

Article

Design and Experimentation of a Self-Propelled Picking Type White Radish Combine Harvester

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Abstract: In view of the low level of mechanized harvesting of white radish in China and other developing countries and the current situation of “no machine can be used” due to the expensive imported machines, a self-propelled white radish combine harvester was designed based on the material, growth characteristics, and agronomic pattern of white radish. This combines harvester can realize the functions of white radish tassel gathering, deep soil loosening, clamping and conveying, tassel cutting, and collecting. In this research, the overall design of the harvester is described, and the structural and working parameters and kinematic requirements of the tassel gathering device, clamping and conveying device, tassel cutting device, and vibrating deep loosening device are determined by mechanical and kinematic analysis. Innovatively, a range of values for the tassel gathering speed ratio of 1.7–4.2 is proposed for the operation of the tassel gathering device suitable for white radish harvesting. The prototype was bench tested with the loss rate, damaged rate, and impurity rate as performance evaluation indexes. The results show that under the pitch of 240 mm between the taper angle of the tassel-raising device, a speed of 80 rpm for the tassel gathering device gathering claw belt rotation, a speed of 120 rpm for the clamping and conveying pulley rotation, a vibration frequency of 2 Hz and an amplitude of 15 mm for the vibrating deep loosening device, and a forward speed of 0.5 m/s (tassel gathering speed ratio: 1.7). The loss rate was 2.75%, the damage rate was 4.99%, and the impurity rate was 1.64%. During the operation, the innovatively designed white radish leaf gathering device can better fulfill the function of tassel gathering, and the systems worked well together, meeting the requirements of mechanized combined harvesting of white radish, but the adaptability to complex working conditions in the field needs to be further strengthened. This research can provide a reference for the design and optimization of mechanized white radish harvesting equipment.

Keywords: white radish combine harvester; tassel raising; tassel gathering; clamping and conveying; tassel cutting; deep soil loosening



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1. Introduction

White radish (*Raphanus sativus* L.), a genus of radish in the cruciferous family, is a root vegetable widely grown worldwide with good economic benefits and high added value [1]. It mainly relies on manual plucking, tassel cutting, and packing, with many operating procedures and high labor costs, and is unable to meet the demand for large-scale production, which restricts the development of the white radish industry. The development of the white radish industry and its production urgently need applicable white radish harvesting machinery [2,3].

At present, mechanized harvesting of root crops mainly adopts two forms: deep loosening and digging and picking. The deep loosening and digging type is suitable for underground tuber crops such as lily [4,5], panax ginseng, and sugar beet that are easy to

achieve fruit-soil separation and not easily damaged, and the operation requires the digging shovel to be deeper into the soil [6–8]. With high resistance and power consumption. As the fleshy root of white radish in the harvesting period has a long underground depth and a brittle texture, it is easy to cause damage to the fleshy root of white radish, such as broken root and broken skin, which affects its commercialization. Radish and other long-root crops are generally harvested by plucking, which includes tassel gathering, deep soil loosening, clamping and conveying, tassel cutting, and collection. Existing research on radish harvesting equipment mainly focuses on carrots, such as: refs. [9–13] conducted relevant research on soil deep loosening; refs. [14,15] optimized the design of the carrot tassel cutting device; refs. [16,17] developed the picking type combination harvester for root crops such as carrots; ref. [18] developed a digging carrot harvester.

A few studies have been conducted on white radish harvesting equipment. Ref. [19] analysed the effects of soil firmness, plucking speed, and plucking angle on the plucking force of white radish by the discrete element method; ref. [20] designed a wheel-type white radish sectional harvester, which is not adapted to the agronomic pattern of white radish monopoly planting; ref. [21] stability analysis of the white radish harvester rollover angle was carried out using Record software; ref. [22] finite element analysis of the white radish harvester pulling system using ANSYS software; ref. [23] a digging type white radish harvester has been designed to perform white radish harvesting operations, but it has a high matching power and a higher loss rate and damage rate than the picking type harvesting.

The Japanese Kubota GRH1700 and Inoseki VH-C114 white radish combine harvesters can better complete the combined harvesting of white radish, but they are developed according to the agronomic model of white radish planting in Japan, and the above models are only sold in their domestic market for the time being, not exported for the time being, and the selling price is high. Shandong Dongtai Machinery Co., Ltd. (Jinan, China) developed the white radish combine harvester by improving the original carrot harvesting model and conducting experiments to verify it, but due to the difference in material characteristics between white radish and carrot, the tassel gathering effect is poor when harvesting white radish, which easily causes incomplete clamping and poor plucking effect during harvesting, and the loss rate and damage rate are high. The picking type harvester basically harvests by holding the tassel of the crop, the material characteristics of white radish differ considerably from those of other root crops (e.g., carrots) that are harvested by picking type, such as the spreading and creeping growth characteristics of the tassel. Therefore, the use of other picking type harvesters that lack tassel gathering functions for the white radish harvesting process may suffer from picking failures and poor tassel cutting results, leading to a high loss rate and damage rate.

The self-propelled white radish combine harvester is based on the biological and mechanical characteristics of white radish, referring to the existing plucking equipment and combining the growth characteristics and agronomic model of white radish with an innovative design of white radish tassel gathering device, with a side-mounted layout of harvesting parts and hydraulic drive, which can complete the functions of tassel gathering, soil deep loosening, clamping and conveying, tassel cutting, and collecting at one time, and the operating position of each executive part can be adjusted by hydraulic cylinder. The machine has strong agronomic applicability. The prototype was tested in indoor and field harvesting trials to determine reasonable operating parameters. This research will provide a reference for the structural innovation and operational performance improvement of the white radish combine harvester.

2. Biomechanical Properties of White Radish

There are various varieties of white radish grown in China with different planting patterns, and the size and morphology of the radish Vary significantly among varieties. The group collected field data and statistics on white radish of the common cultivar “Baichuanxue” in the harvest period, which has a long, conical, fleshy root that is widely

grown in the market. The diameter of fleshy root d_a was about 54.6–75.6 mm, the length of fleshy root h_a was about 230–430 mm, the height of exposed fleshy root h_{a1} was about 50–135 mm, the depth of fleshy root underground h_{a2} was about 150–310 mm, the spreading diameter of tassel d_{b1} was about 610–945 mm, and the diameter of tassel 10 mm from the joint of root and tassel in the state of gathering was about 23.37 mm. d_{b2} was about 23.37–70.66 mm, the total length of the tassel h_b was about 370–520 mm in the upright state, and the total length of the whole plant h was about 600–950 mm in the upright state, as shown in Figure 1. The number of tassel branches in a single white radish plant is about 13–22, the mass of white radish is (1.4 ± 0.5) kg, the tensile strength at the root-tassel union is $(2.45 \pm 1.23) \times 10^5$ Pa, and the tensile strength is (179.8 ± 89.5) N [9].

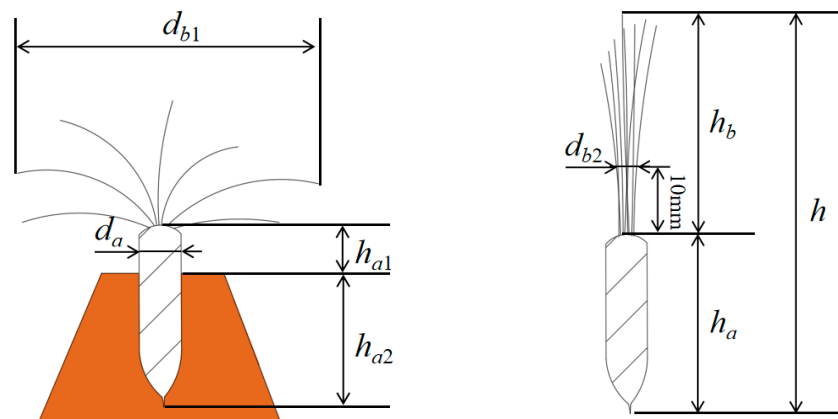


Figure 1. Schematic diagram of the biological characteristics of white radish during harvesting.

3. Main Structure and Working Principle

3.1. Main Structure

The white radish combine harvester is mainly composed of five parts: (1) a forward device; (2) a vibrating deep loosening device; (3) a tassel gathering device; (4) a clamping and conveying device; (5) a tassel cutting device, etc., as shown in Figure 2. The main technical parameters and operational performance index parameters are shown in Table 1.

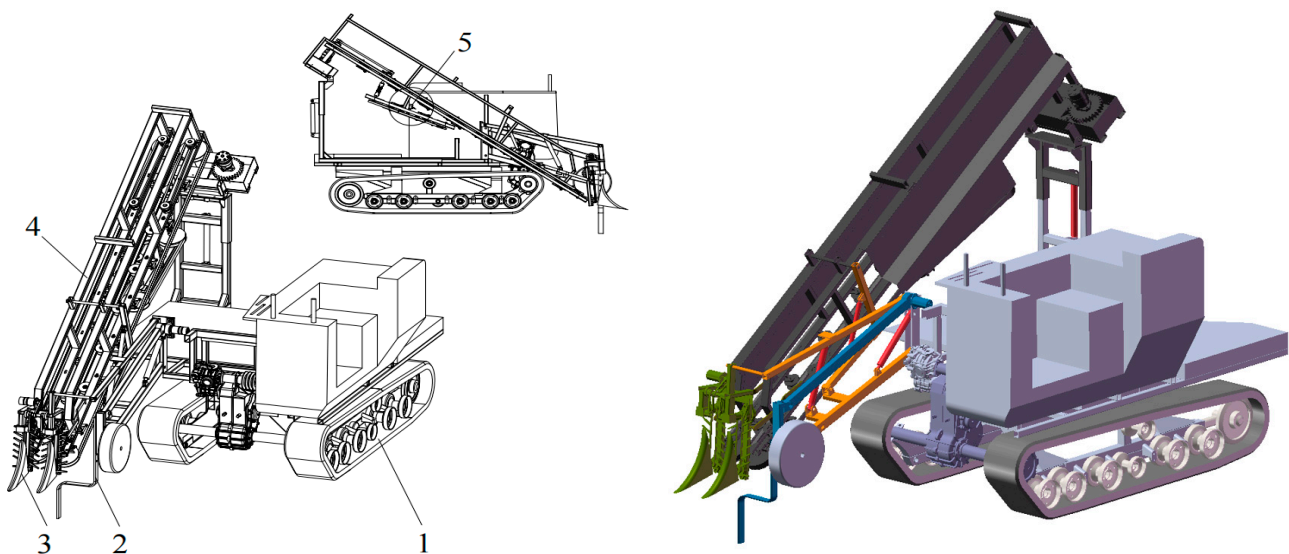


Figure 2. Structure diagram of a self-propelled, picking type, white radish combine harvester.

Table 1. Technical parameters of a self-propelled white radish combine harvester.

Projects	Parameters	Value
Technical parameters	Maximum working size of the machine (L × W × H)/(mm × mm × mm)	3360 × 2326 × 2410
	Machine quality/kg	2770
	Matching power/kW	26
	Forward speed/(m·s ^{−1})	0–1.5
	Depth of loosened soil/mm	0–350
	Number of working rows	1
	Working row spacing/mm	>200
	Maximum approach angle/(°)	24.7
Operating performance	Loss rate/%	2.75
	Damage rate/%	4.99
	Impurity rate/%	1.64

Among them, the forward device is based on the agronomic requirements of 350–550 mm row spacing and 200–250 mm plant spacing in the ridge culture (single ridge single row or single ridge multiple rows) of white radish, combined with the demand for a forward speed less than 1 m/s during harvesting. The 4LBZ-120YA semi-feed combine harvester crawler chassis produced by Hunan “Nongfu” Electromechanical Co., Ltd. (Chenzhou, China) is selected, whose rubber crawler length is 1720 mm, width is 350 mm, and centre distance is 500 mm; a “Changchai” diesel engine with a maximum power of 26 kW and a rated output speed of 2400 r/min; the transmission system consists of an HST (Hydrostatic Stepless Transmission) and a mechanical gearbox, which can realize stepless speed regulation from 0 to 1.51 m/s; and it can meet the field working function under various planting modes of single ridge single row or single ridge multiple rows of white radish.

The harvesting unit adopts hydraulic transmission, and the operating posture of the tassel gathering device, the operating inclination of the clamping and conveying device, and the depth of deep soil loosening can be adjusted in real time by hydraulic cylinders, which can adapt to different agronomic planting modes and different growth states of white radish harvesting and can meet different modes of switching between road transfer and field operation.

3.2. Working Principle

When harvesting in opposite rows, the tassel gathering device first lifts the tassel from the “semi-creeping” state to the upright state by raising and gathering them up left and right and gathering them back and forth, while the deep loosening shovel reaches into the soil and vibrates to loosen the soil on the side of the fleshy roots of the white radish to be plucked in order to destroy the adhesion between the white radish and the soil. At this time, the gathered tassel are fed into the flexible clamping and conveying device in the forward direction and conveyed upward and backward by the clamping belt, at which time the white radish is pulled up and moved upward along the inclined clamping belt; the gathered and clamped tassel are separated from the roots and tassel by cutting the tassels; the fleshy roots of the white radish are collected and loaded into baskets; and the cut tassel are returned to the field after being released from the clamping and conveying device, completing the combined harvest of white radish.

4. Design of Key Component

4.1. Tassel Gathering Device

The tassel is held by the clamping and conveying device to achieve continuous harvesting, and the effect of tassel gathering directly affects the plucking effect. The more the tassel is clamped, the higher the tensile strength of the tassel and the better the tassel pulling and cutting effect, while the opposite is true. Therefore, a tassel gathering device

was designed to gather the tassel in a “semi-prostrate” position in the field into an upright position to facilitate the subsequent operation.

The gathering device consists of a tassel-raising mechanism and a tassel gathering mechanism, as shown in Figure 3b. The growing space of the radish tassel is divided into 5 areas, in which the tassel in area I is forced to be lifted by the tassel-raising mechanism (Figure 4), and the tassel in area II is gathered by the tassel gathering belt. During the work, along the machine’s forward direction, the taper angle of the tassel-raising mechanism divides the tassel-raising area into the outer tassel-raising area I and the inner tassel-raising area II, in which the tassel-raising device forcibly lifts the tassel of white radish on both sides of the fleshy root and concentrates them in the gathering area III. Then the claw-type tassel collecting belt of the tassel gathering mechanism gathers the tassel on the side perpendicular to the forward direction in the gathering area III, and the tassel is gathered from the “semi-prostrate” posture to the upright state, completing the tassel gathering operation.

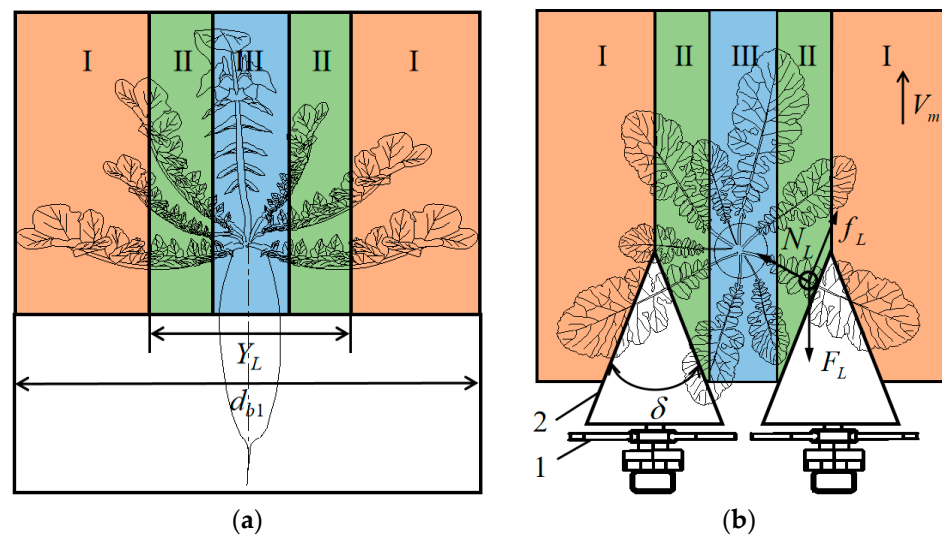


Figure 3. Operating principle of the tassel-raising mechanism. (1) Tassel-raising mechanism; (2) Tassel gathering mechanism; (I) Outer tassel-raising area; (II) Inner tassel-raising area; (III) Gathering area.

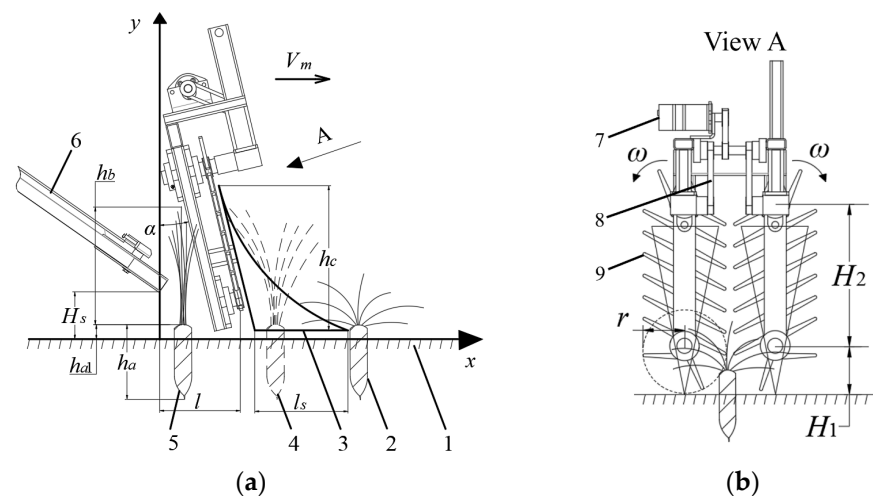


Figure 4. Working principle of the tassel gathering mechanism. (1) Ground (2) White radish in the field to be harvested (3) Tassel-raising mechanism (4) White radish in tassel gathering operation (5) White radish with tassel gathered after tassel gathering operation (6) Clamping and conveying device (7) Drive motor (8) Transmission mechanism (9) Tassel gathering claw belt.

4.1.1. Tassel-Raising Mechanism

As shown in Figure 4a, the front end of the tassel-raising mechanism is small, and the rear end is large in a taper design and installed at a certain angle of inclination on the front side of the tassel gathering mechanism. The spacing Y_L (Figure 3a) and the size of the taper angle δ (Figure 3b) are the main factors determining the operation effect. If δ is too large, the tassel-raising mechanism will be too large and squeeze the fleshy roots.

According to the requirements of the plant spacing of white radish (200–250 mm), the length of the tassel-raising mechanism is 1.5 times the plant spacing (about 300 mm) in the horizontal direction, and the height of the tassel-raising mechanism in the vertical direction is slightly greater than the height of the tassel after it is extended upward.

In order to prevent damage or breakage of the tassel during the tassel-raising process, the tassel is taken as the object of research, the impact of the forward speed of the machine V_m on the tassel is not considered, and the instantaneous force on the tassel is analysed as follows:

$$\begin{cases} F_L \sin \frac{\delta}{2} = N_L \\ F_L \cos \frac{\delta}{2} \geq f_L \\ f_L = \mu_L N_L \end{cases} \quad (1)$$

where μ_L —the friction factor between the tassel-raising mechanism and the white radish tassel; δ —taper angle of the tassel-raising mechanism, ($^\circ$) N_L —positive pressure of the tassel-raising mechanism on the white radish tassels, N; f_L —the friction of the tassel-raising mechanism on the white radish tassel, N; F_L —the maximum friction force of the tassel-raising mechanism on the white radish tassels, N.

In order to enhance the operating performance of the tassel-raising mechanism and minimize the mechanical damage to the tassel-raising mechanism under the premise of ensuring the normal tassel-raising effect, the size of the integrated tassel-raising mechanism, i.e., the length l_s in the horizontal direction is 300 mm; the height h_c in the vertical direction is 380 mm. After calculating the rounding, $\delta = 15^\circ$.

4.1.2. Tassel Gathering Mechanism

The tassel gathering mechanism consists of two rubbery claw belts and a transmission mechanism (Figure 4b). The claw belt is the finished comb belt of the semi-feed combines. When the claw belt is working, its continuously arranged claw fingers will rotate around the centre of the pulley to achieve the tassel gathering function. During operation, the two claw belts are turned in opposite directions, and the continuously arranged tassel fingers rotate around the centre of the pulley, interacting with the “semi-creeping” white radish tassel on the vertical side of the forward direction and the white radish tassel transferred to the gathering area by the tassel gathering mechanism, and gathering the tassel from the bottom up under the action of circular combing of the tassel fingers to realize the tassel gathering function.

As shown in Figure 4a, in order to guide the tassel upward and upright and avoid natural sagging due to gravity, in the direction of the forward level of the machine, the contact point between the tassel finger and the tassel should be lower than the height of the fleshy roots exposed to the ground h_{a1} . The radius r of the tassel finger should be between the height of the Claw belt pulley's lower centre height from the ground (H_1) and the height of the fleshy roots exposed to the ground (h_{a1}), i.e., $H_1 - h_{a1} < r < H_1$. The height of the clamping feeding point from the ground H_s should be higher than the height H_1 ; the distance between the centre of the claw-type belt H_2 and the radius r of the tassel finger is related. With the ground in the forward direction as the x -axis and the direction perpendicular to the ground as the y -axis and the clamping feeding point as the zero point to establish a Cartesian coordinate system, it can be known that the operation process of

tassel gathering claw belt finger on any point in the x - and y -axis directions of the trajectory equation is given as seen in the equation below:

$$\begin{cases} x = V_m t + r \cos \omega t \\ y = (H_1 + H_2) \cos \alpha - r \sin \omega t \end{cases} \quad (2)$$

The first- and second-order derivatives of the trajectory equation can be obtained from the instantaneous velocity and acceleration of the tassel finger in each direction, respectively, as follows:

$$\begin{cases} V_x = \frac{dx}{dt} = V_m - r\omega \sin \omega t \\ V_y = \frac{dy}{dt} = -r\omega \cos \omega t \end{cases} \quad (3)$$

$$\begin{cases} a_x = -r\omega^2 \cos \omega t \\ a_y = r\omega^2 \sin \omega t \end{cases} \quad (4)$$

The combined acceleration of the tassel fingers is:

$$a = -r\omega^2 \cos \omega t \sin \alpha + r\omega^2 \sin \omega t \cos \alpha \quad (5)$$

The force acting on the tassel by the tassel finger is:

$$F = m [r\omega^2 \sin(\omega t_1 - \alpha)] \quad (6)$$

where ω —tassel finger angular velocity, rad/s; V_m —forward speed of the machine, m/s; V_ω —finger line speed, m/s; α —angle of tassel gathering device installation, ($^\circ$); r —radius of tassel finger, mm; t —unit operation time, s; F —the force on the tassel acting on the tassel finger, N.

The tassel gathering force F of the tassel by the tassel finger should be smaller than the critical force F_a of the tassel branch breakage, i.e., satisfying $F < F_a$. The installation angle α of the tassel gathering device will affect the size of the distance l between the claw belt tassel finger and the clamping feed inlet, which are proportional to each other. If the l is too large, the gathered tassel will sag under the action of gravity, and the l should be taken as small as possible under the premise of no interference in the structure, in order to facilitate the subsequent clamping and conveying link feeding operation. Combined with the Formulas (2)–(6), take the angle of tassel gathering device installation $\alpha < 10^\circ$.

The tassel finger should have an absolute motion opposite to the forward direction of the machine when contacting the tassel, so that the tassel can be gathered while avoiding the forward tilt of the tassel. Therefore, the absolute velocity of the tassel finger on the x -axis is $V_x < 0$, so there is: $V_m < r\omega \sin \omega t < V_\omega$.

Let K be the ratio of the linear velocity V_ω of the tassel finger to the forward velocity V_m , i.e., the ratio of the tassel speed, which can be expressed as follows:

$$\frac{V_m}{r\omega} = \frac{1}{K} < \sin \omega t \leq 1 \quad (7)$$

Therefore, the tassel finger speed n :

$$n = \frac{60KV_m}{2\pi r} \quad (8)$$

where K —tassel gathering speed ratio; n —Gathering claw belt rotation, r/min.

Preliminary bench experiments showed that the forward speed of V_m is too large, which may cause damage to the tassel, a poor gathering effect, and poor plucking. It is difficult to ensure the harvesting effect, so the ideal V_m should be controlled at 0.3–0.5 m/s. If the speed n of the claw belt is too large, it will increase the combing times of the tassel, which may cause damage to the tassel and reduce the tensile strength of the tassel; if n is too small, the combing times of the tassel will be reduced, which may cause poor combing

effect. If the n is too small, the combing effect will not be good. When the n is between 80 and 120 rpm, which can have a good combing effect on the tassel, the length of the base belt of the finished tassel claw belt restricts the installation size of the tasseltathering mechanism, and the radius of the finger r is 100 mm. The value of K is 1.7–4.2 in the integrated Formula (8).

4.2. Clamping and Conveying Device

The clamping and conveying device is mainly composed of two parts: the plucking clamping and conveying system and the tassel cutting clamping and conveying system, both of which have the same structure; only the length of the belt is different. The belt is driven by a hydraulic motor through a gear and chain drive. The main function is: under the action of the tassel gathering mechanism, the gathered tassel is pulled up by the pulling force generated by the diagonal upward and backward movement of the extraction and clamping conveyor belt; then the tassel is clamped by the tassel cutting clamping conveyor belt, and the tassel is clamped and pulled tightly under the action of the double clamping system; and then the tassel cutting device completes the separation of the fleshy root and tassel of the white radish to realize the tassel cutting operation. The structure is shown in Figure 5, and combined with Figure 2, the clamping and conveying device can be adjusted by two position adjusting cylinders at the front and rear of the clamping and conveying device to meet the horizontal inclination θ adjustment of the clamping and conveying device and the frame and the highway height limit requirement during the transfer.

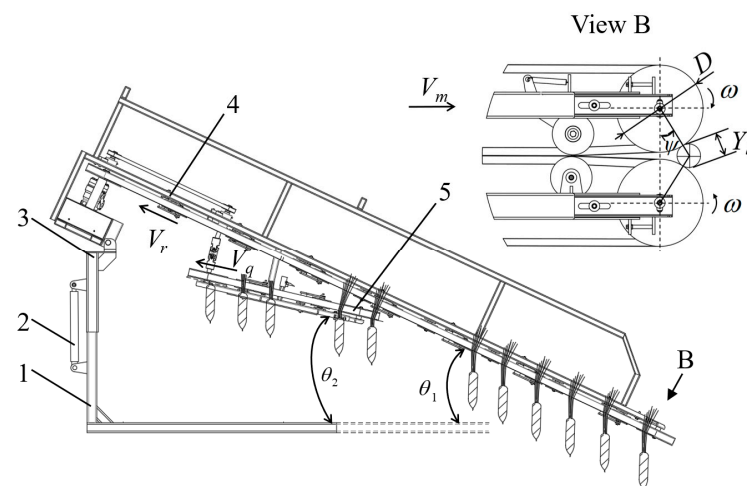


Figure 5. Structure of the clamping and conveying system. (1) Frame; (2) Clamping and conveying device position adjustment cylinder (after); (3) Clamping and conveying device mounting frame (4) Plucking clamping and conveying belt; (5) Cutting tassel clamping and conveying belt.

The belts are all E-type v-belts, with the bottom surface of the V-belt as the clamping surface in contact with the tassel. In order to maintain a certain “strength” of the clamping, several sets of tensioning pulleys with one side fixed and the other side spring-tensioned are installed between the active and driven pulleys to ensure a sufficient and uniform clamping force during the clamping and conveying processes. Referring to literature 14 and 19, it can be seen that the friction angle (φ) between the white radish tassel and the extraction and clamping conveyor belt needs to be greater than the initial starting angle (ψ) for the tassel to be effectively fed into the extraction and clamping belt, i.e.,

$$\varphi > \psi = \arccos \frac{D}{D + Y_b} \quad (9)$$

where φ —the friction angle between the tassel and the extraction clamping conveyor belt, ($^\circ$); ψ —starting rolling angle, ($^\circ$); D —the diameter of the belt pulley, mm; d_{b2} —the gathering tassel bundle diameter, mm.

As can be seen from Equation (9), the pulley diameter D and the starting rolling angle ψ are negatively correlated. Taking into account the row spacing, structural dimensions, and friction between the pulley and the belt, the clamping pulley diameter $D = 200$ mm. When combined with the diameter of the gathering tassel bundle $d_{b2} = 23.37\text{--}70.66$ mm, the starting rolling angle ψ can be calculated as $26.5\text{--}42.4^\circ$.

Combined with Figures 4 and 5, the plucking and clamping points should not be in contact with the ground or fleshy roots but should be higher than the height of the fleshy root exposed to the ground h_{a1} . The distance between the plucking and clamping belt and the tassel cutting belt is $H_D = 60$ mm, so the height of the clamping feeding point from the ground, H_s should meet the following requirements: $H_s > h_{a1} + H_D$. If the clamping position is too high, the clamping belt will be clamped on the upper end of the tassel, which may cause the radish to be missed; therefore, the tassel cluster is more concentrated, and the tensile strength is greater at a point higher than 60 mm above the height of the clamping feeding point from the ground. Therefore, the tassel clusters are more concentrated, and the tensile strength is greater at 60 mm above the height of the clamping feeding point from the ground.

In the process of plucking and clamping conveying, the joint action of the conveying speed V_r of the plucking and clamping conveyor belt and the advancing speed V_m of the machine will cause the axis of the white radish fleshy root to shift $5\text{--}10^\circ$ in the direction opposite to the advancing speed. The horizontal inclination angle θ_1 between the tassel clamping conveyor and the frame affects the speed of the clamping belt, and $\theta_1 = 40^\circ$ with reference [15]. In order to facilitate the subsequent tassel cutting operation, there should be a certain angle difference between the tassel cutting clamping conveyor and the plucking clamping conveyor, and the horizontal inclination angle between the tassel cutting clamping conveyor system and the frame is taken as $\theta_2 = 30^\circ$. The belt speed V_r of the tassel cutting belt is synchronized with the belt speed V_q of the tassel cutting belt, i.e., $V_r = V_q = (1.14\text{--}1.21) V_m$; here $V_r = V_q = 1.2 V_m$, the belt speed is higher than the forward speed of the machine, and it is less likely to be blocked. The maximum working speed of this harvester is $V_m = 0.7$ m/s and $V_r = V_q = 0.84$ m/s. Combined with the diameter of the clamping and conveying pulley, $D = 200$ mm, it can be deduced that the maximum speed of the clamping and conveying pulley $n \approx 120$ rpm.

4.3. Tassel Cutting Device

The tassel cutting device is the core component used to separate the roots and tassels. Currently, the main uses of white radish are in fresh food and post-processing. The fresh food usually retains some of the tassel, while the post-processing use does not need to tassel, and only the fleshy root is retained by cutting at the root-tassel combination. Considering the above harvesting requirements, two types of tassel cutting mechanisms, fixed and movable, are designed, which can be selected according to the length of the tassel to be cut, as shown in Figure 6. Both the fixed and movable knives are made of SKD11 alloy steel with quenched edges and a hardness greater than 60 HRC for good wear resistance.

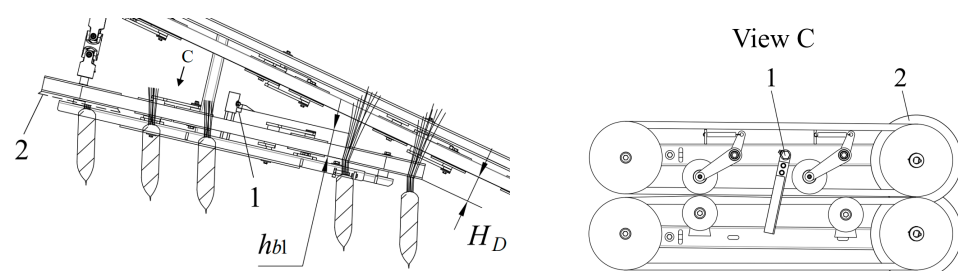


Figure 6. Installation diagram of the tassel cutting device. (1) Fixed knife; (2) Movable knife.

4.3.1. Fixed Knife

The fixing knife mechanism is installed on the tassel cutting clamping conveyor system, and when the fixing knife is working, the tassel retention length h_{b1} can be adjusted by itself according to demand, and the tassel of the white radish will be cut by the fixing knife under the simultaneous clamping action of the plucking clamping conveyor belt and the tassel cutting clamping conveyor belt. There are two main cutting methods: tangent cutting and sliding cutting, with the greatest cutting resistance in tangent cutting [14]. Due to the angle difference between the tassel cutting clamping conveyor and the plucking clamping conveyor, the fixed knife is not perpendicular to the tassel, the cutting method is sliding cutting, and the force analysis of the fixed knife cutting process is shown in Figure 7. The cutting resistance is small, and the cross-section of the cutting head is bevelled.

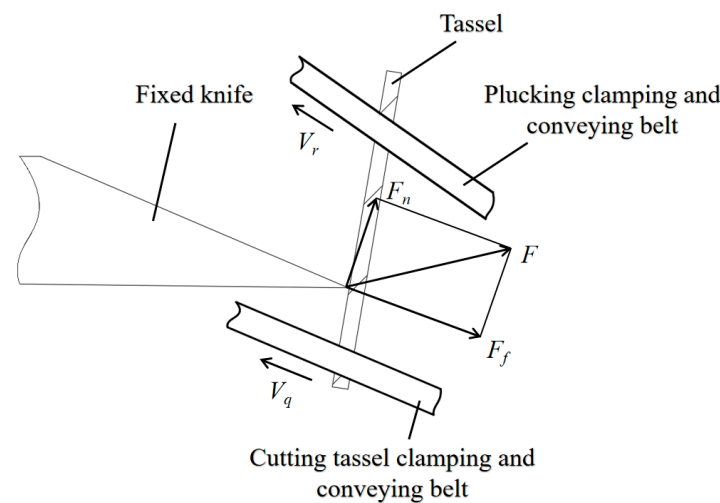


Figure 7. Analysis of the force of tassel cutting by a fixed knife.

4.3.2. Movable Knife

The circular knife is installed under the active pulley of the tassel cutting and clamping conveyor system, and the two circular blades are stacked on top and bottom, rotating at the same speed with the active pulley in the opposite direction (when there is no need to keep the tassel, the fixed knife can be removed). The white radish plant will be plucked by the clamping conveyor belt and the tassel clamping conveyor belt so that the top of the fleshy root will be close to the lower edge of the tassel clamping conveyor belt, and the root and tassel joint will enter between the two movable knives to complete the cutting work, and no leakage of cut will occur. The cutting method is sliding cutting, and the force analysis of the movable knife cutting process is shown in Figure 8. Smooth cutting operation of the movable knife should meet the conditions:

$$T > N_1 \sin \sigma + N_2 \sin \sigma - F_1 \cos \sigma - F_2 \cos \sigma \quad (10)$$

$$\cos \sigma = \frac{a}{A + d} \quad (11)$$

where T —tassel clamping conveyor belt conveying direction tension, N; N_1, N_2 —movable knife normal thrust force, N; F_1, F_2 —knife tangential force of sliding friction, N; σ —knife normal thrust and knife centre line angle, ($^\circ$); a —two movable knife centre distances, mm; A —movable knife diameter, mm; d —radish rootstock connection was cut at the diameter of the part, mm.

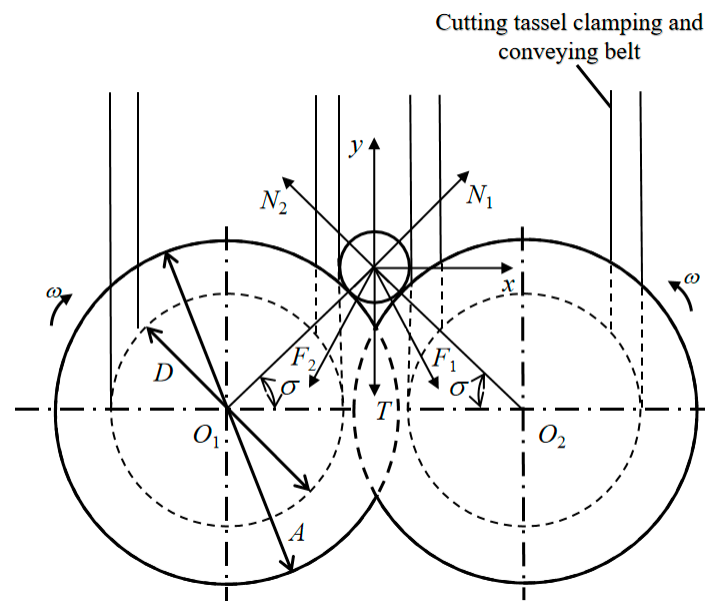


Figure 8. Analysis of the force of tassel cutting by a movable knife.

As the movable knife is installed under the active pulley of the tassel clamping and conveying system, the active pulley diameter D is 200 mm. To ensure cutting quality, the diameter of the movable knife should meet $A \geq D + d$. The range of d measured in the field test is 18.47–44.46 mm, so the diameter of the movable knife is selected as $A = 250$ mm.

4.4. Vibrating Deep Loosening Device

The depth of the underground part of the fleshy roots of white radish varies due to various factors, such as varietal differences. In the natural growth state, there may be a high adhesive force between the fleshy roots and the soil, etc., and forced plucking can easily cause loss and damage, so deep loosening devices are needed. In this research, we used vibration-deep loosening in the lateral direction of the fleshy roots of white radish to reduce the adhesion between the fleshy roots and the soil and to reduce the plucking force required during harvesting of white radish, thus reducing the loss rate and damage rate.

4.4.1. Vibrating Deep Loosening Device

A vibrating deep loosening device consists of a hydraulic motor, an eccentric bearing, a deep loosening rod, a deep loosening rocker, a deep loosening shovel, etc. A deep loosening shovel is installed on a deep loosening rocker, as shown in Figure 9. When working, the hydraulic motor will provide uniform rotary power to drive the eccentric bearing to rotate at the same speed and, at the same time, drive the deep loosening linkage to do plane compound movement and the deep loosening rocker as a follower to do variable speed back and forth swing to drive the deep loosening shovel vibration to realize deep loosening operation.

Referring to the requirement of the general technical requirements of carrot harvesting machinery that the digging depth should be continuously adjustable in the range of 0–350 mm underground, the deep loosening shovel and the deep loosening rocker were set to be movably installed to realize the adjustment of the deep loosening operation depth according to the underground depth of white radish fleshy roots. The lateral spacing between the shovel and the fleshy roots of white radish is the loosening distance, and the loosening distance was taken as 120 mm in this research with reference to the findings of the literature [9].

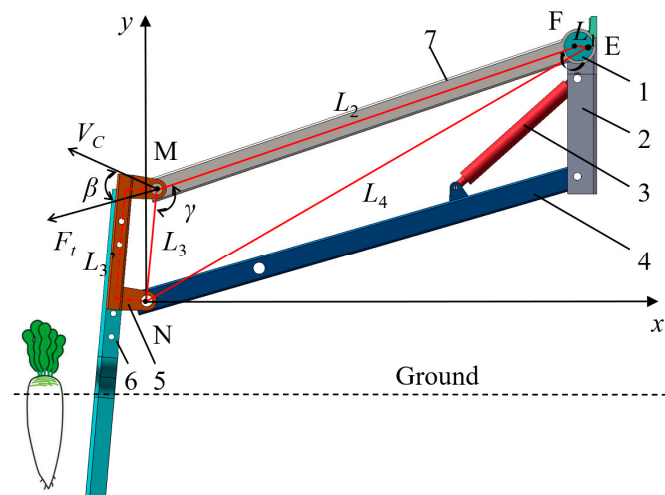


Figure 9. Structure of a vibration deep loosening device. (1) Eccentric bearing (2) Frame (3) Ground wheel lifting cylinder (4) Ground wheel lifting linkage (5) Deep loosening rocker (6) Deep loosening shovel (7) Deep loosening linkage.

4.4.2. Structural Analysis

The vibration deep loosening device keeps a certain position of vibration on the side of the white radish fleshy root to avoid damage to the material while destroying the adhesion between soil and fleshy root. When working, the power is input by the hydraulic motor from point E. Using the crank rocker mechanism, fast-forward and slow backward, the deep loosening shovel makes a reciprocal swing around rocker point N. The deep loosening shovel makes a reciprocal vibration in the forward direction at a certain frequency, under the action of which the adhesion between soil and fleshy root is damaged and broken, avoiding the phenomenon of plucking off and leakage of fleshy root due to excessive plucking force when plucking. The main factors affecting whether the cohesive mass between soil and fleshy roots can be smoothly destroyed are the rocker length L_3 and the rocker swing angle ζ . The point N of the rocker is chosen as the coordinate origin, and the Cartesian right angle coordinate system is established in the direction of the line between the origin and the crank L_1 . The crank rocker's deep loosening mechanism is shown in Figure 9.

Establishing the vector equation from the analytical method yields:

$$\begin{cases} L_1 \cos \varphi_1 + L_2 \cos \varphi_2 = L_4 + L_3 \cos \varphi_3 \\ L_1 \sin \varphi_1 + L_2 \sin \varphi_2 = L_3 \sin \varphi_3 \end{cases} \quad (12)$$

where φ_1 —the angle between crank EF and the negative direction of the x -axis ($^\circ$); φ_2 —the angle between connecting rod FM and the negative direction of the x -axis ($^\circ$); φ_3 —the angle between rocker MN and the negative direction of the x -axis ($^\circ$); L_1 —the length of crank EF, mm; L_2 —the Length of connecting rod FM, mm; L_3 —the length of rocker MN, mm; L_4 —crank and rocker axis distance, mm; $L_{3'}$ —the level of the projection line of rocker MN, mm.

The crank EF is set as the active part, under the condition of ignoring the weight of the connecting rod FM, the inertia force and the friction between the kinematic pair F and M, the thrust force to the driven rocker along the direction of the connecting rod FM is F_t , and the speed at the point of action M is V_C . The angle between the thrust force F_t and the speed V_C is the pressure angle β , the smaller the pressure angle β , the lower the resistance. The angle between the connecting rod L_2 and the rocker L_3 is the transmission angle γ . The difference between the maximum transmission angle $\gamma_{\max}$ and the minimum transmission angle $\gamma_{\min}$ is the rocker swing angle ζ . According to the instantaneous centre

method expression of the hinged four-bar mechanism, the rocker swing angle ζ can be expressed as:

$$\zeta = \arccos \left[\frac{a^2 + b^2 - (c+1)^2}{2ab} \right] - \arccos \left[\frac{a^2 + b^2 - (c-1)^2}{2ab} \right] \quad (13)$$

where $a = L_2/L_1$, $b = L_3/L_1$, $c = L_4/L_1$.

When the soil porosity is large, the smaller the force required for plucking. The vibration frequency is determined by the crank speed, and references [10] showed that a better soil porosity can be obtained at a vibration frequency of 2 Hz and an amplitude of about 15 mm. In the present research, with reference to the above-mentioned findings and the parameter-finding experiments, the vibration frequency was chosen to be 2 Hz at a loosening depth of 150 mm, and the amplitude was used as the finding target. When the rocker swing angle ζ is 7.1° , a better amplitude parameter can be obtained.

Measured according to the actual parameters of the machine: $L_1 = 15$ mm, $L_2 = 1150$ mm, $L_4 = 1282$ mm, $\zeta = 7.1^\circ$; substitute into the Formula (13) to calculate the finishing $L_3 = 290$ mm.

4.5. Hydraulic Transmission System

The radish harvesting unit of this machine adopts hydraulic transmission, which simplifies the complex mechanical transmission structure and makes the work more stable and reliable. The hydraulic system's control flow was designed as shown in Figure 10. The system includes a one-way variable hydraulic pump driven by the walking system diesel engine, a check valve, a direct-acting relief valve, a two-way piston hydraulic cylinder, an M-type three-way four-way reversing valve, a hydraulic lock, a hydraulic motor, a throttle valve, a radiator, and other hydraulic components. The hydraulic cycloidal motor selection and performance parameters are shown in Table 2.

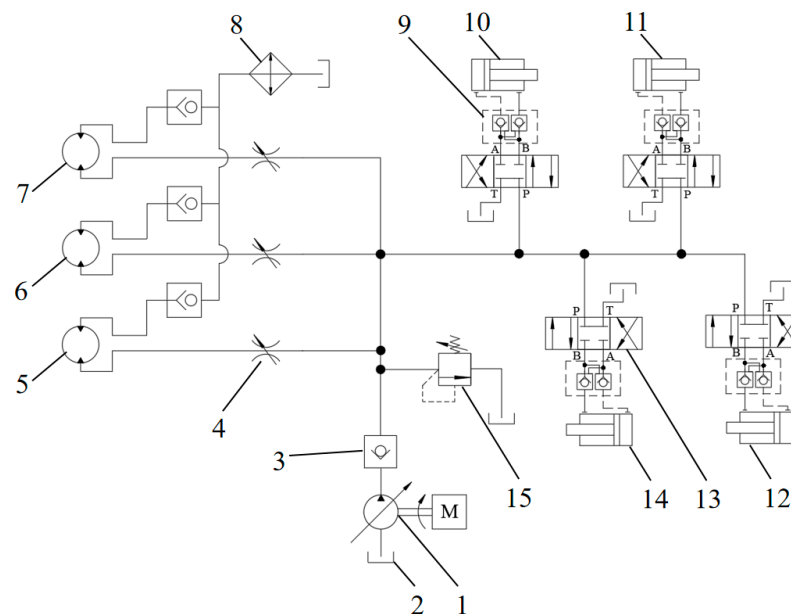


Figure 10. White radishes combine harvester hydraulic system control loop. (1) Hydraulic pump (2) Hydraulic oil tank (3) Check valve (4) Throttle valve (5) Hydraulic motor for tassel gathering device (6) Hydraulic motor for soil deep loosening device (7) Hydraulic motor for clamping and conveying device (8) Radiator (9) Hydraulic lock (10) Hydraulic cylinder for adjusting position of tassel gathering device (11) Hydraulic cylinder for lifting of depth limiting wheel (12) Hydraulic cylinder for adjusting the position of the clamping and conveying device (front end) (13) M-type three-way four-way reversing valve (14) Clamping and conveying device position-adjusting hydraulic cylinder (rear end) (15) Direct-acting relief valve.

Table 2. Hydraulic cycloidal motor performance parameters.

Component	Model	Max. Speed /(r/min)	Max. Torque /(N·m)
Hydraulic cycloidal motor of tassel gathering device	BMR-50	730	89
Hydraulic cycloidal motor of deep soil loosening device	BMR-160	344	285
Hydraulic cycloidal motor of clamping and conveying device	BMR-250	220	350

The one-way valve allows the hydraulic oil to flow in one direction in the hydraulic system to prevent the pump from returning; the direct-acting relief valve can play the role of regulating the main oil pressure in the whole hydraulic system, and when the oil pressure exceeds the preset pressure of the relief valve, it can be connected with the oil tank to unload the pressure and play the role of the safety valve of the hydraulic system.

The bidirectional piston hydraulic cylinder can be adjusted and kept in a stable position by the M-type three-way four-way reversing valve combined with the hydraulic lock for each device of the radish harvesting unit; the power of the tassel gathering device, the clamping and conveying device, and the deep soil loosening device are input by three different types of hydraulic cycloidal motors, and the speed is regulated by the throttle valve; the heat generated by the throttle valve overflow during the operation of the hydraulic system can be realized by the heat sink. The heat generated by the throttle valve overflow during the operation of the hydraulic system can be realized by the heat sink, thus achieving stable and reliable operation of the hydraulic system.

5. Test of Bench and Field

5.1. Test Conditions

Based on this research, a prototype of a white radish combine harvester with a pre-set forward speed of 0.5 m/s, a cone angle pitch of the tassel-raising device of 240 mm, a speed of 80 rpm of the tassel gathering device, and a speed of 120 rpm of the clamping and conveying device was tested on the bench and in the field, respectively. The bench test was conducted by collecting white radish from the field and burying it in the indoor soil tank with uniform plant spacing and exposed height of the fleshy roots of white radish, mainly to verify the operating effect of the machine under ideal growth conditions; the field test was conducted to verify the operating effect of the machine under the natural growth conditions of white radish.

Both bench and field tests were conducted in the middle and late May 2023 at the vegetable planting base of Fujia Technology Company, Yiyang City, China. Located in the subtropical monsoon climate zone (27°58' N, 110°43' E). The field test site length was 60 m, and the soil moisture content of 18.302% was measured according to GB/T 5262-2008: "General Provisions for the Determination of Agricultural Machinery Test Conditions". The average soil firmness in the range of 0–200 mm below ground was 141.3 N, and the soil type of the test site was loamy. The average static pulling force of white radish was 89.62 N. The plot area was 0.36 hm², and the white radish variety "Baichuan Snow" was planted in the form of a 4-row per ridge and with a ridge width of 1.5 m, a furrow depth of 150 mm, a row spacing of 350 mm, and a plant spacing of 150 mm.

5.2. Test Method

Since China has not yet formulated detailed national technical standards for white radish harvesting equipment, reference was made to DB37/T 2878.2-2016 "General technical requirements for carrot harvesting machinery" for the test, with loss rate, damage rate, and impurity rate as the test indexes to comprehensively evaluate the working performance of the prototype. The test area consisted of a stabilization area, measurement area, and parking area, with the stabilization area and measurement area each taking 10 m (5 m for each bench test due to site limitation) and the parking area after the measurement area. The performance measurement was carried out in the measurement area, and the

working condition was not changed during the test. After one harvesting process of the prototype, the white radish that was not pulled out in the measuring area and was buried or missed during the harvesting operation was collected and weighed (the radish with natural damage should be placed separately) and recorded as Q_1 ; all radishes with mechanical damage to the skin were collected and weighed during the operation in the measuring area and recorded as Q_2 ; and the radish that was intact in the collection box was weighed and recorded as Q_3 . The test was repeated three times, and the results were averaged. The bench test site is shown in Figure 11a, and the field test site is shown in Figure 11b.

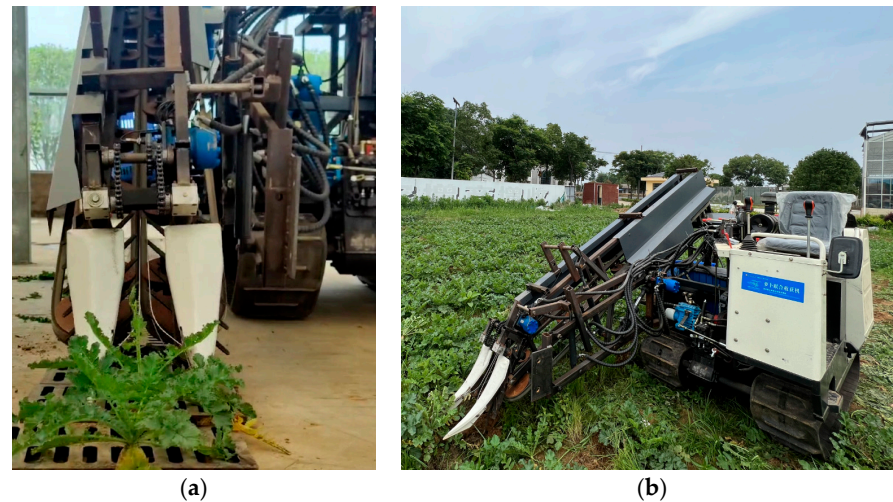


Figure 11. Prototype of white radish harvester testing. (a) Bench test; (b) Field test.

The main performance indicators are calculated as follows:

$$Q = Q_1 + Q_3 \quad (14)$$

$$Y_1 = \frac{Q_1}{Q} \times 100\% \quad (15)$$

$$Y_2 = \frac{Q_2}{Q} \times 100\% \quad (16)$$

$$Y_3 = \frac{Z}{Z + Q_3} \times 100\% \quad (17)$$

where Q —total mass, kg; Q_1 —Loss of radish mass, kg; Q_2 —Mass of damaged radish, kg; Q_3 —Mass of the intact radish in the collection box, kg; Z —mass of impurities, kg; Y_1 —loss rate, %; Y_2 —damage rate, %; Y_3 —impurity rate, %.

5.3. Analysis of Test Results

The results of bench and field test of the prototype are shown in Table 3.

Table 3. Test results of whole machine performance.

Projects	Loss Rate/%	Damage Rate/%	Impurity Rate/%
Field test	12.37	18.92	2.23
Bench test	2.75	4.99	1.64
Digging type harvester [23]	≤ 5	≤ 6	none
Standard: DB37/T2878.2-2016 (China)	≤ 5	≤ 5	≤ 5

The test results showed that the performance indexes of the developed white radish harvester could meet the requirements of the reference standard (DB37/T2878.2-2016) without considering the influence of the planting environment on the harvesting machine during the bench test, indicating that the structure and performance parameters of the tassel gathering, clamping, and tassel cutting parts of the machine basically meet the requirements of use. However, in the field test under the existing single-monopoly multi-row planting mode, the mechanical harvesting loss rate and damage rate exceeded 2–3 times the requirements of the reference standard, and only the impurity rate met the requirements of the standard, indicating that the design of the tassel gathering, clamping, conveying, and tassel cutting parts of the harvester can meet the actual use requirements, but in adapting to different radish growth characteristics, the level of the harvesting part to the rows during harvesting, the walking chassis to the ground undulation. However, further breakthroughs are needed in key technologies that may affect the loss and damage to white radish during harvesting.

6. Discussions

The white radish combine harvester designed in this research can realize the combined harvesting of white radish, and the performance of the whole machine basically meets the initial design function requirements and can better realize the functions of tassel gathering, soil deep loosening, clamping and conveying, tassel cutting and collecting, etc. Meanwhile, the problems that existed during the test, their causes, and possible solutions are analyzed as follows:

- (1) Corresponds to less supporting power required and lower loss and damage rates compared to digging-type harvesters. Therefore, the picking type is more suitable for white radish harvesting than the digging type.
- (2) Compared with the operation effect of using a carrot harvester to harvest white radish, the white radish combine harvester designed in this paper can better adapt to the material growth characteristics of white radish, and the harvesting effect is better, but there are still problems such as incomplete tassel gathering. The main reasons for the incomplete tassel gathering are: The motion parameter of the tassel gathering device, the speed ratio of the tassel, K , is currently in the range of 1.7 to 4.2, which is a relatively wide range, and the best combination of parameters has not yet been reached; secondly, it is limited by the finished tassel claw belt base belt and the short length of the tassel finger, resulting in the compact structure of the tassel gathering device drive system, and the front layout affects the smooth feeding of the tassel, thus The next step is to build a tassel gathering device test stand, develop a suitable tassel claw belt, optimize the structure and motion parameters of the tassel gathering device, and obtain the optimal combination of parameters suitable for white radish harvesting to improve the success rate of tassel gathering.
- (3) The loss rate and damage rate of the field test were significantly higher than those of the bench test. The main reasons for this are the uneven growth of white radish in the field test site and the different height of exposed fleshy roots (i.e., not the ideal field operation environment), which led to different clamping and feeding positions during the operation, and the fact that the clamping and feeding points were too low to cause damage and too high to cause loss. In the future, the height of the exposed fleshy root of white radish can be detected in real time by machine vision and other technologies [24] to achieve adaptive adjustment of the clamping height; developing automatic row alignment technology [25] to realize accurate row alignment during white radish harvesting operations to adapt to the complex operating environment in the field. Secondly, from an agronomic point of view, white radish is suitable for planting in sandy soil, and the field harvesting test site is loamy soil, which increases the firmness of the soil after rain, bringing a greater impact on the field harvesting effect. In addition, since the chassis and harvesting components are rigidly connected, the field operation is complicated, and the chassis without an automatic

levelling function easily causes the harvesting components to tilt, which makes the operation attitude difficult to control and affects the operation effect. The chassis with an automatic levelling function should be used at a later stage to improve the applicability of the machine. The application of intelligent agriculture technology will improve the machine's performance and realize efficient and low-loss harvesting of white radish.

7. Conclusions

This research based on the biological and mechanical characteristics, combining the growth characteristics and agronomic model of white radish, Using mechanical and kinematic analysis, a white radish combine harvester integrating the functions of tassel gathering, clamping and conveying, tassel cutting, and soil deep loosening was designed, and the structural parameters and kinematic parameters of the above mechanism were determined. The innovatively designed white radish leaf gathering device can better fulfill the function of tassel gathering. Through the bench test, it can functionally complete the white radish combine harvest, The performance test shows that in the bench test, the operating loss rate of the whole machine is 2.75%, the damage rate is 4.99%, and the impurity rate is 1.64%, which indicates that the structure and performance parameters of this white harvester basically meet the requirements of use. Under the complicated operation environment in the field, the loss rate of the whole machine was 12.37%, the damage rate was 18.92%, and the impurity rate was 2.23%, which indicated that the adaptability of the machine to the complicated working conditions in the field should be improved. This research can provide research reference for reducing the loss rate and damage rate and improving the qualified rate of cutting heads in the process of mechanized white radish harvesting.

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