Design and test of the key components for a combing-type tobacco harvester

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Abstract: In response to the problems of low efficiency, high labor intensity, and low mechanization in manual tobacco harvesting, a comb-off tobacco picking device for southern hilly tobacco areas was designed following the agronomic requirements and the principle of manual picking of tobacco harvesting in southern China. The device was composed of the power chassis, picking mechanism, and storage mechanism. This study involved the theoretical analysis, structural design, and modeling of the key components, such as chassis structure, combing-type picking mechanism, and power synchronization mechanism. The results of the motion analysis and calculation of the picking process demonstrated that the adjustment range of the comb chain elevation angles was from 12.4° to 20.9°, the comb rod installation distance was 76.2 mm, and the synchronizing mechanism transmission ratio was 3:10. One-factor test and three-factor three-level orthogonal test was performed with the forward speed of the chassis, the distance between the picking device baffles and the elevation angle of the chain with the combing bar as test factors, and the rate of broken and missed tobacco picking as evaluation indicators. It was revealed that the optimal combination of the forward speed of the chassis, the distance between the baffles, and the chain elevation angle were 1.5 km/h, 75 mm, and 12.4°, respectively. Moreover, verification tests suggested that the breakage rate of tobacco leaves was 9.99%, and the probability of missed tobacco picking was 7.31%, both of which satisfy the agriculture requirements and the operational requirements in the agricultural machinery certification syllabus.

Keywords: harvesting machinery, leaf tobacco, combing-type, tiered harvest, synchronizing mechanism
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1 Introduction

Tobacco is an essential economic crop and a potential energy crop. China has a huge amount of tobacco planting scale ranks, accounting for more than 40% of the global production, mainly distributed in Henan, Yunnan, and Hunan. In recent years, with the development of agricultural mechanization, most fields have realized whole-process mechanization of production, such as rice, wheat, and other grain crops, with the development of agricultural mechanization. However, the tobacco harvest was still dominated by manual picking. Tobacco leaves grow in a spiral shape around the stem of the tobacco plant from the bottom up, and are usually divided into lower, middle and upper tobacco according to the different growth positions of the tobacco leaves. As each leaf reaches a different stage of growth and maturity at varying times, it is essential to harvest the tobacco in stages[1]. This process usually involves at least three separate harvests, progressing from the bottom to the top of the plant[2]. In the process of tobacco production, the harvesting period and method were two factors related to the yield and quality of tobacco leaves[3-5]. Simultaneously, traditional manual picking had headaches of low efficiency, high labor intensity, and high cost, which severely restricted the large-scale development of tobacco production[6,7]. Therefore, China must find a scientific and timely harvesting tobacco leaf.

As early as the 1980s, foreign countries developed tobacco leaf harvesting machinery to realize the automation and scale of tobacco leaf mechanical harvesting, such as the number of 6360 self-propelled tobacco leaf harvester developed by Marco Company in the United States, the 2TTH type harvester developed by DeCloet Company in Italy, and the RA632 type full-automatic self-propelled tobacco leaf harvester produced by SPAPPERI Company[8-10]. Due to the similarity of tobacco planting and harvesting agronomy in these countries, all pieces of machinery adopted three-wheel full hydraulic drive technology, with high automation degree and high harvesting efficiency, and thus could work across two ridges.

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However, the machine body is relatively large, making it difficult to adapt to the tobacco planting environment in hilly areas of China. China's representative tobacco harvesters included "a self-propelled tobacco harvester" designed by Li e al.[11], which overcame the complex structure and high cost of the original large equipment with a simple structure. The "adaptive row spacing tobacco harvester" designed by Tao et al.[12] was hung on a walking mechanism, such as a tractor and other small machinery, and could complete the harvesting operation, thus, it belongs to a semi-automatic tobacco harvester. It also developed a bionic machine picking hand based on the principle of machine vision at Henan Agricultural University by Li et al.[13] The bionic machine hand simulates human hands to pick tobacco leaves, contributing to effectively lowering the damage rate of tobacco leaves. Nevertheless, it exhibited low efficiency.

In China, it has been conducting research and exploration in the field of tobacco leaf harvesting machinery through the introduction of advanced foreign technologies for secondary development. Nonetheless, the agricultural production situation was different from foreign countries, e.g., with complex and diverse terrain, relatively scattered planting, and large mechanical equipment resulted in operating normally in the field. The complications faced by existing domestic tobacco leaf harvesting machines comprise high development costs, high tobacco leaf damage rates, and high mechanical failure rates, which cannot achieve yield. Hence, developing a tobacco leaf harvester that meets the requirements of tobacco field operations is of great significance to promoting the development of the tobacco industry and promoting the national economy.

2 Overall structure and working principle

2.1 Agronomic requirements for tobacco planting and picking

Tobacco is an annual herb with a wide planting range[14]. In the southern hilly areas, the planting mode is tobacco rice rotation to improve soil and pest control[15]. At present, the tobacco planting process has realized mechanized trenching, ridging, and removal, and the planting agronomy has formed a certain standard. For example, the center distance of the tobacco ridge was 1200 mm, the height of the ridge was 300 mm, the width of the ridge was 400 mm, and the growth height of the tobacco plant was 1200-1500 mm (Figure 1).

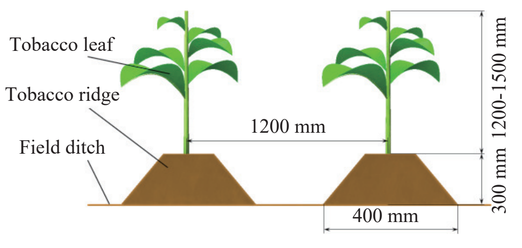
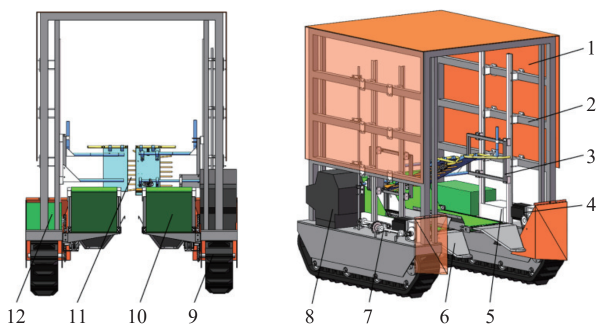


Figure 1 Agronomic schematic diagram of tobacco planting

Tobacco leaf picking is to disconnect the leaves from the connection between the aorta and the tobacco stem. Regarding manual picking, the thumb is employed to apply downward pressure on the connection between the aorta and the tobacco stem, to separate the tobacco leaf from the stem and achieve the purpose of picking[16]. Tobacco maturity is the primary factor influencing the quality of baked tobacco. To ensure the quality of baked tobacco, it is crucial to harvest tobacco when it is mature[17,18].

2.2 Overall structure

The overall structure of the combing-type of tobacco harvester is exhibited in Figure 2. The device mainly primarily consists of the crawler chassis, the stripping picking mechanism, the synchronization mechanism, and the transmission mechanism. According to the agronomic requirements of tobacco picking, the whole machine frame was designed into a gantry structure. The middle of the gantry is convenient for the tobacco plant to pass through without hurting the tobacco leaves during the operation. The picking mechanism is fixed on both sides of the frame. The whole picking mechanism can move up and down, and the elevation angle of the picking baffle can be adjusted, allowing for the picking of different heights and different quantities of tobacco. The synchronizing mechanism is located on the right side of the frame, and the power is provided by the crawler chassis drive motor. The power is transmitted to the stripping rod through the gear transmission shaft to realize the synchronization of the chassis and the power of the picking mechanism. The tobacco leaf transfer mechanism, situated beneath the picking mechanism, is securely mounted on both sides of the chassis frame. Its primary function is to convey the harvested tobacco leaves to the rear of the picker, ensuring efficient transportation within the harvesting system. The main technical parameters of the harvester are listed in Table 1.



1. Fuselage covers; 2. Gantry frame; 3. Regulating mechanism; 4. Drive motor; 5. Control box; 6. Tobacco leaf rightening mechanism; 7. Synchronous drive; 8. Range extender; 9. Crawler chassis; 10. Tobacco leaf delivery mechanism; 11. Comb picking mechanism; 12. Battery module

Figure 2 Structural diagram of the machine

Table 1 Main technical parameters of tobacco leaf harvester

Parameter	Value
Dimensions (L×W×H)/mm³	1400×1300×1800
Quality of machine/kg	500
Aggregate capacity/kW	3
Number of job lines	1
Operating speed/km·h⁻¹	0-2.5
Leaf breakage rate/%	≤15
Tobacco leaf leakage rate/%	≤10

2.3 Working principle

During the operation, the forward speed and travel direction of the crawler chassis were controlled by remote control. Specifically, the synchronous mechanism transmitted the chassis power to the picking mechanism in the chassis driving process. The horizontal component of the picking mechanism chain speed and the chassis driving speed were synchronized by adjusting the transmission ratio. The stripping rod and the left and right baffles formed a closed space. The closed space moved downward with the rotation of the chain, while the whole machine moved forward. As a result, the closed space just moved vertically downward for the stationary tobacco plant and then broke the tobacco leaf at a vertical distance to realize the picking of the tobacco leaf. The picked tobacco leaves fell to the conveyor belt below and were transported to the storage box through the conveyor belt to complete the collection of tobacco leaves.

3 Design of key components

3.1 Gantry-tracked chassis design

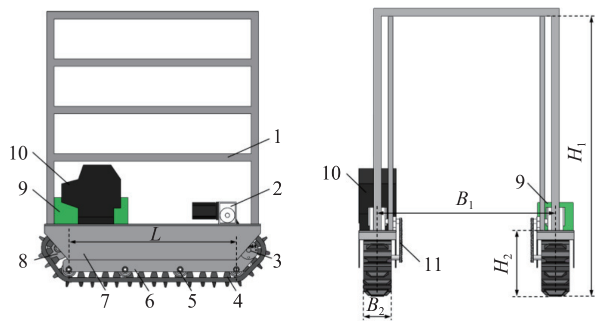
3.1.1 Chassis structure selection

In the southern tobacco region, characterized by mountainous and hilly planting environments with complex terrain, agricultural equipment must adhere to specific operational demands. The driving chassis in such areas is required to have a compact structure, excellent possibility, and high adaptability[19]. The tracked chassis, known for its large ground contact area and superior ground adhesion, minimizes the risk of skidding. This design enhances off-road performance and traction efficiency, proving particularly effective in fields, mountainous terrains, and other challenging operational conditions[20]. Consequently, a remotely operated, electrically powered tracked chassis aligns well with the practical necessities of agricultural production in these regions.

Tobacco is a ridge planting plant. In this study, the gantry crawler chassis was employed to improve the trafficability of the whole machine to prevent the harvester from damaging the tobacco leaves and overcome the complex driving conditions during the driving process in the fields[21-23].

3.1.2 Chassis structural design and principles

The chassis is mainly composed of a gantry, rubber track, support platform, and drive motor. The basic structure is illustrated in Figure 3. The chassis structural parameters determined by the agronomic requirements of tobacco planting are detailed in Table 2.



1. Portal frame; 2. Drive motor; 3. Drive wheel; 4. Rubber track; 5. Support wheel; 6. Support heavy wheel support; 7. Support platform; 8. Thrust wheel; 9. Accumulator; 10. Range extender; 11. Driven chain.

Note: L is the track ground length, mm; B_1 is the track, mm; B_2 is the track height, mm; H_1 is the height of the gantry from the ground, mm; H_2 is the track height, mm.

Figure 3 Schematic diagram of the gantry track chassis structure

Table 2 Main technical parameters of tobacco leaf harvester

Parameter	Value
Track ground length L/mm	1180
Track width B_2/mm	180
Track height H_2/mm	385
Track wheel base B_1/mm	1200
The height of the gantry above the ground H_1/mm	1750

This set of crawler chassis is driven by a bilateral motor, presenting the advantages of low energy consumption, smooth driving, low noise, and high transmission efficiency. It can lessen the pollution of tobacco leaves caused by oil and gas during the operation. The DC brushless motor used can realize intelligent control and establish a set of control systems[24]. Moreover, it allows for remote control through PWM signal speed regulation.

The gantry tracked chassis operates by traversing the ridge on either side of the tracks, as depicted in Figure 4, harvesting a single row of tobacco during each pass. This gantry structure exhibits excellent possibility in tobacco fields, ensuring minimal disturbance to both the operational row and adjacent tobacco plants. Furthermore, it significantly diminishes the potential damage caused by the machinery to the tobacco plants.

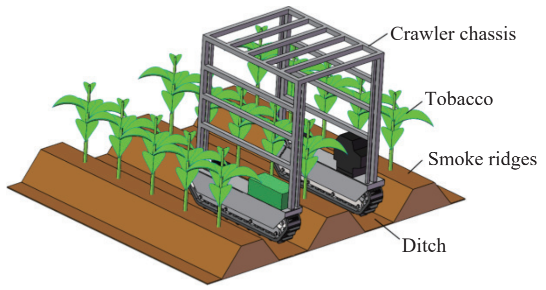


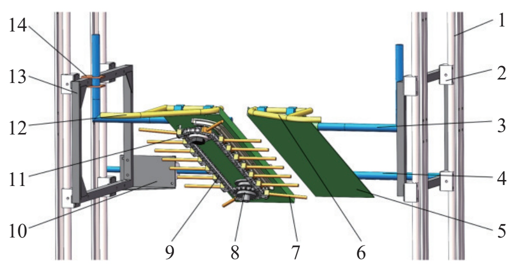
Figure 4 Schematic diagram of gantry crawler chassis operation

3.2 Design of combing-type picking mechanism

To address the issue of the high breakage rate prevalent in current tobacco leaf harvesters, this paper introduces a flexible combing-type picking method, inspired by manual picking techniques. The combing-type approach is predominantly utilized in the harvesting of vulnerable crops such as grains[25], oil-tea fruits[26], grapes[27] and cotton stalks[28]. This method avoids direct contact with the crop's rhizomes or vines, thereby reducing mechanical damage to the crops. Presently, the combing-type picking method has not been applied to tobacco harvesting. Therefore, this study explores the adaptation of the combing-type picking method, grounded in the principles of manual tobacco harvesting, to enhance the efficiency and reduce the damage in mechanical tobacco picking.

3.2.1 Structural design

The combing type picking mechanism mainly includes a slide, slider, comb-off rod, leaf splitter, chain, and sprocket (Figure 5). The leaf baffle plate and comb off-chain constitute the defoliation part with a certain inclination angle, and front high and back low. During the operation process, the tobacco plant enters the gap between the two baffle plates with the leaf splitter, the upper end of the leaf splitter was the non-picking area, and the lower end was the picking operation area (Figure 6 and Figure 7).



1. Slide track 2. Slider 3. Upper pole 4. Lower pole 5. Baffle 6. Baffle divider (right) 7. Comb rod 8. Drive sprocket 9. Chain 10. Drive shaft support plate 11. Following sprocket 12. Leaf divider (left) 13. Fixing bracket 14. U-shaped slider.

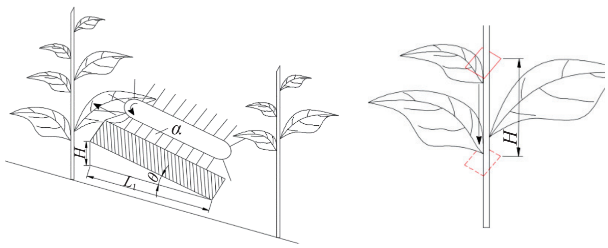
Figure 5 Schematic diagram of the structure of the picking mechanism

Different varieties of tobacco growth and ripening time have certain differences. To meet the requirements of different varieties of picking, the picking mechanism of the height above the ground, the feeding angle and the spacing between the two baffles are designed to be adjustable. To minimize the damage to the stalks during the picking process and to ensure that the pressure application site is near the base of the leaf, and the space surrounding the stalks should be slightly larger than the outer diameter of the stalks; thus, according to the mature tobacco stalk diameter of 30-50 mm, the design of the two baffles spacing adjustment range of 50-100 mm. The length of the stripping rod was designed to be 120 mm to ensure the formation of a relatively closed space with the two baffles and the passing ability of the tobacco plant.

The number of tobacco leaves removed in a harvest was determined by the vertical component H. The height H was set at 100-300 mm following the maturity mechanism of tobacco leaves and the agronomic requirements of harvesting. Therefore, the value range of inclination θ (12.4°C-20.9°C) was determined by the size of H. The length of the baffle was set to 70 cm to ensure that one tobacco plant was picked in each operation, and the account of the standard spacing of tobacco planting is 50 cm in China.

$$\theta = \sin^{-1}\frac{H}{L_1} \tag{1}$$

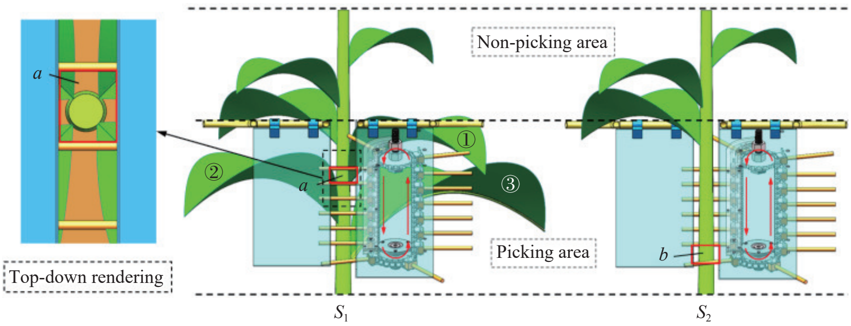
where, H denotes the vertical component of baffle, mm; L_1 represents the horizontal component of baffle, mm.



a. Overall schematic b. Local schematic

Note: α is the enclosed space formed by the comb rod and the baffle; θ is the angle between the chain and the horizontal plane, (°); H is the vertical height of α space movement, mm; L_1 is the horizontal component of the baffle, mm.

Figure 6 Schematic diagram of the operation of the picking mechanism



Note: S_1 is before the picking operation; S_2 is after the picking operation; a is the initial position in comb-off space; b is the post-collection position of the combing space; ①, ② and ③ are for picking.

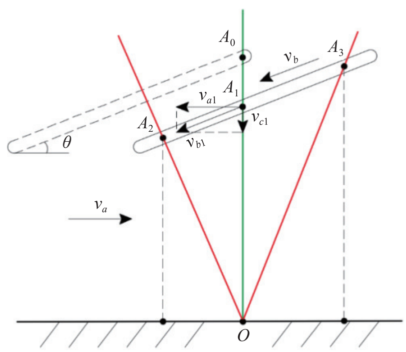
Figure 7 Schematic diagram of the picking process

3.2.2 Analysis of the principle of harvesting

Tobacco leaf picking is to disconnect the leaves from the connection between the aorta and the tobacco stem. Manual picking adopts the thumb to exert downward pressure on the connection between the aorta and the tobacco stem, to separate them and achieve picking. A stripping picking mechanism was designed according to the principle of manual picking. The stripping rod was installed on the chain on one side at a certain interval to form a relatively closed space with the baffles on both sides. This spacious area could guarantee that the stalk could pass through without obstacles. It could be surrounded by space regardless of the direction of the tobacco leaves when the stalk enters the closed space. The operation of the picking mechanism commences in an enclosed space positioned at the starting point a, as depicted in Figure 6, near the target tobacco plant. The picking process concludes when this space moves to position b. Given the static nature of the tobacco plant's growth position, it is crucial to synchronize the movement speed of the chain, which is equipped with the combing off lever, with the driving speed of the chassis. This synchronization ensures that the space moves vertically downward in alignment with a specific stalk.

3.2.3 Kinematic analysis

The forward and backward tilt of the tobacco rod impacts the operation effect of the stripping picking mechanism. First, the tilt of the tobacco rod by external force damages the tobacco plant growth. Second, the direction of downward pressure exerted by the stripping rod on the connection between the tobacco leaf and the stem changes accordingly, and the vertical lowering force is lost, influencing the picking effect. To guarantee the smooth completion of the picking process, the stripping rod in operation moves vertically downward along the stalk, and the moving speed of the chain with the stripping rod needs to be synchronized with the driving speed of the chassis. The movement process of the tobacco picker is shown in Figure 8.



Note: A_1, A_2, and A_3 correspond to the position of point A_0 moving along the direction of chain movement equipped with a comb rod when the cigarette rod is in a vertical, backward and forward tilt state, respectively; V_a is the forward speed of the chassis, km/h; V_b is the chain movement speed, km/h; V_{b1} is the comb rod movement speed, km/h; V_{a1} and V_{c1} are the horizontal and vertical components of the movement speed of the comb rod, respectively, km/h; θ is the angle between the chain and the horizontal plane, (°).

Figure 8 Schematic diagram of the movement of the picking mechanism

As revealed in Equations (2)-(5), the cigarette rod will tilt backward, vertically, and forward during the operation of the stripping rod. The horizontal component speed (v_{a1}) of the stripping rod moving speed (v_{b1}) was greater than the chassis forward speed (v_a) when the cigarette rod was in the tilt back attitude. Concurrently, the horizontal component of the displacement of the stripper rod was greater than the driving distance of the chassis, and the stripper rod contacted the cigarette rod during the movement. Because the cigarette rod was in a static state, the stripper rod exerted a backward thrust on the cigarette rod to tilt the cigarette rod backward. When the cigarette rod was in a vertical position, the movement speed of the stripper rod (v_{b1}) was equal to the horizontal component speed of the stripper rod (v_{a1}), but the direction was opposite. The two displacements generated in the horizontal direction during the movement offset each other. The stripper rod moved vertically downward relative to the stationary cigarette rod, the stripper rod did not exert force on the cigarette rod in the horizontal direction, and the cigarette rod maintained a vertical position. The horizontal component of the movement speed of the stripper rod (v_{a1}) was less than the forward speed of the chassis (v_a) when the cigarette rod was in the forward tilt attitude. Additionally, the horizontal component of the displacement of the stripper rod was less than the driving distance of the chassis, and the stripper rod exerted a forward thrust on the cigarette rod to tilt the cigarette rod forward.

$$v_a = v_{a1} \tag{2}$$

$$v_{b1} = v_b \tag{3}$$

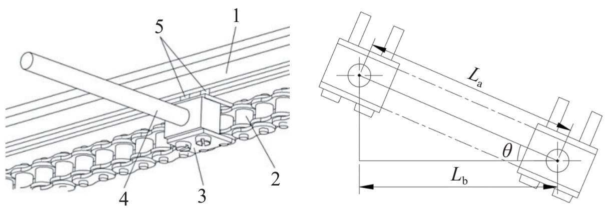
$$v_{a1} = v_{b1}\cos\theta \tag{4}$$

$$\theta v_a = v_b\cos\theta \tag{5}$$

where, v_a signifies the forward speed of the chassis, m/s; v_b indicates the moving speed of the chain, m/s; θ stands for the angle between the chain and the horizontal plane, (°).

3.3 Design of combing parts

The stripping is a key part installed on one side of the chain to exert downward pressure on the main pulse of the tobacco leaf. Its components mainly comprise the stripping rod, mounting lug, limit groove, and limit bolt (Figure 9a). To weaken the destruction of tobacco leaves and stems during the picking process, the stripper bar was designed to be cylindrical, and high-performance resin materials with high strength and toughness were used[29]. Since the stripping rod exerted load on the stem in the horizontal direction, the flexibility of the flexible material could protect the stem from damage when the tobacco stem is inclined in the natural growth state.



a. Comb bar installation b. Comb rod installation dimensions

1. Limiting slot 2. Chain 3. Install the earpieces 4. Comb rod 5. Install the earpieces

Note: L_a is the comb rod installation spacing, mm; L_b is the horizontal component of L_a, mm; θ is the angle between the chain and horizontal plane, (°).

Figure 9 Schematic diagram of the comb bar and comb rod installation

In the process of applying downward pressure on the main pulse of the tobacco leaf by the stripping rod, the stripping rod moved with the chain, and the downward pressure was lost because the chain had a certain flexibility. A bolt with a long length was fixed on one side of the chain when installing the stripper bar, and the protruding bolt was embedded in the limit groove to limit the displacement of the stripper bar caused by the chain looseness, leading to decreased force loss.

Figure 9b presents the installation dimension of the stripper bar. The installation spacing L_a is determined by the baffle spacing on both sides and the elevation angle θ. The adjustment range of baffle spacing is 50-100 mm. According to the design requirements, the horizontal spacing of the stripping bar installation should be equal to the baffle spacing. In other words, the horizontal component L_b of the stripping bar installation spacing should meet the Equation (6). The installation spacing L_a of the stripping rod meets the Equation (7). As suggested in Equations (1), (6), and (7), the value range of the installation spacing L_a of the stripping rod is 53.53-102.35 mm, the specification of the stripping chain is 08B, the pitch is 12.7 mm, and the value of L_a is 76.2 mm.

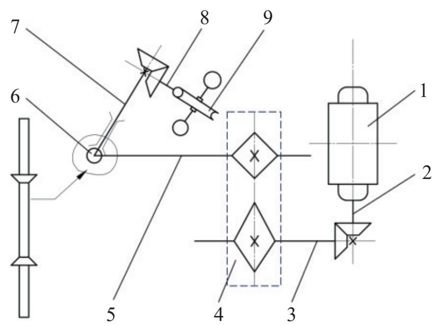
$$50 \text{ mm} \ll L_b \ll 100 \text{ mm} \tag{6}$$

$$L_a = \frac{L_b}{\cos\theta} \tag{7}$$

where, L_a denotes the installation spacing of the stripping rod, mm; L_b represents the horizontal component of the installation spacing of the stripping rod, mm; θ indicates the angle between the chain and the horizontal plane, (°).

3.4 Synchronous drive system

The synchronized transmission mechanism, a vital component of the harvester as illustrated in Figure 6, ensures that tobacco stems maintain a vertical state throughout the harvesting operation. This mechanism effectively prevents the stems from being pushed down or pulled due to speed mismatches. In order to meet the technical requirements of speed synchronization, a transmission system is designed, which is commutated by multiple sets of bevel teeth during operation, and the transmission adjusts the ratio so that the horizontal component of the chain moving speed is equal to the chassis traveling speed, and the transmission schematic is shown in Figure 10.



1. Input side 2. Drive Shaft Ⅰ 3. Drive Shaft Ⅱ 4. Speed changer 5. Drive Shaft Ⅲ 6. Drive Shaft Ⅳ 7. Drive Shaft Ⅴ 8. Drive Shaft Ⅵ 9. Output side

Figure 10 Schematic diagram of the drive train

The synchronization mechanism primarily comprises components such as a drive motor, bevel gear, drive shaft, and transmission system, as shown in Figure 11. Under the driving process of the chassis, the chassis drive motor provides the output power, turns the transmission direction 90° through the bevel gear set Ⅳ to the large sprocket through the transmission shaft Ⅳ, and then transmits it to the small sprocket through the chain transmission, where the transmission ratio was changed. Afterward, the power flows from the small chain wheel to the bevel gear group Ⅱ through the transmission shaft Ⅲ, and the transmission direction turns 90° through the bevel gear group Ⅰ through the transmission shaft Ⅰ to the bevel gear group Ⅰ, where a limit lug was installed to prevent the bevel gear group from jumping. Finally, the output power was transmitted to the bevel gear group Ⅳ through the transmission shaft Ⅳ, and the power was transmitted to the drive sprocket of the stripper bar through the transmission shaft Ⅴ. Consequently, the horizontal component of the running speed of the track chassis was synchronized with the movement speed of the stripper bar.

Ignoring the influence of track slip and other factors, the track travel speed could be calculated by Equation (8). The moving speed of the chain equipped with the stripping rod was expressed in Equation (9). The transmission ratio i was 3:10 according to the two sprockets calculated from Equations (5), (8), and (9).

$$v_a = r_k \omega_k = \frac{2\pi r_k n_k}{60} \tag{8}$$

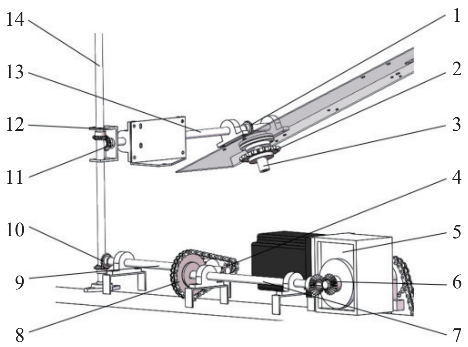
where, v_a indicates the running speed of the track, km/h; r_k denotes the radius of the track drive wheel, m; ω_k represents the angular speed of the track drive wheel, rad/s; n_k signifies the speed of track drive wheel, r/min.

$$v_b = \frac{2\pi r_t n_t}{60} \tag{9}$$

where, v_b is the chain moving speed, km/h; r_t is the radius of the driving wheel of the picking chain, m; n_t is the speed of the driving wheel of the picking chain, r/min.

$$i = \frac{n_k}{n_t} = \frac{r_t}{r_k}\cos\theta \tag{10}$$

where, i is the transmission ratio.



1. Bevel gear combination Ⅳ; 2. The comb rod drives the sprocket; 3. Propeller shaft Ⅴ; 4. Small sprockets; 5. Drive motor; 6. Bevel gear combination Ⅲ; 7. Drive shaft Ⅳ; 8. Large sprocket; 9. Propeller shaft Ⅲ; 10. Bevel gear combination Ⅱ; 11. Bevel gear combination Ⅰ; 12. Limit box; 13. Drive shaft Ⅱ; 14. Drive shaft Ⅰ

Figure 11 Schematic diagram of the synchronization mechanism

4 Performance test of stripping picking device

4.1 Test equipment and materials

In this study, the parameters of the stripping tobacco leaf-picking device were tested and optimized. The prototype of the tobacco leaf harvester was trial-manufactured by the overall design scheme of the tobacco leaf harvester, involving the crawler chassis, the stripping tobacco leaf picking mechanism, and the synchronous mechanism. The measuring instruments used in the test comprise the meter ruler (measuring range 3 m), vernier caliper, and stopwatch.

The test was conducted in the Engineering Training Center of Hunan Agricultural University in the middle of July 2022. The test materials were tobacco (Xiangyan 7) planted in the cultivation base of Hunan Agricultural University. Plants with uniform growth, vertical growth posture, no disease and insect pests, withered leaves, and the same maturity of tobacco leaves were selected for the test. During the test, the tobacco was transplanted into the flower pot. The plant spacing was set to 50 mm, and the picking height was 1000 mm (Figure 12).

1. Tobacco; 2. Smoke sticks; 3. Tracked chassis; 4. Comb picking device

Figure 12 Performance test of card-type picking mechanism

4.2 Test method

4.2.1 Selection of test factors

Following the agronomic requirements of tobacco planting and picking, the advance progress of the tobacco harvester chassis was adjusted from 0 to 2.5 km/h, the spacing between the two baffles of the picking device was adjusted from 50 to 100 mm, and the range of one-time picking height was adjusted from 150 to 250 mm. The included angle between the picking chain and the water level was regulated from 12.4° to 20.9° by Equation (1) and the picking height. The forward speed of the chassis, the spacing between the two baffles of the picking device, and the elevation angle of the stripping chain were selected as the test factors to investigate their influence on the tobacco picking effects and optimize the performance parameters of the stripping picking device.

4.2.2 Harvesting performance evaluation index

The test was conducted with referencing to DG/T 275-2022 “Agricultural Machinery Extension and Identification Program Tobacco Harvester”[30]. The damage rate K_p and the missed harvest rate K_s of tobacco were selected as the evaluation factors[31]. Equations (11) and (12) are adopted for specific calculation methods and indicators. Considering the provisions of the appraisal outline, the leaves whose central part of the main vein is broken or whose missing area exceeds 1/3 are damaged leaves after being harvested in the process of calculating the number of damaged tobacco leaves.

$$K_p = \frac{m_{ps}}{m_{cs} + m_{ps}} \times 100\% \tag{11}$$

where, K_p denotes the damage rate, %; m_{ps} represents the number of damaged tobacco leaves; m_{cs} indicates the number of complete tobacco leaves.

$$K_s = \frac{m_{ss}}{m_{cs} + m_{ps} + m_{ss}} \times 100\% \tag{12}$$

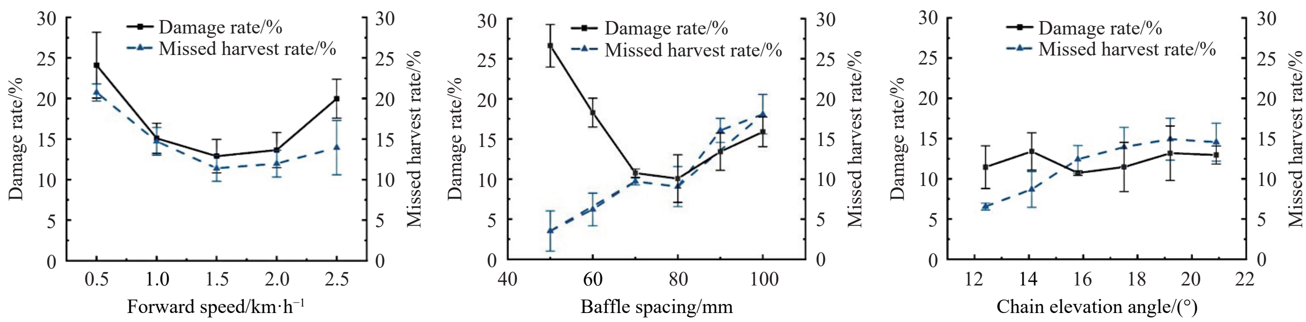
where, K_s signifies the lost recovery rate, %; m_{ss} refers to the number of uncollected tobacco leaves.

4.3 Test results

4.3.1 Single factor test results and analysis

A single-factor test was conducted on the selected three experimental factors to explore the impact of various factors on the damage rate and missed harvest rate of tobacco leaves and further refine the value range of the factors. As revealed by subjective evaluation of the test results, the best harvesting effect was achieved when the chassis forward speed was 1.2 km/h, the spacing between the two baffles was 80 mm, and the elevation angle of the stripping chain was 15°. When conducting a single-factor test on a certain factor, the remaining parameters were set as the best values selected initially, and each test was repeated 3 times with 10 tobacco plants per trial. The average value was taken as the result.

The test results were presented in Figure 13. Under the condition that the spacing between baffles and the elevation angle of the chain remain unchanged, the damage rate and missed harvest rate of tobacco leaves first decreased and then increased as the advancing speed of the chassis increased. When the advancing speed was 0.5 km/h, the damage rate and missed harvest rate were the highest, and the harvesting effect was the worst. When the speed was 1.0-2.0 km/h, the damage rate and missed harvest rate were lower, and the harvesting effect was better. Observation and analysis revealed that when the chassis advanced too slowly, the downward pressure exerted by the stripping dryer on the tobacco stem was lost due to the deformation of the chain, and the impact load on the tobacco stem was reduced, leading to unsatisfactory harvesting results. With the constant advance speed and chain elevation angle, the damage rate of tobacco leaves first rapidly decreased and then slowly increased as the spacing between baffles increased. Besides, the missed harvest rate increased as the spacing between baffles increased. When the spacing was 50 mm, the damage rate was the highest, and the missed harvest rate was the lowest. When the spacing was 60-90 mm, the damage rate and the missed harvest rate gradually approached, and the harvesting effect was relatively ideal. Observational analysis revealed that a minimal distance between the baffle plates results in excessive clamping of the tobacco pole, leading to increased damage to the tobacco leaves during the picking process. Conversely, a larger distance between the baffle plates causes insufficient clamping of the tobacco pole, increasing the likelihood of missed tobacco leaf picking. When the advance speed and baffle spacing remained unchanged, the leakage rate slowly increased with the increasing elevation, while the change in damage rate was insignificant and relatively stable. When the elevation was 12.4°, the leakage rate was the lowest, and the harvesting effect was the best. Observation and analysis revealed that with increasing chain elevation angle, the number of target-picked tobacco leaves will be increased, and the probability of missed picking will be increased, which has little effect on the breakage rate.



a. Effect of forward speed on harvesting efficiency　b. Effect of baffle spacing on harvesting efficiency　c. Influence of chain elevation angle on harvesting efficiency

Figure 13　Analysis of single-factor test results

4.3.2　Orthogonal test results and analysis

As unveiled in single-factor test results, the forward speed of the chassis, the spacing between the two baffles of the picking device, and the elevation angle of the stripping strip were selected as the test factors to conduct three factors and three levels of orthogonal experiment with the damaged rate and the missing rate of the tobacco leaf as the evaluation indicators (Table 3 and Table 4)[32]. In each experimental set, two replicates were conducted, involving 10 tobacco plants per trial. The number of intact, broken, and missed leaves picked was meticulously recorded, as depicted in Figure 14. Subsequently, the results were averaged to ensure accuracy and reliability in the findings. The best combination of factors was obtained by analyzing the range and variance of the test results.

The range analysis of the orthogonal test is provided in Table 5. The results demonstrated that factor B considerably influenced the damage rate, which was the main influence factor, followed by factor A and factor C. The optimal combination was $A_2B_2C_1$. The lost recovery rate under factor A had significant impacts, followed by factor B and factor C. The optimal combination was $A_2B_2C_1$.

The analysis of the variance of the orthogonal test was detailed in Table 6. Factors A and B have a significant impact on the damage rate (p<0.05), among which factor B has a relatively significant impact on factor A, while factor C has no significant impact. Concerning the lost recovery rate, factors A and B have a significant impact, of which factor A has a relatively significant impact on factor B, while factor C has no significant impact. This result is consistent with the range analysis, verifying that the test result is reliable. Thus, baffle spacing, forward speed, and chain elevation exert a decreasing influence on the damage rate of tobacco leaves sequentially; the forward speed, the spacing between baffles, and the elevation angle of the chain have a decreasing influence on the leakage rate of tobacco leaves sequentially. Briefly, the best combination of damage rate and missed recovery rate in the evaluation index is $A_2B_2C_1$. In other words, the chassis forward speed was 1.5 km/h, the baffle spacing was 75 mm, and the chain elevation was 12.4°.

Table 3　Coding of test factors

Levels	Factors		
	Forward speed/km·h⁻¹	Baffle spacing/mm	Chain elevation angle/(°)
−1	1.0	60	12.4
0	1.5	75	14.1
1	2.0	90	15.8

Table 4 Orthogonal test scheme and results

No.	Factors			Evaluation indicators	
	A	B	C	K_p/%	K_s/%
1	–1	–1	–1	17.27	16.82
2	–1	0	0	8.20	17.00
3	–1	1	1	13.46	25.67
4	0	–1	0	17.86	4.62
5	0	0	1	7.14	4.10
6	0	1	–1	2.78	14.65
7	1	–1	1	24.62	6.80
8	1	0	–1	8.05	2.50
9	1	1	0	15.38	16.04

Note: A, B, and C are the factor forward speed, baffle spacing, and chain elevation angle.

a. Intact tobacco leaves b. Broken tobacco leaves

Figure 14 Postharvest tobacco leaves grouping

Table 5 Analysis of the range between damage rate and lost production rate

Source	Damage rate K_p/%			Missed harvest rate K_s/%		
	A	B	C	A	B	C
K_1	38.93	59.75	28.10	59.49	28.24	33.97
K_2	27.78	23.39	41.44	23.37	23.60	37.66
K_3	48.05	31.62	45.22	25.34	56.36	36.57
k_1	12.977	19.917	9.367	19.830	9.413	11.323
k_2	9.260	7.797	13.813	7.790	7.867	12.553
k_3	16.017	10.540	15.073	8.447	18.787	12.190
Range	6.757	12.120	5.706	12.040	10.920	1.230
Primary and secondary factors	$B≥A≥C$			$A≥B≥C$		
Optimal combination	$A_2B_2C_1$			$A_2B_2C_1$		

Table 6 Variance analysis of damage rate and lost production rate

Source	Damage rate/K_p					Missed harvest rate/K_s				
	Sum of squares	DF	Mean square	F value	p value	Sum of squares	DF	Mean square	F value	p value
A	68.708	2	34.354	19.357	0.049*	274.973	2	137.487	47.919	0.020*
B	242.342	2	121.171	68.275	0.014*	209.498	2	104.749	36.509	0.027*
C	53.926	2	26.963	15.193	0.062	2.396	2	1.198	0.418	0.705
Error	3.549	2	1.775			5.738	2	2.869		
Sum	368.526	8				492.605	8			

Note: * indicates significant impact (p<0.05).

Factor B, representing the spacing between the baffles, exhibited the most substantial influence on the evaluation index concerning the breakage rate in the extreme variance analysis. This factor recorded an extreme variance value of 12.12, which is twice that of the other two factors, and displayed a significant effect in the ANOVA analysis with a p-value of 0.014. Observational analysis revealed that a minimal distance between the baffles results in the application of force too close to the stem, thus increasing the force required for picking. This leads to the deformation of the flexible comb off the rod, potentially scratching the tobacco. Conversely, an excessive baffle distance causes the application of force to be too distant, resulting in missed picks or incomplete separation of the tobacco.

Factor A, representing the chassis forward speed, demonstrates a profound impact on the evaluation index in the extreme variance analysis of the leakage rate, registering a value of 12.04. This factor's influence is further emphasized in the analysis of variance, evidenced by a p-value of 0.027. Detailed analysis indicates that the driving speed directly influences the synchronization between the picking mechanism and the chassis. Speeds that are either too fast or too slow impede the picking mechanism's ability to align vertically with the tobacco stems, thereby affecting the picking efficiency. The experimental results corroborate the findings of the kinematic analysis designed for this study.

Factor C, denoting the picking chain elevation angle, exhibited the least impact on breakage and leakage rates in both the extreme variance and ANOVA analyses. This angle directly influences the range of picking: a smaller elevation angle corresponds to a reduced number of leaves picked, while a larger angle increases the quantity of leaves picked. Importantly, the elevation angle does not affect the force exerted by the picking mechanism, thus exerting minimal influence on the experimental outcomes. However, it should be noted that a higher quantity of picked leaves might also escalate the likelihood of leaf breakage and leakage.

4.4 Optimal group validation test

The tobacco leaf-picking device was readjusted, and the verification test was conducted at the Engineering Training Center of Hunan Agricultural University. Three tests were performed with the same parameters. Ten tobacco plants were tested at a time and the results were averaged. The picking effect was displayed in Figure 15, and the test results were listed in Table 7.

a. Tobacco leaves picked b. Tobacco stalk and veins

Figure 15 Picking effect chart

Table 7 Validation test results

Number of trials	Number of test tobaccos	Number of damaged tobacco leaves	Damage rate K_p/%	Number of missed tobacco picks	Missed harvest rate K_s/%
1	32	3	10.34	3	9.38
2	30	2	7.14	2	6.67
3	34	4	12.50	2	5.88
Average value			9.99		7.31

In summary, the damage rate and the missing recovery rate of the stripping picking device reached 9.99% and 7.31%, respectively under the optimal conditions. The test results meet the requirements of the syllabus that the breakage rate of tobacco shall not be more than 15% and the leakage rate of tobacco shall not be more than 10%. As depicted in Figure 15, the morphology of the harvested tobacco leaves remained intact, closely mirroring the results of manual harvesting. Notably, the stem-leaf separation effect was efficient, and the harvesting process incurred no damage to the tobacco stems, thereby indicating favorable test results.

5 Conclusions

1) Given the agronomic requirements of stratified and multi-batch harvesting of southern tobacco leaves, a comb-type tobacco leaf harvester was designed based on the principle of manual harvesting. The harvester was mainly composed of a crawler chassis, comb-type harvesting mechanism, and synchronous mechanism and could realize the mechanized harvesting of tobacco leaves.

2) A stripping tobacco leaf-picking device was designed. The adjusting mechanism, baffle, stripping parts, and synchronous transmission mechanism of the picking device were designed. The mechanism parameters of the picking device were determined through theoretical analysis and calculation following the physical parameters of tobacco and the agronomic requirements of planting. The adjustable range of the chain elevation was 12.4°-20.9°, the installation spacing of the stripping rod was 76.2 mm, and the input and output transmission ratio of the synchronous mechanism was 3:10.

3) An orthogonal experiment with three factors and three levels was performed with the forward speed of the chassis, the distance between the baffles of the picking device, and the elevation angle of the chain equipped with combing rods as the test factors, and the damage rate and missed harvest rate of tobacco leaves as the evaluation indicators. The results revealed that baffle spacing, forward speed, and chain elevation exerted a decreasing influence on the damage rate of tobacco leaves sequentially; the forward speed, the spacing between baffles, and the elevation angle of the chain had a decreasing influence on the leakage rate of tobacco leaves sequentially. The optimal combination of the chassis forward speed, baffle spacing, and chain elevation were 1.5 km/h, 75 mm, and 12.4°. The verification test of the optimal combination unveiled that the damage rate and missed harvest rate of tobacco leaves reached 9.99% and 7.31%, respectively, which met the operation requirements

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