions, the predicted peanut inversion degree was 95.49%, and the pod loss rate was 3.17%. Considering the practical operating conditions and structural adjustability of the equipment, the final optimal parameter combination was determined as follows: a center distance between the grille and the sprocket of 170 mm, a clamping conveying speed of 1.5 m/s, and a clamping chain inclination angle of 15°.

$$\begin{cases} \max\ Y_1(X_1, X_2, X_3); \min\ Y_2(X_1, X_2, X_3) \\ s.t \begin{cases} 160mm \le X_1 \le 180mm \\ 10° \le X_2 \le 20° \\ 1.3\,\mathrm{m/s} \le X_3 \le 1.7\,\mathrm{m/s} \end{cases} \end{cases} \tag{8}$$

To verify the operational performance under the optimized parameter combination, a 50 m test section was selected for field validation, with three repeated trials conducted. The average measured peanut inversion degree and pod loss rate were 94.4% and 3.5%, respectively. These values were in good agreement with the predicted results and met the operational quality requirements for peanut harvesting.

CONCLUSIONS

(1) In response to the problems of poor field-drying quality and large moisture content differences between upper and lower peanut pods associated with traditional two-stage harvesting, an optimized laying method was proposed and a directional plant-inversion conveying device was developed. The device integrates functions of impurity removal, clamping and conveying, and inversion and laying. By placing the pods upward and the vines downward, field drying quality is effectively improved.

(2) The main operating parameters influencing peanut inversion degree and pod loss rate were identified as clamping height, conveying speed, and the horizontal inclination angle of the clamping chain. The response surface methodology was employed to analyze the interaction effects among these factors on inversion degree and pod loss rate, and to determine the optimal parameter combination.

(3) Field test results demonstrated that, under the optimal parameter combination - clamping height of 170 mm, conveying speed of 1.5 m/s, and clamping chain inclination angle of 16° - the peanut inversion degree reached 94.4%, while the pod loss rate was limited to 3.5%.

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