Research and optimization of the hand-over lifting mechanism of a sweet potato combine harvester based on EDEM

Haiyang Shen[1,3], Bing Wang[1], Gongpu Wang[1], Yemeng Wang[1], Guocheng Bao[1,2], Lianglong Hu[1*], Zhichao Hu[3*]

(1. *Nanjing Institute of Agricultural Mechanization, Ministry of Agriculture and Rural Affairs, Nanjing 210014, China*; 2. *Chinese Academy of Agricultural Mechanization Sciences Group Co., Ltd., Beijing 100083, China*; 3. *Graduate School of Chinese Academy of Agricultural Sciences, Beijing 100081, China*)

Abstract: In order to meet the challenge of high loss rate and high tuber injury rate during the operation of the 4UZL-1 sweet potato combine harvester, the sweet potato tuber hand-over lifting mechanism was designed based on a comprehensive analysis of the entire structure of the harvester. Taking the average normal force on conveying sweet potato tubers as evaluation indexes, the EDEM simulation experiment was carried out considering the factors of the angle of the excavating and conveying mechanism, the conveying angle of the scraper chain, the speed of the excavating and conveying mechanism, and the speed of the scraper chain conveying. The experimental findings indicated that the optimal operational performance of the hand-over lifting mechanism was achieved at a speed of 1.15 m/s for the excavating and conveying mechanism, an angle of 24° for the excavating and conveying mechanism, a conveying speed of 0.66 m/s for the scraper chain, and a conveying angle of 60° for the scraper chain. Field experiments were conducted based on the EDEM simulation experiment, using the loss rate and the injury rate of conveying sweet potato tubers as evaluation indexes. The results showed that the hand-over lifting mechanism demonstrated optimal operational effectiveness with an excavating and conveying mechanism angle of 20°, a scraper chain angle of 68°, an excavating and conveying mechanism speed of 1.2 m/s, and a scraper chain speed of 0.66 m/s, while the machine running speed was maintained at 1 m/s. At the moment, the hand-over lifting structure exhibited a loss rate of 1.12% and a tuber injury rate of 0.94%. The conclusions obtained serve as a valuable reference for future research and optimization of sweet potato combines.

Keywords: agricultural mechanization, sweet potato combine harvester, hand-over and lifting mechanism, EDEM simulation experiment, field experiment

DOI: 10.25165/j.ijabe.20231605.7825

Citation: Shen H Y, Wang B, Wang G P, Wang Y M, Bao G C, Hu L L, et al. Research and optimization of the hand-over lifting mechanism of a sweet potato combine harvester based on EDEM. Int J Agric & Biol Eng, 2023; 16(5): 71–79.

1 Introduction

Sweet potato, a member of the Solanaceae family, is an annual or perennial herbaceous plant[1]. It is one of the world's most important cereal crops and a competitive energy crop[2], a major source of economic income in underdeveloped areas of the world[3-5], and an anti-cancer health food[6-9]. According to statistics from the United Nations Food and Agriculture Organization (FAO), in 2019, China's sweet potato planting area reached 2.38 million hm², which accounted for 29.51% of the world's total area, the total output was 53.25 million t, accounting for 57.91 percent of the total output globally, the single output was 22 374 kg/hm² nationally, which makes China as the world's largest sweet potato producer[10].

Sweet potato cultivation involves five steps: seedling, soil preparation, planting, field management and harvesting. Generally, sweet potato is mainly planted in high ridges in China, the ridge height is 250-330 mm, the ridge distance is 900 mm, the growing depth in harvest is 200-250 mm, the tuberization range is about 300 mm, which leads to difficulties in mechanized harvesting[11-13]. At present, segmented harvesting is mainly used[14]. First, the vine is cut manually or mechanized, then the ridges are ploughed to lose soil, or the sweet potato tubers are pulled out with the chain-type sweet potato harvester, and finally the sweet potatoes are picked up manually. However, the sweet potato combine harvester with high operational integration and significant overall advantages is still in the research and development stage[15]. Due to high cost, lack of stability and immature technology, the machine is not widely used in China. Lifting and conveying sweet potato tubers is one of the important operation steps in sweet potato harvesting, which directly determines the smoothness of machine operation and is the main cause of tuber injury and loss rate[16-18]. Therefore, the research and optimization design of sweet potato harvesting improved transport technology is of great significance to improve the level of mechanized harvesting and provide technical support for the future

Received date: 2022-07-28 **Accepted date:** 2023-07-27

Biographies: Haiyang Shen, PhD candidate, research interest: agricultural equipment engineering technology, Email: 1466265003@qq.com; **Bing Wang**, PhD, Associated Professor, research interest: agricultural mechanization engineering, Email: supbing@163.com; **Gongpu Wang**, MD, Assistant Researcher, research interest: agricultural mechanization engineering, Email: wanggongpu37@163.com; **Yemeng Wang**, MD, Assistant Researcher, research interest: agricultural economy, Email: 1059073776@qq.com; **Guocheng Bao**, PhD candidate, research interest: agricultural engineering and information technology, Email: 82101196209@caas.com.

***Corresponding author: Lianglong Hu**, Researcher, research interests: agricultural machinery design and agricultural products processing equipment. Nanjing Institute of Agricultural Mechanization, Ministry of Agriculture and Rural Affairs, Nanjing 210014, China. Tel: +86-25-84346269, Email: hurxbb@163.com; **Zhichao Hu**, Senior Researcher, research interest: agricultural machinery design and agricultural products processing equipment. Graduate School of Chinese Academy of Agricultural Sciences, Beijing 100081, China Email: zchu369@163.com.

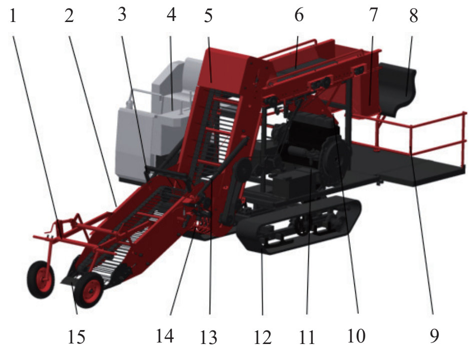
development of sweet potato combine harvesters[19].

Sweet potato tubers are collected in bins or woven sacks for combined harvesting. This process includes excavation, conveying and separation between tubers and soil, separation of sweet potato seedlings, lifting and conveying of sweet potato tubers, separation between sweet potatoes and impurities, etc. The main function of the transfer lifting mechanism is to lift and convey the tubers to the rear conveyor belts with the excavating and conveying mechanism. It is difficult to analyze the conveying and lifting process of sweet potato tubers theoretically, and granular crops could be analyzed by Discrete Element Method (DEM) and related simulation software (EDEM)[20,21].Based on the mechanism design and INVENTOR modeling, in this study the EDEM software was used to simulate the conveying state of tubers on the hand-over lifting mechanism, and the optimal parameters were found to provide theoretical evidence for subsequent bench tests and field tests.

2 Composition and working principle

2.1 Overall Structure

The design of 4UZL-1 sweet potato harvester is mainly composed of six parts: power system, excavating and conveying mechanism, sweet potato seedling separation mechanism, scraper chain transmission mechanism, operating system, and collecting platform. It could finish limited excavation in a single ridge and line, the separation between potato and soil, the separation of sweet potato seedlings, scraper chain conveying and collecting, etc. The basic structure is shown in Figure 1. The main components include: the depth-limited mechanism, the separating and conveying structure, the sweet potato seedling separating structure, the cab, the scraper chain conveying structure, the rear conveyor belt, the earth falling device, the sweet potato collecting seat, the rack, the discharge port, the gearbox, the caterpillar chassis, the hydraulic cylinder, the arc grid transmission device, and the digging blade, etc[22,23].



1.Depth-limited mechanism 2.Separating and conveying structure 3.Sweet potato seedling separating structure 4.Cab 5.Scraper chain conveying structure 6.Rear conveyor belt 7.Earth falling device 8.Sweet potato collecting seat 9.Rack 10.Discharge port 11.Gearbox 12.Caterpillar chassis 13.Hydraulic cylinder 14. Arc grid transmission device 15.Digging blade

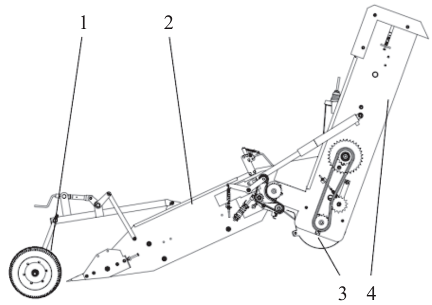
Figure 1 Structure diagram of 4UZL-1 sweet potato combine harvester

2.2 Working principles

The 4UZL-1 sweet potato combine harvester could complete the excavation of sweet potato tubers in the single ridge, separation of tubers from soil, separation of sweet potato seedlings, scraper chain transport and collection, etc. When working, the excavating and conveying device digs into the soil at a certain angle, driven by a hydraulic cylinder. The front depth-limiting wheel ensures that the digging blade enters the soil at a reasonable depth. The excavated potatoes and impurities are conveyed to the sweet potato planting mechanism by the excavating and conveying device. The residual vine on top of the sweet potato is removed by a chain roller clamping mechanism and the vine-removed tubers are dropped into the arc-grid transfer device. The tubers are then collected by the scraper and lifted by the scraper chain lifting device and conveyed to the rear conveyor. The clods are further separated or artificially separated on the rear conveyor. Finally, the tubers are collected using the tuber collection box or woven bags attached to the discharge opening.

2.3 Design of the hand-over lifting mechanism

The hand-over lifting mechanism mainly consists of the depth limiting mechanism, the excavating and conveying mechanism, the arc grid transfer mechanism and the scraper chain conveying mechanism, as shown in Figure 2. The working principle is as follows: when the machine is started, the engine rotates the conveyor structure of the scraper chain through the gearbox. The excavating and conveying device is further rotated by a scraper chain conveyor. The linear speeds can be adjusted by the size of the sprocket and the transmission ratio. The main function of the transfer and lifting mechanism is to smoothly transfer the dug tubers to the rear conveyor.



1. Depth limited mechanism 2. Excavating and conveying mechanism 3. Arc grid transmission mechanism 4. Scraper chain conveying mechanism

Figure 2 Diagram for 4UZL-1 sweet potato combine harvester's hand-over conveying mechanism

3 EDEM simulation analysis

According to the characteristics of EDEM and the actual working conditions, and also to save simulation time, the simulation model of the hand-over lifting mechanism is simplified:

(1) The rectangular tuber collecting box in the rear hand-over lifting mechanism could be designed to simplify the rod conveying as a conveyor belt conveying model uniformly.

(2) The shape of conveyed tubers on the hand-over lifting mechanism is in normal distribution, and irregular tubers are not considered.

(3) In the simulation process, sweet potato tubers are only particles, and impurities are not considered.

3.1 Construction of the 3D simulation platform

3.1.1 Sweet potato model

The shape of sweet potato tuber is generally round, oval or spindle. To facilitate the calculation, the length, width and thickness of the sweet potato tuber are taken as part of the mechanical and physical properties in the design[24]. The thickness of "Sushu 16" tubers is mainly distributed in 40-70 mm, the width is mainly distributed in 40-100 mm, and the length is mainly distributed in 70-120 mm. According to the measurement results, the modelling of

"Sushu 16" tubers is constructed by using several spherical granules of different radii to make an approximate linear combination, and the average mass is more than 300 g, the sweet potato model is shown in Figure 3.

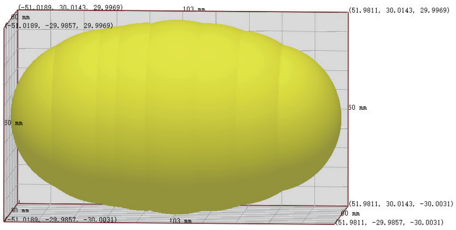
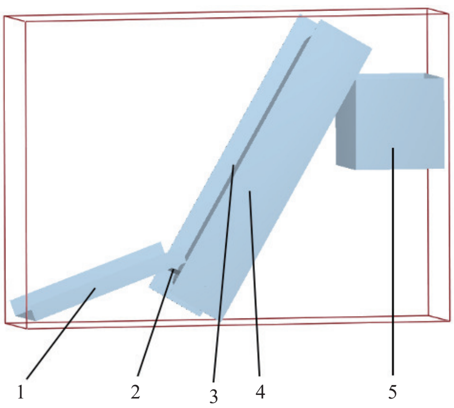


Figure 3 Sweet potato model

3.1.2 Modeling the Scraper Lifting Mechanism

The hand-over lifting mechanism is modeled by INVENTOR, which mainly consists of the excavating and conveying mechanism, the scraper, the lifting and conveying mechanism, the sideboard, and the box receiver. After modeling, the STL format is saved then EDEM is introduced, as shown in Figure 4. A particle factory is established on the plane of excavating and conveying mechanism, and particles are doing planar motions on the plane. Therefore, the motion constraints of the excavation conveyor mechanism and the sweet potato tubers in EDEM are set to "Add Conveyor Translation". The scraper moves mainly along the plane of the scraper chain conveyor mechanism and rotates on the up and down rotation axis of the scraper chain conveyor mechanism. Therefore, 19 scrapers start moving from the lower circle of the scraper chain conveyor mechanism at equal time intervals. Each scraper sets the constraints of "Add Linear Translation Kinematic" and "Add Linear Rotation Kinematic" multiple times according to the movement time required for translation and rotation. At the end of the hand-over lifting mechanism, a square box is set to replace the movements of the harvester's rear conveyor belt and to act as a collection box for the tubers.



1.Excavating and conveying mechanism 2.Scraper 3.Hand-over lifting mechanism 4.The side panel 5.Pick up container

Figure 4 Machine model

3.1.3 Setting of the contact model and material parameters

In the sweet potato harvesting process, the collisions and contacts between tubers, tuber and scraper, tuber and conveyor rod occur when the tubers pass through a hand-over lifting mechanism. None of these are associated with adhesion or electrical heating. Therefore, the Hertz-Mindin (no slip) non-slip model and the standard rolling friction contact model are adopted to analyze the movements of tubers on the hand-over lifting mechanism[25].

When the simulation of the hand-over lifting device is manipulated by EDEM software, the material parameter setting includes two materials. The material properties of each component and material have a direct influence on the analysis of the discrete element simulation results. The conveyor belt, scraper, feed box and loop conveyor mechanism are set to the relevant material property parameters of Q235. The scraper is set to the relevant rubber material property parameters. The material property parameters of the sweet potato tubers are taken from the relevant literature. The material property parameters and contact mechanics parameters of sweet potato, rubber and Q235 are given in Table 1[26-29].

Table 1 Related material properties and contact mechanics parameters

Project	Sweet potato	Q235	Rubber
Density/(g·cm^{-3})	1.13	7.8	1.8
Shear modulus/Pa	1.31E+6	8.05E+10	1.7E+6
Poisson's ratio	0.41	0.30	0.47
Dynamic friction coefficient	0.12	0.18	0.21
Static friction coefficient	0.36	0.38	0.61
Collision recovery coefficient	0.66	0.47	0.72

3.2 Analysis of the simulation results

In the process of conveying sweet potatoes, the sweet potato tubers could collide with the rod and the scraper, also between the tubers. Therefore, in the EDEM post-processing, the degree of potato tuber damage can be determined by analyzing the average normal force received, and further selecting the optimum working parameters for the machine, which can be a reference for subsequent single factor experiments[30-32], the sweet potator simulation diagram model is shown in Figure 5.

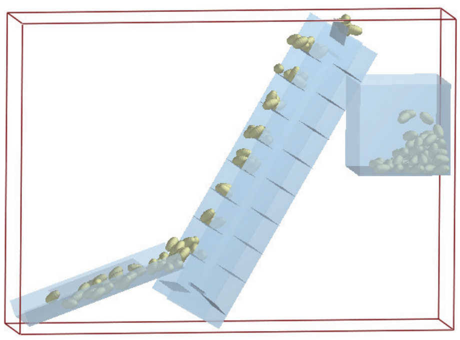
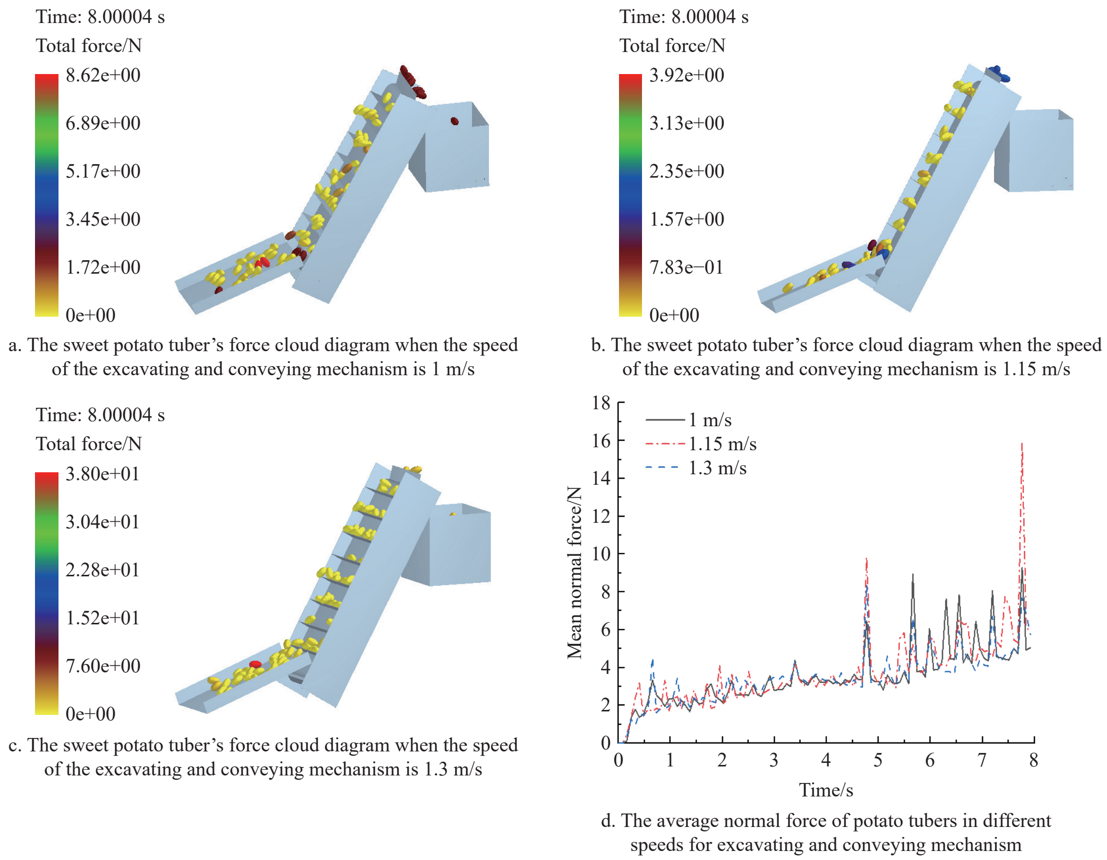


Figure 5 Sweet potato tuber simulation diagram

3.2.1 Influence of the speed of excavating and conveying mechanism on the force of sweet potato tubers

When the angle of the excavating and conveying mechanism is 24°, the speed of the scraper chain conveying is 0.66 m/s and the angle of the scraper chain conveying mechanism is 60°, the speeds of the excavating and conveying mechanism are 1 m/s, 1.15 m/s and 1.3 m/s respectively for simulation. The force analysis is performed at the above three different speeds simultaneously. The force cloud diagram is shown in Figures 6a-6c. During the EDEM simulation process, as time changes, the movement of the sweet potato and the mechanism also changes, resulting in different normal forces on the potato tubers at different times. Therefore, the average force of the normal force on the sweet potato tubers and the smoothness of the sweet potato transport on the working plane are used to comprehensively analyze the operational performance of the transfer and lifting mechanism. Data statistics and further analysis are performed on the simulation results as shown in Figure 6d.



a. The sweet potato tuber's force cloud diagram when the speed of the excavating and conveying mechanism is 1 m/s

b. The sweet potato tuber's force cloud diagram when the speed of the excavating and conveying mechanism is 1.15 m/s

c. The sweet potato tuber's force cloud diagram when the speed of the excavating and conveying mechanism is 1.3 m/s

d. The average normal force of potato tubers in different speeds for excavating and conveying mechanism

Figure 6 Diagram sweet potato tuber's forces at different the speeds of the excavating and conveying mechanism

It can be seen from Figures 6a-6c that the force on the tubers is mainly concentrated at the junction of the first and second levels and at the end of the scraper chain conveyor mechanism, due to the parabolic movements that the tubers made at these two positions at certain initial speeds. Therefore, the normal force decreased as the speed increased. It can be seen from Figure 6d that when the time reached 5 s, the average normal force on the potato tubers increased to the peak value, indicating that the speed of the excavating and conveying mechanism had little influence on the tuber damage. From the EDEM visual interface, it can be seen that the faster the speed of the mechanism, the shorter the time, while the smoother the conveying process. However, the average normal force on the tubers is relatively weak when the speed is too fast or too slow. According to the length of time and the magnitude of the force, when the speed of excavation and conveying is 1.15 m/s, the hand-over lifting mechanism works better.

3.2.2 Influence of the angle of the excavating and conveying mechanism on the force of sweet potato tubers

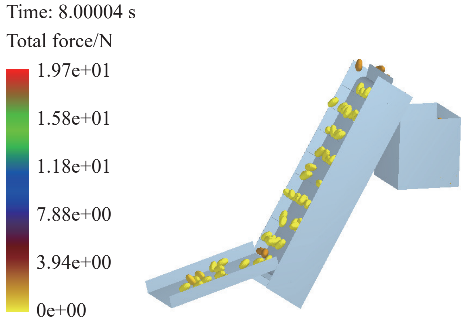
When the speed of the excavating and conveying mechanism is 1.15 m/s, the speed of the scraper chain conveying is 0.66m/s and the angle of the scraper chain conveying mechanism is 60°, the angles of the excavating and conveying mechanism are 20°, 24° and 28° respectively for the simulation, the above three different speeds were subjected to force analysis at the same time. The force cloud diagram is shown in Figures 7a-7c, and the results of the simulation data analysis are shown in Figure 7d.

It can be seen from Figures 7a-7c that the number of tubers on the scraper chain conveyor decreased as the angle of the excavating and conveying mechanism increased. In the simulation, the contact between the tubers and the mechanism is relatively ideal. There is no contact between the soil and the tubers, relying only on the friction between the tubers and the bar in the fields. Therefore, as the angle of the digging and conveying mechanism increased, the tubers sliding down could not slide up along the mechanism. From Figure 7d, it could be seen that when the angle of the excavating and conveying mechanism was 28°, the average normal force on the tubers first increased and then decreased. Therefore, the angle of the excavating and conveying mechanism should not be too large. If the angle of the excavating and conveying mechanism is too small, there is a design problem. It could be analyzed from the EDEM visual interface of conveying smoothness and average normal force on tubers. When the digging and conveying angle was 24°, the transfer lifting mechanism worked better.

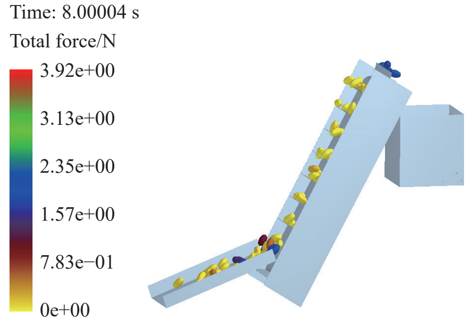
3.2.3 Influence of the speed of the scraper chain conveying on the force of the sweet potato tubers

When the angle of the excavation conveying mechanism is 24°, the speed of the excavation conveying mechanism is 1.15 m/s and the angle of the scraper chain conveying mechanism is 60°, the scraper chain conveying speeds are 0.6 m/s, 0.66 m/s and 0.72 m/s respectively for the simulation, the above three different speeds were subjected to force analysis at the same time. The force cloud diagram is shown in Figures 8a-8c, and the results of the simulation data analysis are shown in Figures 8d.

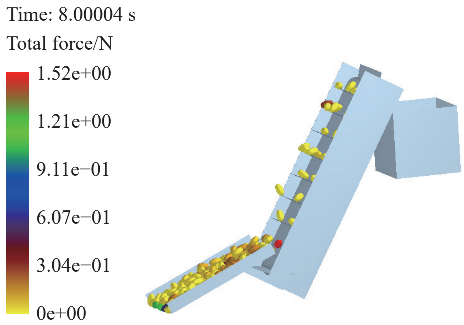
It can be seen from Figures 8a-8c that the normal force on the tubers at the junction of the first and second levels and at the end of the scraper chain conveyor mechanism is relatively large. The speed at the junction increased as the conveying speed of the scraper chain increased, while the speed at the end of the mechanism decreased as the conveying speed increased. As the speed at the junction increased as the conveyor speed increased, the rebound time between the tuber and the conveyor increased. At the end of the conveyor, the slower the conveyor speed, the harder the tubers were pushed out and the longer the time between the tubers and the conveyor. It can be seen from Figures 8d that when the speed of the



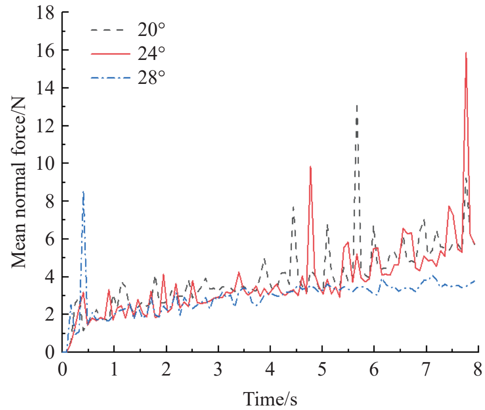
a. The sweet potato tuber's force cloud diagram when the angle of excavating and conveying mechanism is 20°



b. The sweet potato tuber's force cloud diagram when the angle of excavating and conveying mechanism is 24°



c. The sweet potato tuber's force cloud diagram when the angle of excavating and conveying mechanism is 28°



d. The average normal force of potato tuber with different angle of conveyor excavation mechanism

Figure 7　Diagram of sweet potato tuber's forces at different angles of the excavating and conveying mechanism

scraper chain conveyor is 0.66 m/s, the normal force on the potato tubers increases over time to the maximum peak value. Therefore, according to the visual analysis of the tubers and the average normal force, the transfer chain conveyor works best when the conveyor speed is 0.66 m/s.

3.2.4　Influence of the angle of the scraper chain conveying on the force of the sweet potato tubers

When the angle of the excavating conveyor is 24°, the speed of the excavating conveyor is 1.15m/s and the conveying speed of the scraper chain is 0.66 m/s, the angles of the scraper chain conveying are 50°, 60° and 70° respectively for simulation, the above three different speeds were subjected to force analysis at the same time. The force cloud diagram is shown in Figures 9a-9c, and the results of the simulation data analysis are shown in Figure 9d.

Figure 9 shows that the force on the tubers increased and then decreased as the angle of the scraper chain conveyor increased. With time, the force on the lump follows the same variation trend. The force increased steadily and approached the peak time, which, due to the angle of the scraper chain conveyor, has little damaging effect on the tubers. The tubers are easily dropped when the conveying angle of the scraper chain is relatively large. Conversely, when the angle is small, the tubers bounce back easily. Therefore, according to the visual analysis of the tubers and the average normal force, the transfer lifting mechanism works best when the scraper chain conveying angle is 60°.

4　Field experiments

4.1　Test equipment and instruments

The test equipment mainly includes a 4UZL-1 sweet potato combine harvester, measuring tape, tapeline, electronic platform scale, electronic stopwatch, tachometer, electronic balance, aluminum box, potato collecting box, tool kit, etc. The 4UZL-1 sweet potato combine harvester is shown in Figure 10.

4.2　Test conditions

The experimental variety was "Sushu 16", cultivated by the Jiangsu Academy of Agricultural Sciences. The trial was conducted at the Sweet Potato Experimental Demonstration Field of the Baima Experimental Base of the Nanjing Institute of Agricultural Mechanisation, Ministry of Agriculture and Rural Affairs. The experimental demonstration field is flat and the soil is relatively viscous. An experimental plot with a length of 50 m and a width of 30 m was selected for experimental research. According to the experimental design, the soil moisture content, the planting height of the sweet potato and the distribution size were to be determined.

The demonstration field has a gentle terrain and sticky soil. A test plot of 50 m length and 30 m width was selected for the experimental research.

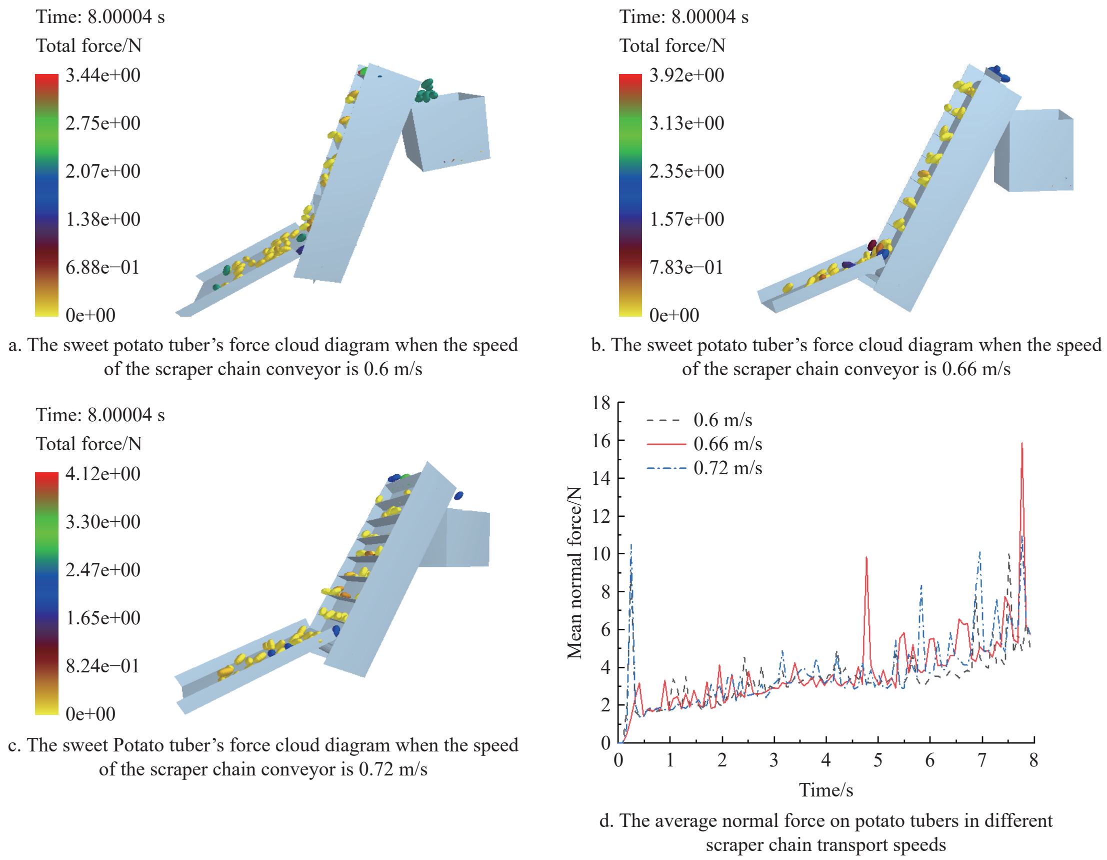
4.2.1　Soil moisture determination

The sweet potato trial and demonstration field was planted with high ridges. Five samples were taken from the ridges using the five-point positioning method, and soil samples from 100 mm to 200 mm below the surface were placed in aluminum boxes. It was required that there should be no large blocks of soil. The samples taken were weighed in the test field using an electronic balance and then dried using a DGF30/-1A electric blast dryer. The samples were dried at 105°C until the weight of the samples remained unchanged[33]. The soil moisture content was then calculated using Equation (1):

$$\eta = \frac{m_1 - m_2}{m_1} \times 100\% \qquad (1)$$

where, η is the soil moisture content, %; m_1 is the sample mass before drying, g; m_2 is the quality of the sample after drying, g.

In 2019, there was less rainfall in Nanjing, and the soil was more viscous, so the soil moisture content was lower than that in the past few years. According to the test results, the soil moisture



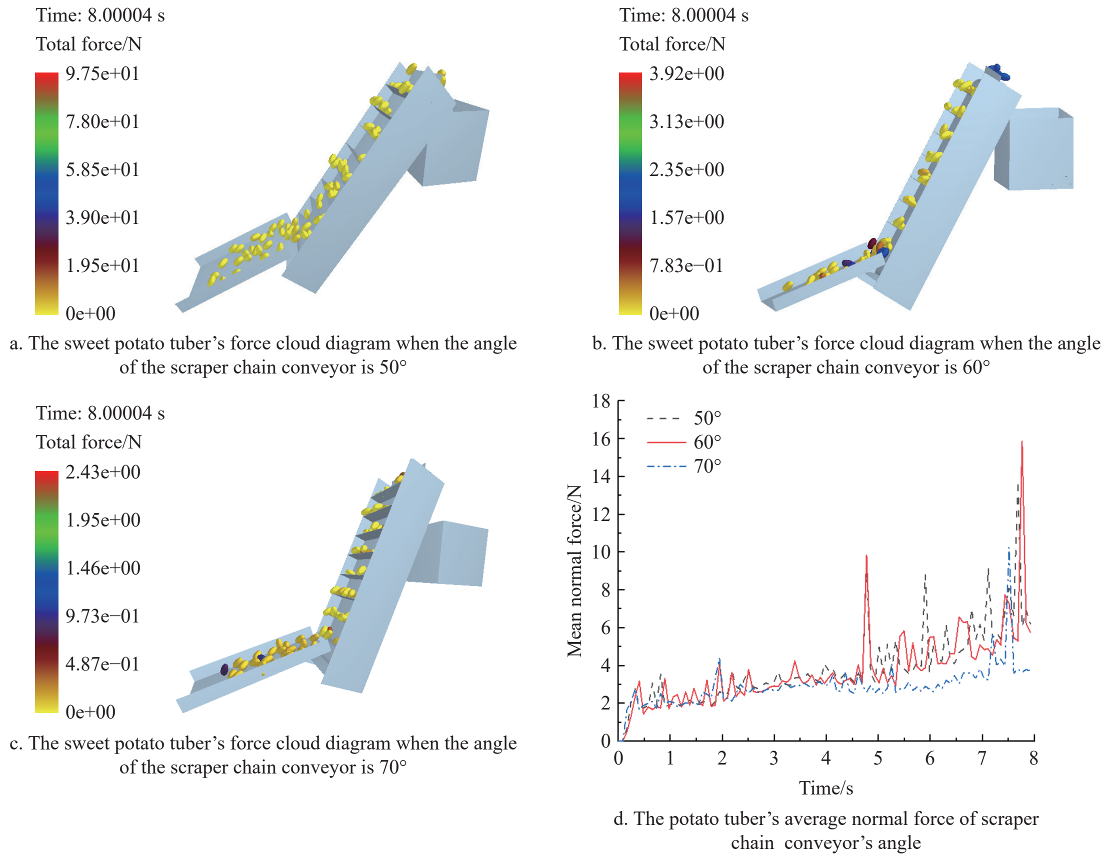
a. The sweet potato tuber's force cloud diagram when the speed of the scraper chain conveyor is 0.6 m/s

b. The sweet potato tuber's force cloud diagram when the speed of the scraper chain conveyor is 0.66 m/s

c. The sweet Potato tuber's force cloud diagram when the speed of the scraper chain conveyor is 0.72 m/s

d. The average normal force on potato tubers in different scraper chain transport speeds

Figure 8 Diagram of sweet potato tuber's force at different speeds of the scraper chain conveyor



a. The sweet potato tuber's force cloud diagram when the angle of the scraper chain conveyor is 50°

b. The sweet potato tuber's force cloud diagram when the angle of the scraper chain conveyor is 60°

c. The sweet potato tuber's force cloud diagram when the angle of the scraper chain conveyor is 70°

d. The potato tuber's average normal force of scraper chain conveyor's angle

Figure 9 Diagram of sweet potato tuber's force in different angles of the scraper chain conveyor

content was 12.16% when the sweet potato combine harvester was tested in the sweet potato experimental demonstration field of Baima Base.

4.2.2 Determination of the body of the planting ridge

Five samples were randomly taken in the sweet potato ridges in the field using the five-point positioning method. According to the

Figure 10 4UZL-1 sweet potato combine harvester

test measurement results, when the sweet potato combine was tested in Baima Base, the average planting distance of sweet potato was 162 mm, the average ridge distance was 905.4 mm, the average ridge height was 141.8 mm, and the average ridge top width was 280.4 mm. The average ridge bottom width, tuber width and tuber depth were 675.8 mm, 222.8 mm and 224.4 mm respectively.

4.3 The evaluation indexes

4.3.1 Selection of test site and test method

The terrain of the test site was flat with mechanical ridges, and the absolute moisture content of the soil was not more than 25%. The length of the test area was not less than 30 m, the preparation area at both ends was not less than 10 m and the width was not less than 8 times the working width. In the test area, three districts were randomly selected, each with a length of 3 m and a width of the working width of the machine[34].

The test area consisted of a stability zone, a measurement zone and a parking zone. The length of the stability zone was 10 m and the length of the measurement zone was 10 m. The measurement zone was followed by a parking zone and the performance measurement was carried out in the measurement zone[34].

4.3.2 Measuring the loss rate and tuber injury rate

After the operation of the machine is finished, the potato tubers in the measurement area are collected, and the lost sweet potato tubers are picked up manually, and then they are weighed. From the collected and lost tubers, all the injured tubers (the sweet potato tubers broken due to inappropriate mechanism and working parameters during operation) were selected and then weighed (all the above tubers were weighed without small tubers)[34]. The loss rate T_1 and the tuber injury rate T_2 were calculated according to Equations (2) and (3).

$$T_1 = \frac{W_2}{W} \times 100 \quad (2)$$

$$T_2 = \frac{W_3}{W} \times 100 \quad (3)$$

$$W = W_1 + W_2 \quad (4)$$

where, T_1 is the loss rate, %; T_2 is the rate of tuber injury, %; W_1 is the mass of sweet potato tubers collected, kg; W_2 is sweet potato weight loss, kg; W_3 was the weight of injured tubers, kg; W is the total sweet potato mass, kg.

4.4 Determining the test scheme

Through the simulation results and mechanism design, the angle of the excavating and conveying mechanism was set to 20°, the scraper chain conveying angle was set to 68°, the speed of the excavating and conveying mechanism was set to 1.2 m/s, and the scraper chain conveying speed was set to 0.66 m/s. Field tests were carried out in the sweet potato test base with the machine running at a speed of 1 m/s, as shown in Figure 11. The experimental results are given in Table 2.

Figure 11 Field operation diagram of the 4UZL-1 sweet potato combine harvester

Table 2 Experimental value of evaluation indices in optimum condition

Project	Loss rate Y_1/%	Tuber injury rate Y_2/%
1	1.22	0.90
2	1.00	0.95
3	1.16	1.00
4	1.08	0.92
5	1.14	0.93
The average	1.12	0.94

It can be seen from Table 2 that the average test values of loss rate Y_1 and tuber injury rate Y_2 were lower than the theoretical values of DB41/T 1010-2015 “Technical Regulations for Sweet Potato Mechanization Ridging and Harvesting Operations”. Therefore, this parameter combination was certainly reliable. The parameter combination could be adopted in the operation of a sweet potato combine harvester. That is to say, an excavating and conveying mechanism angle of 20°, a scraper chain angle of 68°, an excavating and conveying mechanism speed of 1.2 m/s, and a scraper chain speed of 0.66 m/s. At the moment, the hand-over lifting structure had a loss rate of 1.12% and a tuber injury rate of 0.94%.

4.5 Discussion

The experimental results of the sweet potato combine verified the simulation results well, because the parameters of the sweet potato simulation were obtained through a large number of physical characteristics of the sweet potato experiments. The injury rate of the sweet potato combine was lower than that of the sweet potato segment harvester because the sweet potato tubers move on the conveyor chain during the working process of the sweet potato combine, while the sweet potato tubers fall off at the end of the conveyor chain during the working process of the sweet potato segment harvester, so the injury rate can be reduced by 50%. At the same time, the injury rate of the 4UGL-1 sweet potato combine was 15% lower than that of the two-stage sweet potato combine because it had fewer collisions than the two-stage combine. The loss rate is only for the sweet potato combine evaluations, so no data are available for comparison. The experimental data pairs are shown in Table 3.

Table 3 Comparison of performance index test results

Type of sweet potato harvesting structure	Sources	Performance Indexes	
		Tuber injury rate/%	Loss rate/%
The sweet potato combine harvester	This study	0.94	1.12
The sweet potato two-stage combine harvester	[35]	1.11	
The sweet potato harvester	[36]	2.1	
The 4GS-600 sweet potato harvester	[37]	2.0	

5 Conclusions

Based on the analysis of the sweet potato combined harvester, the handover lifting mechanism was designed. The mechanism is mainly composed of a depth limiting mechanism, excavation conveying mechanism, arc grid handover mechanism, and scraper chain conveying mechanism. The main function is to smoothly transport the excavated potato blocks to the rear conveyor belt.

Based on the introduction of the discrete element method and EDEM function, the advantage and the applicable range, the paper carried out a simulation analysis on the sweet potato hand-over lifting mechanism. Through the analysis of the average normal force on the potato tuber and the observation of the movement of the visual interface, it can be seen that the optimum operational performance of the hand-over lifting mechanism was achieved at a speed of 1.15 m/s for the excavating and conveying mechanism, an angle of 24° for the excavating and conveying mechanism, a conveying speed of 0.66 m/s for the scraper chain and a conveying angle of 60° for the scraper chain. Field tests were carried out to verify the results.

The field experiments were conducted based on the EDEM simulation experiment. The results showed that the hand-over lifting mechanism demonstrated optimal operational effectiveness with an excavating and conveying mechanism angle of 20°, a scraper chain angle of 68°, an excavating and conveying mechanism speed of 1.2 m/s, and a scraper chain speed of 0.66 m/s, while maintaining the machine's running speed at 1m/s. At the moment, the hand-over lifting structure exhibited a loss rate of 1.12%, and a tuber injury rate of 0.94%. The obtained conclusions serve as a valuable reference for future research and optimization of sweet potato combines.

Acknowledgements

This work was financially supported by the Nanjing Agricultural Machinery Equipment Industry Intellectual Property Operation Center (04 City 2202-01), the Natural Science Foundation of Jiangsu Province(BK20201124), the earmarked fund for CARS-10-Sweetpotato, the innovation project of the Chinese Academy of Agricultural Sciences(31-NIAM-02).

[References]

[1] Vithu P, Dash S K, Rayaguru K. Post-harvest processing and utilization of sweet potato: A review. Food Reviews International, 2019; 35(5): 726–762.

[2] Mohanraj R, Sivasankar S. Sweet Potato (*Ipomoea batatas* L. Lam) - A Valuable Medicinal Food: A Review. Journal of Medicinal Food, 2014; 17(7): 733–741.

[3] Alam M K. A comprehensive review of sweet potato (*Ipomoea batatas* L. Lam): Revisiting the associated health benefits. Trends in Food Science & Technology, 2021; 115: 512–529.

[4] Wang S N, Nie S P, Zhu F. Chemical constituents and health effects of sweet potato. Food Research International, 2016; 89: 90–116.

[5] Liu Q, Hu L L, Zheng Y Y, Tan L K, Wang Y M, Chen Q. Development status of intelligent harvesting technology for tea and vegetables in China. Journal of Intelligent Agricultural Mechanization, 2021; 2(1): 20–27. (in Chinese)

[6] Chen W M, Hu L L, Yuan J N, Wang G P, Wang B, Wu W. Research status and prospects of automatic control technology of vegetable harvester in China. Journal of Intelligent Agricultural Mechanization, 2021; 2(2): 57–63. (in Chinese)

[7] Ayeleso T B, Ramachela K, Mukwevho E. A review of therapeutic potentials of sweet potato: Pharmacological activities and influence of the cultivar. Tropical Journal of Pharmaceutical Research, 2016; 15(12): 2751–2761.

[8] Iese V, Holland E, Wairiu M, Havea R, Patolo S, Nishi M, et al. Facing food security risks: The rise and rise of the sweet potato in the Pacific Islands. Global Food Security, 2018; 18: 48–56.

[9] Motsa N M, Modi A T, Mabhaudhi T. Sweet potato (*Ipomoea batatas* L.) as a drought tolerant and food security crop. South African Journal of Science, 2015; 111(12): 38–45.

[10] FAO. The state of food insecurity in the world: The multiple dimensions of food security. 2019. Available at: www. fao. org/publications.

[11] Shen G W, Wang G P, Hu L L, Yuan J N, Wang Y M, Wu T. Development of harvesting mechanism for stem tips of sweet potatoes. Transactions of the CSAE, 2019; 35(19): 46–55. (in Chinese)

[12] Wu T, Hu L L, Wang G P, Hu Z C, Yan W, Wang B. Design and test of walking sweet potato vines crushing and returning machine. Transactions of the CSAE, 2017; 33(16): 8–17. (in Chinese)

[13] Mu G Z, Xin Q Q, Xuan G T, Lv Z Q, Wang H N, Xin Q S. Design and experimental research of knife roller and throwing device for sweet potato vine recycling machine. Journal of agricultural machinery, 2019; 50(12): 53–62. (in Chinese)

[14] Hu L L, Wang B, Wang G P, Yu Z Y, You Z Y, Hu Z C. Design and experiment of type 2ZGF-2 duplex sweet potato transplanter. Transactions of the CSAE, 2016; 32(10): 8–16. (in Chinese)

[15] Shen H Y, Hu L L, Wang B, Shen G W, Wang G P. Research status and prospect of potato harvest transfer lifting conveyor. Journal of Chinese Agricultural Mechanization, 2020; 41(5): 17–25. (in Chinese)

[16] Chen X D, Hu Z C, Wang B, You Z Y, Peng B L, Hu L L. Design and parameter optimization of sweet potato stalk separator for single row sweet potato combine harvester. Transactions of the CSAE, 2019; 35(14): 12–21. (in Chinese)

[17] Hu L L, Wang G P, Ling X Y, Wang B, Wang B K, You Z Y. Mechanical properties of sweet potato vine and stalk during harvest. Transactions of the CSAE, 2015; 31(9): 45–49. (in Chinese)

[18] Zheng W X, Lv Z Q, Zhang W Z, Liu Z D, Lu Y, Li Y D. Design and test of single row sweet potato vine recycling machine. Transactions of the CSAE, 2019; 35(6): 1–9. (in Chinese)

[19] Shen H Y, Wang B, Hu L L, Wang G P, Ji L L, Shen G W. Design of potato connecting and conveying mechanism for 4UZL-1 type sweet potato combine harvester. Transactions of the CSAE, 2020; 36(17): 9–17. (in Chinese)

[20] Liu W Z, He J, Li H W, Li X Q, Zheng K, Wei Z C. Calibration of Simulation parameters for potato minituber based on EDEM. Transactions of the CSAM, 2018; 49(5): 125–135, 142. (in Chinese)
[21] Gao G H, Xie H F. Numerical analysis and simulation of potato soil separation mechanism based on EDEM. Journal of Agricultural Mechanization Research, 2019; 41(1): 15–21. (in Chinese)
[22] Hu L L, Wang G P, Wang B, Hu Z C, Tian L J, Ji F L, et al. The utility model relates to a multifunctional self-carrying sweet potato combine harvester: CN204837056U, 2015-12-09.
[23] Wang B, Hu L L, Ji F L, Hu Z C, Tian L J, Wang G P, et al. The utility model relates to a small bar lift chain type sweet potato harvester: Chinese Patent, CN203896732U, 2014-10-29. (in Chinese)
[24] Peng Z C, Lu X H, Niu X D, Liu R X. Design scraper conveyor of 4U-1400 potato combine harvester. Journal of Chinese Agricultural Mechanization, 2017; 38(2): 7–11, 23. (in Chinese)
[25] Feng B. Study on physical characteristics and injury of potato tubers at harvesting stage. Gansu Agricultural University, 2018. (in Chinese)
[26] Feng B, Sun W, Shi L R, Sun B G, Zhang T, Wu J M. Determination of restitution coefficient of potato tubers collision in harvest and analysis of its influence factors. Transactions of the CSAE, 2017; 33(13): 58–65. (in Chinese)
[27] Shen H Y, Ji L L, Hu L L, Wang B, Wang G P, Bao G C. Study on the mechanical and Physical parameters of sweet potato tuber during harvest. Journal of Chinese Agricultural Mechanization, 2020; 41(12): 55–61. (in Chinese)
[28] Yang R B, Yang H G, Shang S Q, Ni Z W, Liu Z S, Guo D. Design and experiment of vertical circular separating and conveying device for potato combine harvester. Transactions of the CSAE, 2018; 34(3): 10–18.
[29] Yu H Y, Qiao J L, Xiao Y K, Wang S J, Zhang Y P. Physical properties of potato tuber cultured by aeroponics. Journal of Jilin University (Science Edition), 2011; 41(1): 282–287. (in Chinese)
[30] Wang F Y. Optimization and field experiment of an adjustable device for sugar beet digger. Int J Agric & Biol Eng, 2021; 14(6): 68–74.
[31] Tian Z W, Ma W, Yang Q C, Yao S, Guo X Y, Duan F M. Design and experiment of gripper for greenhouse plug seedling transplanting based on EDM. Agronomy, 2022; 12: 1487.
[32] Yin J J, Wang Z L, Zhou M L, Wu L N, Zhang Y. Optimized design and experiment of the three-arm transplanting mechanism for rice potted seedlings. Int J Agric & Biol Eng, 2021; 14(5): 56–62.
[33] Mei S, Xiao S W, Jiang Q H, Lü X L, Tong Y F. Design and experiment of self-propelled precision sowing and fertilizing control system for vegetables. Journal of Intelligent Agricultural Mechanization, 2022; 3(1): 54–61. (in Chinese)
[34] DB41/T1010-2015. Technical regulations for mechanized ridging and harvesting of sweet potato. Zhengzhou: Henan Provincial Bureau of Quality and Technical Supervision, 2015. (in Chinese)
[35] Yang R B, Zhang J, Shang S Q, Tian G B, Zhai Y M, Pan Z G. Design and test of secondary conveyor separator device for sweet potato combine harvester. Journal of Jilin University (Engineering and Technology Edition): 2023; pp.1–14. doi:10.13229/j.cnki.jdxbgxb.20221454.
[36] Cui Z K, Zhang H, Zhou J, Li T. Design and test of 4U-750 trailing type sweet potato harvester. Journal of Chinese Agricultural Mechanization, 2020; 41(5): 1–5, 25.
[37] Hu L L, Tian L J, Hu Z C, Ji F L, Wang B, Ma B. Research design and test of 4GS-1500 type wide sweet potato harvester. Journal of Chinese Agricultural Mechanization, 2013; 34(3): 151–154.