Design and test of a collecting machine for orchard waste fruit pouches

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Abstract: In response to the issues posed by non-biodegradable orchard fruit pouches causing environmental pollution, as well as the inefficiency and high cost of manual recovery, a design for an orchard fruit pouch collecting machine was proposed. The study involved analyzing the structure and working principle of the entire machine, as well as proposing two types of pick-up and recovery devices: a spring-tooth roller type pickup device and an air-suction collecting device. After comparative analysis, the spring-tooth roller type pickup device was selected. Based on the physical characteristics of the fruit pouch, theoretical calculations and kinematic analysis were performed for the key components of the orchard fruit pouch collecting machine. This analysis yielded working parameters for each component, with a focus on roller rotational speed, machine travel speed, and number of spring-tooth rows as critical factors influencing operational effectiveness. Subsequently, the ADAMS simulations were conducted based on these findings. Then the response surface methodology was applied, and an optimal parameter combination for the orchard fruit pouch collecting machine was determined: a machine travel speed of 2 km/h, roller rotational speed of 60 r/min, and five rows of spring teeth. The prototype was made, and the results of orchard experiments indicated that with the optimal parameter combination, the recovery rate predicted by the model was 85.2% and that of the orchard experiment was 80.9%. The relative error between them is 5.3%. These findings confirmed that the designed orchard fruit pouch collecting machine could achieve the expected performance and effectively recover fruit pouches with good efficiency.

Keywords: waste fruit pouches, collecting machinery, structure design, ADAMS simulation analysis, orchard experiment
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1 Introduction

The technology of apple pouching[1] has been widely applied in apple orchards across the country. Wrapping apples with a fruit pouch can bring many benefits, not only effectively reducing diseases and pests and isolating pesticide spraying, but also promoting apple ripening and bringing high-quality fruit for farmers[2]. To ensure uniform coloring and increase the sweetness of the apples, farmers typically remove the fruit pouches from the fruit trees approximately 20 d before harvest, allowing the apples to receive sufficient sunlight exposure[3,4]. The discarded fruit pouch scattered in the orchard contains moisture-resistant components, which make it difficult to degrade naturally, and lead to environmental pollution and damage in the orchard[5]. Collecting the discarded fruit pouches not only helps protect the orchard environment but also makes the most use of it and saves renewable resources, thereby enhancing both economic and social benefits[6].

With the active response to the national sustainable development strategy, farmers' demand for agricultural machinery has gradually shifted from production machinery to recycling machinery[7,8]. As an essential component of the fruit industry, mechanization of discarded fruit pouches collecting will become a major focus of research and development in the production process[9]. Currently, there is a lack of research on orchard fruit pouch collecting machines domestically and internationally. However, some scholars have conducted in-depth comparative studies on picking devices and profiling terrain devices[10,11]. Wang et al.[12] conducted 3D design and motion simulation of the picking device's roller by using Solidworks software, and preliminarily identified working parameters such as the arrangement of elastic teeth to meet requirements, roller rotational speed, and operating height. Zhao et al.[13-16] applied CATIA software to conduct motion simulation analysis of the parallel four-bar simulated device, determining factors and parameters affecting imitating device performance. Zhao et al.[17] proposed a frictionless toothed roller picking device, which adopted a curved tooth shape and adjusted the clamping angle between the curved picking teeth and the guard plate, improving the adaptability of the picking device and the picking capability. The aforementioned studies primarily focus on applications such as peanut harvesters and wheat seeders, and there is a lack of research specifically on the application of orchard fruit pouch collecting machines[18-20].

Therefore, to address the aforementioned issues, a fruit pouch collecting machine for orchards was designed, which can perform uniform picking, conveying, and collecting of discarded fruit pouch, ultimately achieving the goal of recycling.

Based on the required working conditions and characteristics of the fruit pouch collecting machine, the spring-tooth roller type

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pickup device and the five-bar profiling mechanism (which can vary with the orchard terrain) were autonomously designed for the collection of waste fruit pouches. Based on theoretical analysis, the motion states of the spring-tooth roller type pickup device and the five-bar profiling mechanism were simulated and analyzed using ADAMS simulation software to determine the motion states of key components. Response surface simulated experiments were conducted, and the recovery rate was the evaluation index. Through the optimization of the objective function, the optimal parameter combination for the fruit pouch collecting machine was determined to validate the feasibility of the fruit pouch collecting machine and provide reference for subsequent prototype optimization.

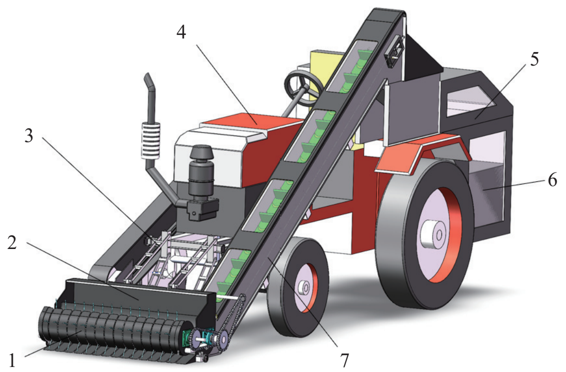
2 Proposal of machine structure

Waste fruit pouches collected from the apple orchard and their relevant physical characteristics parameters were measured: the average length was 150.5 mm, the average width was 183 mm, the average height was 2 mm, and the sliding friction coefficient was 0.53. The schematic diagram of the fruit pouch dimensions is shown in Figure 1.

a. Fruit pouches in tree b. Partial enlarged image

Figure 1 Schematic diagram of the fruit pouch dimensions

According to the scattered fruit pouches the proposed collecting machine mainly consists of a spring-tooth roller type pickup device, a screw conveyor device, a conveyor belt device, a five-bar profiling mechanism (which can vary with the orchard terrain), a collection box device, a compression device, a tractor, and other components. The schematic diagram of the overall machine structure is shown in Figure 2.



1.Spring-tooth roller type pickup device 2.Screw conveyor device 3.Five-bar profiling mechanism 4.Tractor 5.Collection box device 6.Compression device 7.Conveyor belt device

Figure 2 Schematic diagram of the overall structure of the orchard fruit pouch collecting machine

The fruit pouch collecting machine was powered by the tractor' s power output shaft. During the machine working, the five rows of spring-tooth in the spring-tooth roller type pickup device rotate downward, pushing the fruit pouches into the screw conveyor device, and the fruit pouches are then pushed by the spiral blades to the inlet on the right side and transferred onto the conveyor belt. With the conveyor belt's motion, the fruit pouches enter the collection box and are compressed to complete the collecting process.

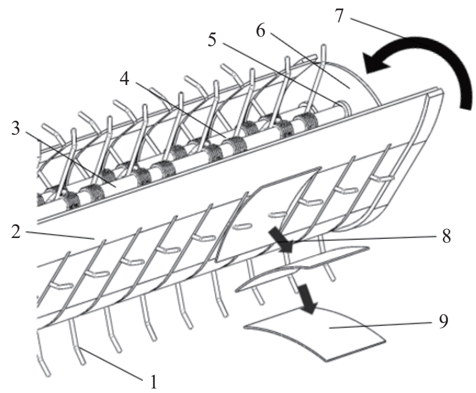
Among these components, the pick-up collecting device was the most critical working mechanism of the machine. In this paper two design options were proposed, namely the spring-tooth roller type pickup device and the air suction-recovery mechanism. Through comparative analysis, the spring-tooth roller pickup device was chosen for application in this collecting machine. For optimal performance the design and analysis of the spring-tooth roller device would be carried out.

3 Key components design

3.1 Comparison analysis of pick-up collecting devices

3.1.1 Scheme 1 for spring-tooth roller pickup device

The spring-tooth roller pickup device mainly consists of components such as the roller main shaft, spring-toothed shaft, spring-tooth, coupling discs, roller baffle, and roller side covers, etc. The overall structure diagram is shown in Figure 3.



1. Spring-tooth 2. Roller baffle 3. Spring-toothed shaft 4. Roller main shaft 5. Coupling disc 6. Roller side cover 7. Forward direction of the spring-tooth roller type pickup device 8. Falling trajectory of the fruit pouch 9. Fruit pouch

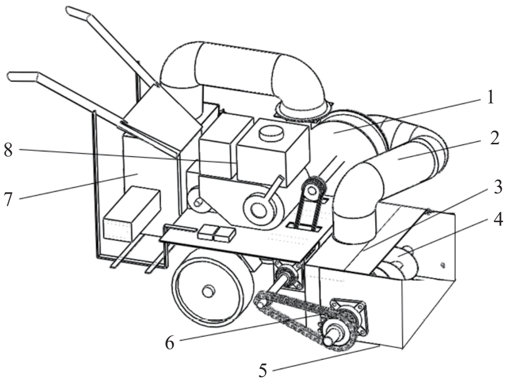
Figure 3 Structure diagram of the spring-tooth roller pickup device

The spring-tooth roller pickup device in the fruit pouch collecting machine was designed with an under rotation feeding method. This design aims to mitigate the issue of fruit pouches being scattered by the spring-tooth, attributed to their small size and tendency to float. Throughout the feeding process, there may be instances where some fruit pouches are hooked or pierced by the spring-tooth. In such scenarios, the fruit pouches will rotate together with the spring-tooth until they come into contact with the roller baffle, and then they will autonomously descend into the screw conveyor device, as shown in Figure 3.

3.1.2 Scheme 2 for air-suction collecting device

The air-suction collecting device mainly consists of components such as a centrifugal fan, air duct, settling chamber, screw conveyor device, filter screen, compression device, power device, transmission system, and so on. An overall structural schematic diagram is shown in Figure 4.

During working, the power system provides power to the centrifugal fan through the power output shaft cooperating with the pulley, while the screw conveyor device gathers the fruit pouches towards the center. The bottom filter screen removes impurities for the first time, and the centrifugal fan sucks the gathered fruit pouches into the settling chamber. Inside the settling chamber, larger impurities are removed again before the fruit pouches are transported to the collection box via the air duct. The compression device compresses the fruit pouches to complete the recovery process.



1. Centrifugal fan 2. Air duct 3. Settling chamber 4. Screw conveyor device 5. Filter screen 6. Transmission system 7. Compression device 8. Power device

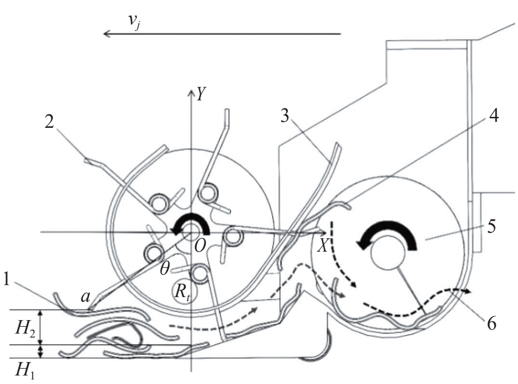
Figure 4 Structure diagram of air-suction collecting device

Through comparing the spring-tooth roller pickup device with the air-suction collecting device, the air-suction collecting device had low humidity requirements in the orchard for the retrieval of paper fruit pouches, thus making it more appropriate for collecting dry fruit pouches. In the usual orchard setting, the spring-tooth roller type pickup device was more applicable. Consequently, the theoretical calculations and kinematic analysis will be centered on the spring-tooth roller type orchard fruit pouch collecting machine.

3.2 Design and analysis of the spring-tooth roller device

3.2.1 Roller radius

The roller radius was determined by factors such as the height of the working area, the stacking height of the fruit pouches, the contact position of the spring-tooth and the fruit pouches, and the distance of the roller above the ground. In order to ensure that the fruit pouches were stably collected by the spring-tooth into the screw conveyor device at the rear, the contact point of the fruit pouches and the spring-tooth endpoint should be at point *a*, and the angle between the connecting line *O-a* and *Y* axis was θ, as shown in Figure 5.



1. fruit pouch 2. spring-tooth 3. roller baffle 4. hooked fruit pouch 5. spiral blade 6. movement trajectory of fruit pouch

Figure 5 Working principle of spring-tooth roller pick-up device

The working principle of the spring-tooth roller type pickup device satisfies the following equation:

$$\frac{R_t - H_1}{R_t} \leq \cos\theta \tag{1}$$

where, R_t is the roller radius, mm; H_1 is the maximum height of a single fruit pouch, mm; θ is the angle between the *O-a* line and *Y* axis.

To ensure that the roller radius R_t and working range θ can cover the entire area of the stacked fruit pouches, the following formula needed to be satisfied:

$$H_2 \leq R_t \cos\theta \tag{2}$$

where, H_2 is the maximum stacking height of the fruit pouches, mm.

By rearranging Equations (1) and (2), the permissible range of the roller radius R_t can be obtained as:

$$\frac{H_2}{\cos\theta} \leq R_t \leq \frac{H_1}{1-\cos\theta} \tag{3}$$

Based on the physical parameters of the fruit pouches and on-site investigations of the orchard, the maximum stack height H_2 of the waste fruit pouches was about 120 mm. Equation (3) indicated that the angle θ should be less than 39°, leading to a roller radius range of 120-150 mm. Considering the overall dimensions of the spring-tooth roller device, the roller radius R_t was designed as 150 mm.

3.2.2 Roller rotational speed

During the working of the spring-tooth roller device, the spring-teeth moved in a continuous cycloid trajectory as they rotated and also underwent horizontal motion along the direction of travel of the collecting machine. The characteristic parameter λ of the cycloid shape was defined as:

$$\lambda = \frac{2\pi R_t n_t}{v_j} \tag{4}$$

where, R_t is the roller radius, mm; n_t is the roller rotational speed, r/min; v_j is the travel speed of the tractor, km/h.

The cycloid shape characteristic parameter λ affected the picking efficiency of the fruit pouches. When $\lambda \geq 1$, the spring-tooth located in the lower half of the cycloid had a horizontal velocity component opposite to the direction of travel of the collecting machine, which helped to guide the fruit pouches towards the blades and continued to push them into the screw conveyor device. Therefore, $\lambda \geq 1$ was a necessary condition for the normal working of the spring-tooth roller device.

From Equation (4), it was evident that the roller rotational speed was dependent on the roller radius and the travel speed of the tractor. If the travel speed was set at 2 km/h and λ was 1, with a designed roller radius of 150 mm, the roller rotational speed could be calculated to be approximately 36 r/min using Equation (4). A rotational speed greater than 36 r/min would meet the requirements for normal collecting work.

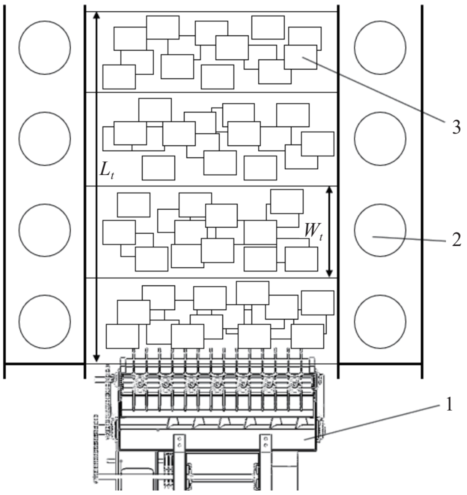
3.2.3 Number of spring-tooth rows

According to the survey of the orchard fruit tree planting pattern, the length of the roller was designed to 920 mm, and the spacing of the spring-tooth was 60 mm. When removing the fruit pouches from the fruit trees, farmers tended to discard them on the ground between two rows of the fruit trees. Therefore, the middle ground between two rows of the fruit trees was designated as a section where fruit pouches were scattered, as shown in Figure 6.

In order to ensure thorough collection of the scattered fruit pouches during the machine working, the time t_t taken by the spring-tooth roller type pickup device to pass through a section of scattered fruit pouches can be expressed as:

$$t_t = \frac{W_t}{v_j} \tag{5}$$

where, W_t is the length of the scattered area of fruit pouches, mm.



Note: W_t is the length of every scattered area of fruit pouches, L_t is the length of the whole scattered area of fruit pouches.

1. Spring-tooth roller 2. Fruit tree 3. Discarded fruit pouch

Figure 6 Fruit pouches scattered area

When passing through the scattered area of the fruit pouches, the angle θ_t of the roller rotation was:

$$\theta_t = \frac{2\pi n_t t_t}{60} = \frac{2\pi n_t W_t}{60 v_j} \tag{6}$$

If the machine is going through the fruit pouch scattered area, and collecting cleanly, then the relationship between the number N of spring-teeth on the roller and various factors can be expressed as:

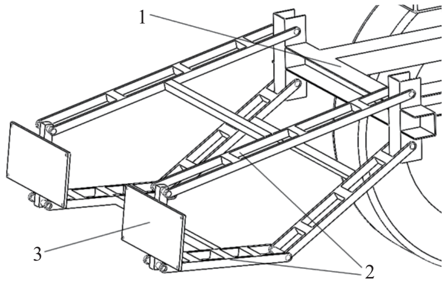
$$N = \frac{2\pi}{\theta_t} = \frac{60 v_j}{n_t W_t} \tag{7}$$

Based on the research on the distribution of waste fruit pouches in the orchard, the length W_t of scattered fruit pouches area was 1200 mm. Then according to Equation (7) the spring-tooth row count N=4.8, which was rounded up to 5, thus the spring-tooth row count as 5 rows. Considering the length of the roller and the spacing between the spring-tooth, the number of spring-tooth per row was set at 14, resulting in a total of 70 spring-teeth.

3.3 Design and analysis of five-bar profiling mechanism

Usually there is uneven ground in orchards, and in order to adapt to the varying terrain the five-bar profiling mechanism was proposed for the fruit pouch collecting machine. This profiling mechanism was designed and fixed in the front frame of the tractor, and had a left and right symmetrical structure, as shown in Figure 7, which mainly consisted of the front frame of the tractor, upper and lower simulated frames, screw conveyor frame, damping wheel, and other components.

In order to match the five-bar profiling mechanism to the fruit pouch collecting machine, the profiling displacement was calculated, as shown in Figure 8. When the collecting machine was working on flat ground, the five-bar profiling mechanism maintained its initial state, with the lower bar CD in a horizontal position and an initial horizontal angle of β. Taking the initial state as a reference, the displacement range of the upper bar AB was defined as the upper profiling displacement h$_1$, and the displacement range of downward adjustment was defined as the lower profiling displacement h_2.



1. Front frame of the tractor 2. Upper and lower profiling frame 3. Screw conveyor frame

Figure 7 Five-bar profiling mechanism

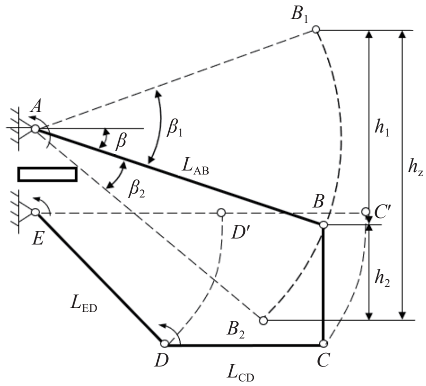


Figure 8 Diagram illustrating the profiling displacement range of the five-bar profiling mechanism

The expression could be obtained from Figure 8:

$$h_z = L_{AB}\left[\sin(\beta_1 - \beta) + \sin(\beta_2 + \beta)\right] \tag{8}$$

where, h_z is the total profiling displacement, mm; β_1 is the upward profiling angle, (°); β_2 is the downward profiling angle, (°); L_{AB} is the length of AB, mm.

Based on the structure and dimensions of the collecting machine, the angle β was set at 25°, β_1 was set at 47°, β_2 was set at 35°, and L_{AB} was set at 600 mm, and all these values were input into Equation (8). Then the total profiling displacement could be calculated as h_z = 750 mm.

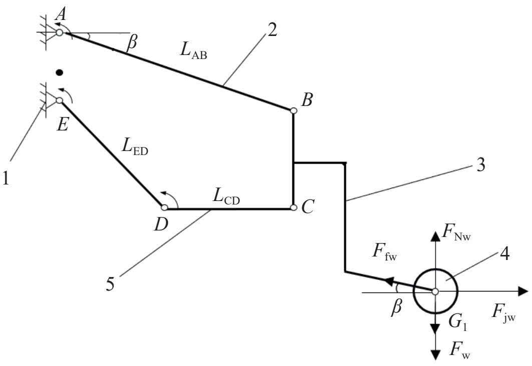
In order for the five-bar profiling mechanism to achieve stable working, the calculation of force equilibrium was essential. The damping wheel of profiling mechanism contacted the ground, then the force analysis was conducted on the damping wheel, as shown in Figure 9. The damping wheel was primarily subject to the forces of gravity G_1, tension from the screw conveyor F_w, ground support force F_{Nw}, propulsion force from the tractor F_{jw}, and resistance from the ground soil F_{fw}.

When the collecting machine worked stably on the ground, the force balance condition was:

$$\begin{cases} F_{jw} - F_{fw}\cos\beta = 0 \\ F_{Nw} + F_{fw}\sin\beta - G_1 - F_w = 0 \end{cases} \tag{9}$$

where, G_1 is the gravity, N; F_{Nw} is the supporting force of the ground, N; F_{jw} is the driving force of the tractor, N; F_{fw} is the resistance of ground soil, N; F_w is the tension of the screw conveyor, N.

Rearranging Equation (9), the resistance of the ground soil could be determined as follows:



1. Front frame of the tractor 2. Upper profiling frame 3. Screw conveyor frame 4. Damping wheel 5. Lower profiling frame

Figure 9 Force diagram of the damping wheel

$$F_{fw} = \mu_1 \frac{G_1 + F_w}{1 + \mu_1 \sin\beta} \tag{10}$$

where, μ_1 is the soil friction coefficient.

According to Equation (10), it could be inferred that the resistance of the ground soil was influenced by the gravity G_1, the tension F_w of the screw conveyor, the soil friction coefficient μ_1, and the horizontal angle β. When the gravity and tension of the screw conveyor remained constant, the larger the horizontal angle, the smaller the resistance exerted by the ground soil.

4 Motion simulation analysis of key components

In order to verify whether the orchard fruit pouch collecting machine could realize the expected movement, ADAMS simulation software was used to simulate the kinematics of key components. In the three-dimensional design software SolidWorks, the model of the spring-tooth roller type pickup device and the model of the five-bar profiling mechanism were established respectively.

4.1 Simulation analysis of spring-tooth roller type pickup device

The model of the spring-tooth roller pickup device was imported into the ADAMS software. According to the movement relationship between the components, the constraints were added to the model as listed in Table 1, and the drive was applied to the constraints to analyze the spring-tooth movement law of the pickup device and the effect of fruit pouches collecting under the condition of different roller rotational speed n_t. The collecting effect was expressed by the number of collecting fruit pouches. Generally, the more working time in a certain area of the orchard, the more fruit pouches were collected, and the better the collecting effect was. The simulation duration was set to 5 seconds, with a total of 300 simulation steps.

Table 1 Model constraint of the spring-tooth roller

Serial number	Kinematic pair	Constrained member
1	Fixed pair	Spring-tooth, axle
2	Fixed pair	Spring-toothed shaft, coupling disc
3	Rotational pair	Coupling disc, roller shaft
4	Sliding pair	Roller shaft, floor
5	Sliding pair	Roller, floor

According to the calculation of the above Section 3, the machine traveling speed v_j was set to 2 km/h, and the range of the roller rotational speed was 36-107 r/min. It was noted that as the roller rotational speed increased, the cycle period of the speed curve for the spring-tooth endpoint decreased. Consequently, within the same working time, the pickup device could execute the collecting action more frequently, leading to an enhanced fruit pouch collecting outcome. However, if the rotational speed of the spring-tooth roller was too fast, the load of the machine would be increased, which was rather unfavorable to the improvement of the efficiency of picking up and collecting. Through the simulation analysis of several roller rotational speeds, it was obtained that on the basis of meeting the working requirements, a more moderate roller rotational speed should be selected, i.e., the speed n_t was taken as 60 r/min.

Based on the determined roller rotational speed and the number of spring-tooth rows, the displacement and velocity curves of the spring-tooth are shown in Figure 10 with the travel speeds 1, 2, and 3 km/h, respectively.

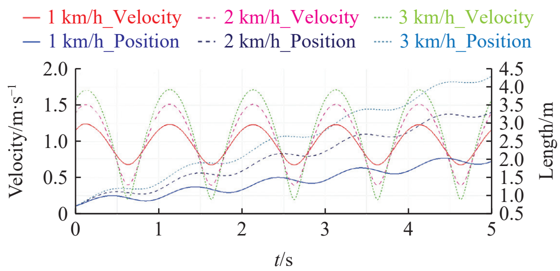


Figure 10 Displacement curve and velocity curve of the spring-tooth at different travel speeds

As could be seen from Figure 10, when the travel speed of the orchard fruit pouch collecting machine increased, the motion displacement of the spring tooth became larger, and the area of the missed pick-up area expanded accordingly. In addition, as the machine travel speed increased, the horizontal moving speed of the spring tooth had a greater absolute value. According to Equation (4), the value of the characteristic parameter λ would decrease. In summary, it could be seen that the motion displacement would increase with the increase of the machine travel speed, and the lower the value of the characteristic parameter λ, the larger the area of the missed pick-up area would be.

4.2 Simulation analysis of five-bar profiling mechanism

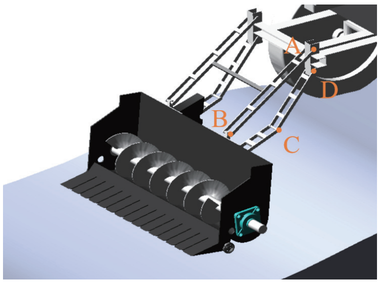
The model of five-bar profiling mechanism was imported into ADAMS software and a random road surface was generated to simulate and analyze the performance of the five-bar profiling mechanism during the working process.

According to the motion relationship between the components, the constraints and drive were added to the model. The model constraint table is listed in Table 2; the total profiling displacement was 750 mm, the simulation time was 15 s, and there were 3000 steps. The simulation results are shown in Figure 11.

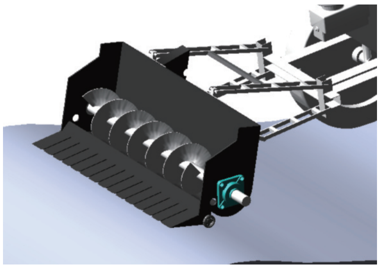
Table 2 Model constraint of profiling mechanism

Serial number	Kinematic pair/ Special force	Load-bearing/Constrained member
1	Rotational pair	Damping wheel, Screw conveyor frame
2	Rotational pair	Spiral blade, Screw conveyor frame
3	Fixed pair	Connector, Screw conveyor frame
4	Rotational pair	Connector, Upper and lower simulated frame
5	Rotational pair	Upper and lower simulated frame, Tractor beams
6	Rotational pair	Tractor tires, Axles
7	Contact force	Tires, Road surface
8	Contact force	Damping wheel, Road surface
9	Contact force	Frame, Road surface

Points A, B, C, and D in Figure 11 were articulation points on the five-bar profiling mechanism, and the profiling mechanism was at different states when the machine was going downhill and uphill. The screw conveyor connected to the profiling mechanism could adjust and adapt to the changes in the random road surface according to the different states of the profiling mechanism, and could pass through the random road surface smoothly.



a. Status of the profiling mechanism going downhill



b. Status of the profiling mechanism going uphill

Figure 11 Different states of the five-bar profiling mechanism on uneven ground

The displacement curves of points A, B, C, and D are shown in Figure 12, corresponding to the change of random road surface, and the displacement curves of the four points on the profiling mechanism had the tendency to fluctuate up and down. After the 10 s of simulation, the displacement trends of the four points were basically the same, and the orchard fruit pouch collecting machine could stably pass through the uneven road surface, which indicated that the five-bar profiling mechanism could greatly improve the performance of the orchard fruit pouch collecting machine and adapt it to the orchard ground conditions.

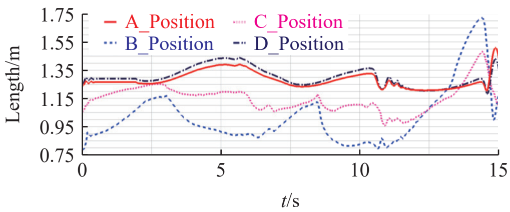


Figure 12 Displacement curves of the profiling mechanism

5 Parameter optimization test

Based on the design of the orchard fruit pouch collecting machine and the performance analysis of the key mechanisms, the prototype machine was made and the tests were conducted in the orchard. The Box-Behnken function of Design-Expert software was used to design the three-factor three-level orthogonal combination experiment, the effects of working parameters on the machine performance were studied, and the parameter combinations were optimized.

5.1 Test condition

The tests were carried out in the demonstration orchard of Qingdao Agricultural University. The row spacing of fruit trees in the orchard was 150-200 mm, and the plant spacing was 120-150 mm. The main technical parameters of the orchard fruit pouch collecting machine were: the driving form was the tractor power output shaft, the size of the whole machine was 4025 mm×1200 mm×1730 mm, the machine travel speed was in the range of 1-3 km/h, the working width was 910 mm, the working height was in the range of 0-50 mm, the speed of the spring-tooth roller was in the range of 36-107 r/min, and the experiment in the orchard is shown in Figure 13.

Figure 13 Orchard test

5.2 Test design

According to the previous analysis and calculation, the experimental factors were determined as the machine travel speed X_1 (1-3 km/h), the roller rotational speed X_2 (50-70 r/min), and the number of spring-tooth rows X_3 (3-5 rows), and the establishment of the experimental factor coding was established and is listed in Table 3. The selected test index was the fruit pouches recovery rate Y_1, denoted as:

$$Y_1 = \frac{M_q}{M_h} \times 100\% \tag{11}$$

where, M_h was the total mass of all fruit pouches in each test, g; M_q was the total mass of fruit pouches collected in each test, g.

Table 3 Codes of test factors

Codes	Factors		
	Machine travel speed/km·h^{-1}	Roller rotational speed/r·min^{-1}	The number of spring-tooth rows
–1	1	50	3
0	2	60	4
1	3	70	5

5.3 Test results and analysis

According to the Box-Behnken response surface test scheme, there were 17 groups in the orchard test, and the test scheme and results are listed in Table 4.

The variance analysis results are listed in Table 5, and the significant term was obtained by the regression model (p<0.05) and lack-of-fit term (p>0.05), which indicated that the regression model was well-fitted to the data. The factors X_3, X_1^2, X_2^2 were highly significant, X_1, X_2, X_1X_2, X_3^2 were significant, and the effects of the three factors on fruit pouches recovery rate Y were in a descending order as the number of spring-tooth rows X_3, roller rotational speed X_2, and machine travel speed X_1.

The response surface was plotted based on test results and regression model, which reflected the significant interactive effects on the test index, as shown in Figure 14. When the machine travel speed was constant, the recovery rate exhibited a trend of initially increasing and then decreasing with the increase of roller rotational speed. Moreover, the roller rotational speed had the maximum value in the interval of 55-65 r/min, and the travel speed of the machine had the maximum value in the interval of 1.5-2.5 km/h.

Table 4 Test scheme and results

Test number	Factors			Recovery rate Y_1/%
	Machine travel speed X_1	Roller rotational speed X_2	The number of spring-tooth rows X_3	
1	1	70	4	70
2	2	60	4	83.1
3	2	60	4	82.7
4	3	60	3	75.2
5	1	60	5	80
6	3	60	5	78.4
7	2	70	5	80.7
8	2	60	4	83.1
9	2	70	3	78.3
10	2	50	3	78.7
11	3	50	4	72.4
12	1	60	3	78.4
13	2	60	4	82.8
14	2	60	4	83.1
15	3	70	4	74.2
16	1	50	4	74.7
17	2	50	5	82.1

Table 5 Variance analysis of regression model

Source of variance	Square sum	Degrees of freedom	Sum of mean square	*F-value*	*p-value*
Model	266.32	9	29.59	34.3	< 0.0001**
X_1	1.05	1	1.05	1.22	0.0306*
X_2	2.76	1	2.76	3.2	0.0117*
X_3	14.04	1	14.04	16.28	0.005**
X_1X_2	10.56	1	10.56	12.24	0.01*
X_1X_3	0.64	1	0.64	0.7418	0.4176
X_2X_3	0.25	1	0.25	0.2898	0.6071
X_1^2	153.73	1	153.73	178.18	< 0.0001**
X_2^2	70.52	1	70.52	81.74	< 0.0001**
X_3^2	4.93	1	4.93	5.72	0.0481*
Residuals	6.04	7	0.8628		
Lack of fit	5.89	3	1.96	51.64	0.052
Pure error	0.152	4	0.038		
Total	272.36	16			

Note: * indicates significant impact ($0.01 \leq p \leq 0.05$); ** indicates highly significant impact ($p<0.01$)

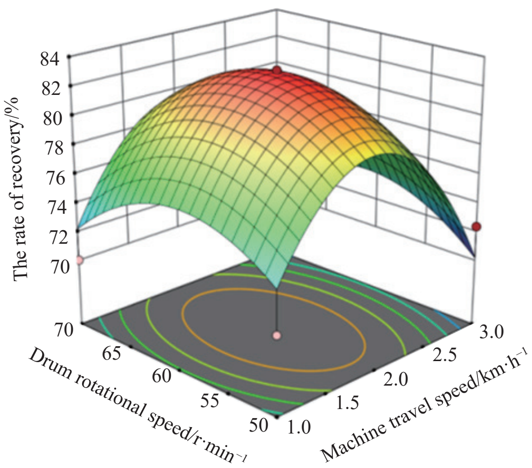


Figure 14 Response surface of interaction effect for recovery rate

Based on the results of variance analysis and response surface analysis, the expression of the regression model for fruit pouches recovery rate Y_1 was obtained as:

$$Y_1 = 82.96 - 0.3625X_1 - 0.5875X_2 + 1.32X_3 + 1.62X_1X_2 - 6.04X_1^2 - 4.09X_2^2 + 1.08X_3^2 \quad (12)$$

According to the working parameters and test results of the orchard fruit pouches collecting machine, the optimization module in the Design-Expert software was used to optimize and solve the objective equations, and the optimal combination of parameters was obtained: the travel speed of the machine was 2.04 km/h, the roller rotational speed was 59 r/min, and the number of spring-tooth rows was 4.97 rows, and the fruit pouches recovery rate predicted by the model was 85.2%.

5.4 Machine experiment in orchard

Based on the outcomes of the optimization test, the number of spring-tooth rows was set to 5 rows, and the experiments were divided into nine groups, with each group conducted 10 times and recording the average value and standard deviation. The results were denoted as the recovery rate Y_2, which served as the test index. The recycling rate of the fruit pouches was as shown in Equation (13):

$$Y_2 = \left(1 - \frac{M_2}{M_1}\right) \times 100\% \quad (13)$$

where, Y_2 was the recovery rate of fruit pouches, %; M_2 was the total mass of fruit pouches collected, g; M_1 was the total mass of fruit pouches before collecting, g.

The results of the machine experiment in orchard are listed in Table 6, which shows that the optimal combination of parameters of the machine was: travel speed of 2 km/h, roller rotational speed of 60 r/min, the number of spring-tooth rows was 5, and the highest recovery rate was 80.9%.

Table 6 Orchard experiment results

Test group number	Machine travel speed/km·h^{-1}	Roller rotational speed/r·min^{-1}	Recovery rate Y_2/%	Standard deviation
1	1	50	76.9	0.53
2	1	60	72.0	0.78
3	1	70	77.8	0.46
4	2	50	74.1	0.52
5	2	60	80.9	0.59
6	2	70	72.7	0.63
7	3	50	69.1	0.32
8	3	60	70.4	0.34
9	3	70	77.7	0.52

6 Discussion

Based on the structural design and theoretical calculation of the spring-tooth roller type pickup device and five-bar profiling mechanism, it could be obtained that the roller radius was 150 mm, the roller rotational speed was in the range of 36-107 r/min, and the total profiling displacement of the profiling mechanism was 750 mm, which could well complete the collecting work of discarded fruit pouches.

With the optimized working parameters, the orchard experiment was carried out. The number of spring-tooth rows was 5 rows, and the machine travel speeds were set as 1 km/h, 2 km/h, and 3 km/h, respectively, and the roller rotational speeds were set as 50 r/min, 60 r/min, and 70 r/min, respectively. Through a number of groups of orchard experiments, the average value of the test recovery rate was 74.6%, and the maximum recovery rate was 80.9%. Compared with the model-predicted value, the relative error was 5.3%, which was due to the deviation from the ideal state caused by factors such as the actual environment and test conditions during the test. In the case of selecting an optimal combination of parameters, the recovery rate could be effectively optimized, and the collecting quality and working effectiveness of the orchard fruit pouches collecting machine could be improved.

7 Conclusions

In this study, the pollution impact of waste fruit pouches on the orchard environment and the significant recycling and reusing value of them were investigated. Then the structural design, simulation analysis, and experimental research of the collecting machine were conducted. The conclusions drawn from these activities were as follows:

(1) The structural design of the collecting machine was conducted, and two types of collecting mechanisms were proposed, namely the spring-tooth roller type pickup device and the air-suction collecting device. Through comparison and analysis, the spring-tooth roller type pickup device was selected. Structural design and theoretical calculations of the key components were performed to determine the motion and force characteristics of both the spring-tooth roller type pickup device and the five-bar profiling mechanism. Multi-body dynamic analysis of the machine was carried out by the software of ADAMS, and the action laws of the different motion patterns and different working parameters were obtained.

(2) The prototype machine was made and the experiments in orchard were carried out. The response surface method was used to generate the model and optimize the experiment design. The results were that the machine travel speed was 2 km/h, the roller rotational speed was 60 r/min, and there were 5 rows of spring-teeth. The recovery rate predicted by the model was 85.2%, the recovery rate of experiments was 80.9%, and the relative error between the two was 5.3%, meeting the work demands for orchard fruit pouches recovery, with a good collection effect.

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