DESIGN AND PERFORMANCE TESTING OF AN AUTOMATIC ORIENTATION AND CONVEYING DEVICE FOR POSTHARVEST CABBAGE TRIMMING BASED ON A CONICAL TREAD
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基于圆锥踏面的采后甘蓝自动定向输送装置设计及试验

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ABSTRACT
Automatic orientation and conveying are critical to enhancing the operational efficiency of postharvest cabbage commercial processing (e.g., trimming), reducing labor input costs, and boosting commodity added value. To address this demand, this study presents the optimal design of an automatic orientation and conveying device for postharvest cabbages based on conical treads, leveraging the moment of inertia principle. Through dynamic modeling and analysis, the key structural parameters governing orientation performance and their feasible ranges were quantified. Furthermore, the orientation reliability of the proposed structure was validated via ADAMS-based motion simulation. A prototype of the postharvest cabbage orientation and conveying device was fabricated, and parameter optimization experiments were conducted to determine the optimal operating conditions. The results indicate that the device achieves superior operational performance when the orientation roller angle is set to 20°, the axial clearance is 60 mm, and the conveying chain linear speed is 300 mm/s. Under these optimal parameters, the orientation success rate of postharvest cabbages reaches 98.67 ± 1.05%, with an orientation angle deviation of 5.18 ± 0.39°. This design remarkably improves the orientation and conveying precision of postharvest cabbages, laying a solid theoretical foundation and providing technical support for subsequent commercial processing operations such as root cutting.

摘 要
自动定向输送可有效提升采后甘蓝整修等商品化处理的作业效率，减少人工成本，提升其商品附加值。本文根据转动惯量原理优化设计了一种基于圆锥踏面的采后甘蓝自动定向输送装置，通过动力学分析确定了影响定向效果的关键结构参数及范围，并基于 ADAMS 运动仿真分析进一步验证了该结构的定向可行性。搭建采后甘蓝定向输送装置样机并进行参数优化试验，结果表明：定向辊锥度角度为 20°，轴向间隙为 60 mm，输送链条线速度为 300 mm/s 时作业效果最佳，采后甘蓝定向成功率为 98.67±1.05%，其夹角为 5.18±0.39°，进一步提升了采后甘蓝的定向输送性能，为后续根茎整修等商品化处理提供理论依据和技术支撑。

INTRODUCTION
Cabbage is one of the most widely cultivated and consumed vegetables in China. In 2024, its cultivation area amounted to 1.03×10^6 hectares with a total yield of 3.68×10^7 tons (*FAO, 2026*). Commercial processing represents an effective means to elevate the commodity added value of postharvest cabbage, and automatic orientation and conveying constitutes a pivotal procedural step in this workflow (*Du et al., 2019; Xiong et al., 2025*). Specifically, this process entails adjusting randomly arranged cabbages into a standardized posture via external force intervention, thereby facilitating subsequent postharvest operations including trimming, grading, packaging and storage (*Cui et al., 2023*).

Currently, scholars at home and abroad have conducted extensive relevant research in the field of automatic orientation and conveying for postharvest fruit and vegetable processing. Nevertheless, the majority of these studies focused on small and medium-sized spherical fruits and vegetables.

Bennedsen et al., (2005), developed an apple orientation and rotation device based on the differences in physical characteristics between apple stalks and calyxes. On this basis, *Li et al., (2009)*, added freely rotatable positioning wheels to adapt to apples of different diameters. Moreover, *Lefcourt et al., (2008, 2009)*, proposed an automatic apple orientation method based on two parallel tracks, which relies on the rotational inertia effect.

Mizushima and Lu., (2013), found that the orientation of apples could also be achieved using a double-cone roller structure. *Li et al., (2014)*, utilized the offset center-of-gravity position of lychees and the structural characteristics of curved rollers to realize automatic posture adjustment and single-row oriented conveying of lychees through counter-rotating rollers.

Kang et al., (2017, 2018), employed the rolling friction effect to keep jujubes in a stable state with minimum momentum during rotation, thereby gradually achieving sequential oriented arrangement of individual jujubes.

Zheng et al., (2015), adopted a pair of rollers with different diameters and a certain inclination angle to realize the oriented conveying of peppers. Considering the significant differences in the three-axis dimensions of fresh apricots and their symmetry along the suture plane, *Liu et al., (2012, 2016)*, proposed a differential belt-type dynamic orientation and conveying method based on the minimum action principle of space geometry.

Lin et al., (2017), optimized the design of a strawberry guiding roller with an hourglass-like geometric structure; strawberries completed the orientation process at the depressions between two adjacent rollers.

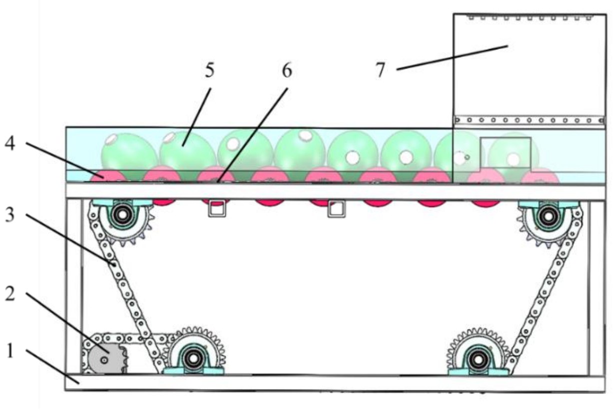
Wang et al., (2020), designed an oriented arrangement vertical and horizontal cutting machine suitable for large-scale processing of potato seed tubers, whose orientation arrangement device can effectively adjust the position and posture of seed tubers. However, unlike the aforementioned small and medium-sized quasi-spherical fruits and vegetables, cabbage presents structural characteristics of non-homogeneous mass distribution and axial offset of the mass center (*Cui et al., 2020*). Conventional cylindrical rollers fail to satisfy the automatic orientation requirements of cabbage. Hence, a novel orientation device is proposed, which can counteract the eccentric effect of cabbage's mass center through lateral friction torque.

To further enhance the orientation and conveying performance of postharvest cabbage, this study proposed an automatic orientation and conveying method for postharvest cabbage based on conical treads, building on previous research findings (*Cui et al., 2020; Zheng et al., 2021; Wang et al., 2021*). Conical rollers feature tapered surfaces with variable diameters. The constraint space formed by such rollers generates lateral friction torque on cabbages to counteract the influence induced by the axial offset of cabbage's mass center. Under the combined effect of the moment of inertia and the principle of minimum action, cabbages are guided to rotate stably around their minimum inertia axis, delivering superior automatic orientation performance. Through dynamic analysis, the key structural parameters and their feasible ranges affecting the orientation effect were determined, followed by the implementation of ADAMS motion simulation. Subsequently, a prototype of the postharvest cabbage orientation and conveying device was fabricated, and parameter optimization experiments were conducted to obtain the optimal combination of operating parameters. This research provides a solid theoretical basis and technical support for subsequent commercial processing operations of postharvest cabbage, such as root cutting.

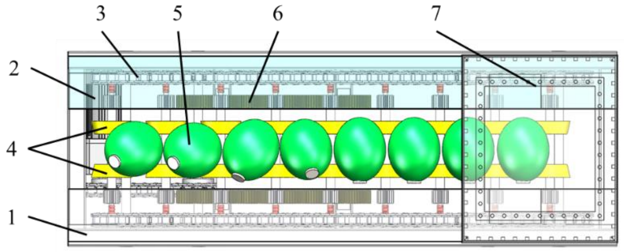
MATERIALS AND METHODS

Automatic orientation and conveying device for postharvest cabbage based on conical treads

Automatic orientation and conveying device for postharvest cabbage based on conical treads was simplified as illustrated in Figure 1. It is composed of a frame, a drive motor, a chain transmission mechanism, a conical tread orientation roller group, a rack-and-pinion pair, an image detection mechanism, and other auxiliary components. Among these components, the conical tread orientation roller group comprises orientation rollers symmetrically fixed on the roller shaft. Gears engaged with the rack for transmission are symmetrically installed on the outer side of the roller shaft. Both ends of the roller shaft are connected to the chain transmission mechanism through couplings. Both the rack and the chain transmission mechanism are fixedly mounted on the frame.



a) Main view



b) Top view

Fig.1 - Schematic diagram of the structure of an automatic orientation conveying device for postharvest cabbage based on conical treads

1 – Rack; 2 – Drive motor; 3 – Chain transmission mechanism; 4 – Conical tread orientation roller group; 5 –Postharvest cabbage; 6 – Rack and pinion pair; 7 – Image detection mechanism.

Specifically, the drive motor drives the chain transmission mechanism to operate backward at a constant speed. Through the couplings, the conical tread orientation roller group is also driven to move backward at a constant speed. Meanwhile, under the drive of the rack-and-pinion pair, the conical tread orientation roller groups rotate passively, and adjacent conical tread orientation roller groups form a stable orientation space. According to the kinematic transmission relationship, a conversion relationship exists between the linear velocity of the conveying chain and the angular velocity of the rollers, as expressed in Eq. (1).

$$v = \omega r \tag{1}$$

where v is the linear velocity of the conveying chain, [m/s]; ω is the angular velocity of the rollers, [rad/s]; r is the pitch radius of the pinion in the rack-and-pinion pair, [m].

When postharvest cabbages fall into this orientation space, the conical tread orientation rollers exert forces on them, enabling the cabbages to achieve automatic orientation under the combined action of rotational inertia and the principle of minimum action, and then be conveyed backward under the drive of the chain transmission mechanism. When the gears leave the action area of the rack, no external force acts on the conical tread orientation rollers. Under the action of gravity and friction, the conical tread orientation rollers form a stable state with the oriented cabbages and continue to be conveyed backward. Finally, the cabbages reach the area of the image detection mechanism, where pose images are collected to evaluate the orientation effect, providing data support for subsequent commercial processing such as trimming.

Kinematics analysis of postharvest cabbage orientation

The conical tread possesses excellent self-centering and curve-guiding capabilities (*Zhong et al., 2016; Ren et al., 2010*). Furthermore, the orientation movement of postharvest cabbage on this structure conforms to the principles of moment of inertia and least action. Therefore, the orientation kinematics of postharvest cabbage was analyzed, as illustrated in Figure 2, and the structure was optimized to enhance the orientation and conveying performance of postharvest cabbage. At this point, the postharvest cabbage on the conical tread orientation roller group is subjected to the combined action of its own gravity, as well as the supporting force and frictional force from each conical tread orientation roller rotating in the same direction at the same speed. As a result, it gradually achieves stable rotational motion around its central axis, and the circumferences of the trajectories of the two contact points formed between the cabbage and the conical tread orientation rollers are equal.

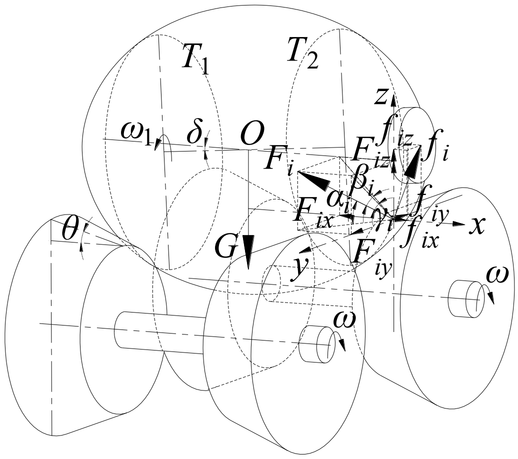


Fig. 2- Force analysis of postharvest cabbage movement on the conical tread orientation roller groups

Note: F_i denotes the support force exerted by the conical tread-oriented roller on postharvest cabbage, while f_i represents the frictional force exerted by the roller wheel on postharvest cabbage. F_{ix}, F_{iy}, and F_{iz} denote the component forces of the support force along the x, y, and z axes respectively, whereas f_{ix}, f_{iy}, and f_{iz} denote the component forces of the frictional force along the x, y, and z axes respectively. G denotes the gravitational force of the postharvest cabbage itself, ω represents the rotational angular velocity of the roller, $ω_1$ denotes the rotational angular velocity of the postharvest cabbage, $α_i$, $β_i$, $γ_i$ denote the angles between the support force and the planes of the three coordinate axes respectively, θ denotes the taper angle of the roller, δ denotes the angle between the central axis of the postharvest cabbage and the roller axis, T_1 and T_2 denote the motion trajectories of contact points between the postharvest cabbage and the conical tread-oriented roller, and O represents the center of mass of the postharvest cabbage.

In this state, the postharvest cabbage moves dynamically and stably on the conical tread orientation rollers; that is, the force system within its rigid-body inertial force system reaches equilibrium. Therefore, it can be concluded that:

$$\sum M_x = \sum M_e + \sum M_{Ix} = 0 \tag{2}$$

where: M_x is the torque generated by postharvest cabbage rotating about the x-axis at angular velocity $ω_x$, [N·m]; M_e is the torque produced by external forces when postharvest cabbage rotates about its central axis, [N·m]; M_{Ix} is the principal moment of inertia of postharvest cabbage in the inertial coordinate system, [N·m].

As shown in Figure 2, the instantaneous forces acting on the postharvest cabbage in all directions have reached equilibrium. Furthermore, the angle between the support force exerted by the conical tread orientation roller on the postharvest cabbage and the component force at its point of contact is equal to the taper angle of the conical tread orientation roller. Therefore, when the postharvest cabbage rotates about its central axis, the torque generated by the external force is:

$$M_e = \sum \left| \vec{f}_{iy} + \vec{f}_{iz} \right| L_i = \mu_0 \sum F_i \cos\gamma_i L_i = \mu_0 \sum F_i \cos\theta L_i \tag{3}$$

where: f_{iy} and f_{iz} are the components of the friction force exerted by the conical tread-oriented roller on the postharvest cabbage along the y and z axes respectively, [N]; L_i is the perpendicular distance from the contact point between the postharvest cabbage and the roller to the rotational axis, [m]; μ_0 is the coefficient of friction between the roller and the postharvest cabbage; F_i is the support force exerted by the roller on the postharvest cabbage, [N]; γ_i is the angle between the support force and the component force at the contact point's cross-section, [°]; θ is the taper angle of the roller, [°].

Meanwhile, based on the theorem of motion of the center of mass and D'Alembert's principle in the center-of-mass frame, the rigid-body inertial force system of postharvest cabbage is simplified. The calculation methods for the principal vector of the inertial forces of the particle system and the principal moment of the inertial forces about the central axis are given in Eq. (4).

$$\begin{cases} \vec{F}_{IO} = \sum \vec{F}_{Ii} = -m\vec{a}_O \\ M_{Ix} = \sum M_x(F_{Ii}^{\mathrm{n}}) + \sum M_x(F_{Ii}^{\mathrm{t}}) \end{cases} \tag{4}$$

where: F_{I0} is the principal vector of the inertial force of the particle system, [N]; F_{Ii} is the inertial force of the center of mass of the postharvest cabbage, [N]; m is the mass of the postharvest cabbage, [kg]; a_O is the acceleration of the center of mass, [m/s]; F_{Ii}^n is the normal component of the inertial force of the center of mass of the postharvest cabbage, [N]; F_{Ii}^{t} is the tangential component of the inertial force of the center of mass of the postharvest cabbage, [N].

Among these, the magnitudes of the various components of the inertial forces acting on the postharvest cabbage pith are as follows

$$\begin{cases} F_{Ii}^{\mathrm{t}} = m_i a_i^{\mathrm{t}} = m_i r_i \alpha \\ F_{Ii}^{\mathrm{n}} = m_i a_i^{\mathrm{n}} = m_i r_i \omega_1^2 \end{cases} \tag{5}$$

where: m_i is mass of any particle in the postharvest cabbage, [kg]; a_i^t is tangential component of acceleration for that particle, [m/s]; r_i is perpendicular distance from a given particle in the postharvest cabbage to the rotational axis, [m]; α is angular acceleration of the postharvest cabbage rotating about its central axis, [rad/s²]; a_i^n is normal acceleration component of the particle, [m/s]; ω_1 is angular velocity of the postharvest cabbage around the x-axis under slight disturbance, [rad/s].

As previously established, postharvest cabbage undergoes stable rotational motion about its central axis on the conical tread orientation roller group assembly, with its center of gravity positioned along the central axis. Therefore, it follows that:

$$\begin{cases} F_{IO} = 0 \\ \sum M_x(F_{Ii}^{\mathrm{n}}) = 0 \end{cases} \tag{6}$$

According to the simplified mathematical model of postharvest cabbage, the moments of inertia in the three directions of the x, y, and z axes can be calculated, and it can be obtained that:

$$\begin{cases} I_x = \frac{1}{5}\rho_2 V\left(b^2+c^2\right)+\frac{1}{2}V_1\left(\rho_1-\rho_2\right)r^2 \\ I_y = \frac{1}{5}\rho_2 V\left(a^2+c^2\right)+\frac{1}{2}V_1\left(\rho_1-\rho_2\right)\left(\frac{1}{6}\left(3r^2+h^2\right)+2\left(a-\frac{h}{2}\right)^2\right) \\ I_z = \frac{1}{5}\rho_2 V\left(a^2+b^2\right)+\frac{1}{2}V_1\left(\rho_1-\rho_2\right)\left(\frac{1}{6}\left(3r^2+h^2\right)+2\left(a-\frac{h}{2}\right)^2\right) \end{cases} \tag{7}$$

where: I_x, I_y, *and* I_z are moments of inertia of postharvest cabbage along the x, y, and z axes respectively, [kg·m²]; V is volume of postharvest cabbage, [m³]; V_1 is volume of the central column, [m³]; ρ_1 is density of the central column, [kg/m³]; ρ_2 is density of the head, [kg/m³]. The density of the above two tissue structures was calculated following the method proposed by *Zheng et al., 2021*, and their volumes were measured via the water displacement method; r is radius of the central column, [m]; h is length of the central column, [m]; a, b and c are radii of the postharvest cabbage along the x, y, and z axes, respectively, [m].

By combining Eqs. (4) to (7), the following expression is obtained:

$$M_{Ix} = \sum M_x(F_{Ii}^{\mathrm{t}}) = -\sum F_{Ii}^{\mathrm{t}}\cdot r_i = -\sum(m_i r_i^2)\alpha = -I_x\alpha = -\left[\frac{1}{5}\rho_2 V\left(b^2+c^2\right)+\frac{1}{2}V_1\left(\rho_1-\rho_2\right)r^2\right]\alpha \tag{8}$$

By combining Eqs. (2) to (8), the following expression is obtained:

$$\alpha = \frac{10\mu_0\sum F_i\cos\theta L_i}{2\rho_2 V\left(b^2+c^2\right)+5V_1\left(\rho_1-\rho_2\right)r^2} \tag{9}$$

In addition, for the conical tread orientation roller set to achieve orientation operation, it should meet the basic geometric position relationship and have no assembly interference. That is, postharvest cabbage in random orientations should not fall off during transport. Meanwhile, to ensure smooth execution of subsequent rhizome cutting, the rhizomes of postharvest cabbage must be positioned outside the conical tread orientation roller group. Therefore, the structural design and spatial arrangement of the conical tread orientation roller must meet these functional requirements:

$$\begin{cases} \min(D_x, D_y) > D_{\min} > D_A - D_R \\ \min(H) > C_A + 2T_R > \min(D_x, D_y) > C_A \\ D_A > D_R + 2T_R\tan\theta \end{cases} \tag{10}$$

where: D_x is the postharvest cabbage transverse diameter, [mm]; D_y is the postharvest cabbage longitudinal diameter, [mm]; D_{min} is the minimum diameter of the contact point trajectory between postharvest cabbage and roller, [mm]; D_A is center distance between axes of conical tread-oriented rollers, [mm]; D_R is Inner diameter of roller, [mm]; H is plant height of postharvest cabbage, [mm]; C_A is axial clearance of roller, [mm]; T_R is thickness of roller, [mm].

Calculated from Eq. (10):

$$\begin{cases} \theta < \arctan\left[\dfrac{\min(D_x, D_y)}{2T_R}\right] \\ \min(D_x, D_y) - 2T_R < C_A < \min(H) - 2T_R \end{cases} \tag{11}$$

Eqs. (9) and (11) demonstrate that during postharvest cabbage orientation on the conical tread orientation roller assembly, its motion state is influenced not only by the physical parameters of the cabbage itself but also by structural parameters such as the taper angle of the conical tread orientation roller and its positional relationship. This provides a theoretical basis for selecting factors in subsequent experiments aimed at optimizing the automatic orientation parameters for postharvest cabbage.

Simulation and Analysis of Orientation Movement of Postharvest Cabbage Based on ADAMS

Firstly, SolidWorks software was employed to establish a three-dimensional simulation model for the orientation motion of postharvest cabbage. By integrating the physical parameters of postharvest cabbage with the results of orientation kinematic analysis, the inner diameter of the conical tread orientation roller was determined to be 70 mm, with a taper angle of 20° and a thickness of 30 mm. The structural parameters of the roller were derived from the optimal parameter combinations reported in previous studies (*Cui et al., 2020; 2021*), with the radial and axial clearances set at 50 mm and 60 mm, respectively. Furthermore, postharvest cabbage was modeled as an isotropic elastic body (*Duet et al., 2019*) and simplified into two components: a central stem solid and a head solid. Both the physical parameters and material properties were kept consistent with the settings in *Cui et al., (2020),* to better verify the orientation performance of the conical tread orientation roller assembly. Subsequently, this three-dimensional model was converted into the universal IGS format and imported into ADAMS software. The simulation model for the orientation movement of postharvest cabbage is shown in Figure 3.

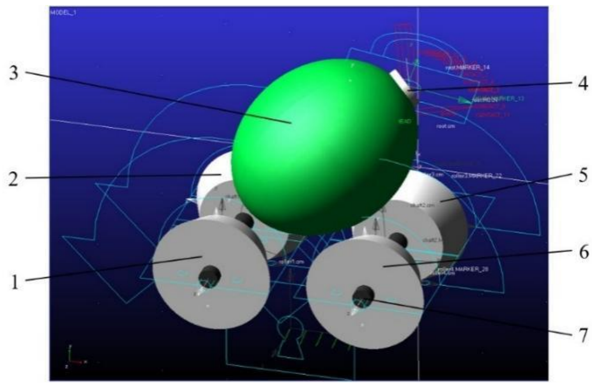


Fig. 3 - Postharvest cabbage automatic orientation simulation model

1 – Conical tread orientation roller 1; 2 – Conical tread orientation roller 2; 3 – Blade ball; 4 – Central column; 5 – Conical tread orientation roller 3; 6 – Conical tread orientation roller 4; 7 – Support shaft.

The simulation analysis workflow for postharvest cabbage orientation essentially followed that of *Cui et al., 2020*, with the specific steps outlined below:

(1) Material definition. The material properties of key components, including the orientation roller, leaf head, central stem, and support shaft, were set.

(2) Motion constraint conditions. Constraints were added to the conical tread orientation roller model, including fixed pairs, rotating pairs, drive mechanisms, and contact forces. The impact function method was adopted to define the contact forces between the central stem and head of postharvest cabbage and the roller.

The stiffness coefficient, collision index, maximum damping coefficient, static friction coefficient, and dynamic friction coefficient were set to 278 N/mm, 1.5, 0.3 N·s/mm, 0.5, and 0.48, respectively (*Zheng et al., 2021*).

(3) Marker point addition. One marker point was selected at the center of the base of the central stem and another at the center of the head, designated as point A (x_1, y_1, z_1) and point B (x_2, y_2, z_2), respectively. Both marker points are located along the central axis of postharvest cabbage.

(4) Motion parameter configuration. The initial pose of postharvest cabbage was divided into 26 distinct configurations (*Cui et al., 2020*) for simulation testing. The drive parameters were set to 12.00 rad/s, 15.00 rad/s, and 18.00 rad/s, respectively. The simulation duration was uniformly set to 10.0 seconds, with 500 simulation steps for each configuration.

(5) Orientation metric calculation method. In this study, orientation was analyzed solely based on the angle between the central axis of postharvest cabbage and the axis of the conical orientation roller, which was calculated according to Eq. (12).

$$\begin{cases} \delta = \arccos\left|\dfrac{l_{AB}^2 + l_{AC}^2 - l_{BC}^2}{2 l_{AC} l_{AB}}\right| \\ l_{BC} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 + k - z_2)^2} \\ l_{AC} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 + k - z_1)^2} = k \\ l_{AB} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \end{cases} \tag{12}$$

where: δ is angle between the central axis of the postharvest cabbage and the roller axis, [°]; l_{BC}, l_{AC} and l_{AB} are lengths of line segments BC, AC, and AB respectively, [mm]; wherein the parameter k of the marked point C (x_1, y_1, $z_1 + k$) is a constant value set at 150 (*Cui et al., 2020*).

Automatic orientation performance optimization test based on conical treads

Based on the aforementioned kinematic and simulation analyses of the automatic orientation of postharvest cabbage using conical treads, a conical tread orientation conveying device for postharvest cabbage was designed and trial-manufactured, as illustrated in Figure 4. A total of 120 postharvest cabbages of the "Zhonggan 15" variety were selected as test samples. Their transverse diameters ranged from 114 to 128 mm, longitudinal diameters from 108 to 124 mm, plant heights from 132 to 155 mm, masses from 527 to 795 g, and sphericities from 87% to 94%.

Fig. 4 - Prototype of a Postharvest Cabbage Cone-Tread Oriented Conveying Device

1 – Frame; 2 – Rack and pinion assembly; 3 – Chain drive mechanism; 4 – Laptop computer; 5 – Image acquisition system; 6 – Motor control system; 7 – Power supply.

In addition, the test equipment included a digital vernier caliper (accuracy: 0.01 mm, measuring range: 0–300 mm, manufactured by AIRAJ, Germany) and an AR926 laser tachometer (accuracy: ±0.05%, measuring range: 2.5–99999 r/min, manufactured by Dongguan Wanchuang Electronic Products Co., Ltd., China).

In this experiment, an orthogonal test was carried out with the taper angle of the conical tread orientation roller, the axial clearance, and the linear velocity of the conveyor chain as experimental factors, and the orientation angle of postharvest cabbage and the orientation success rate as experimental indicators, with details shown in Table 1.

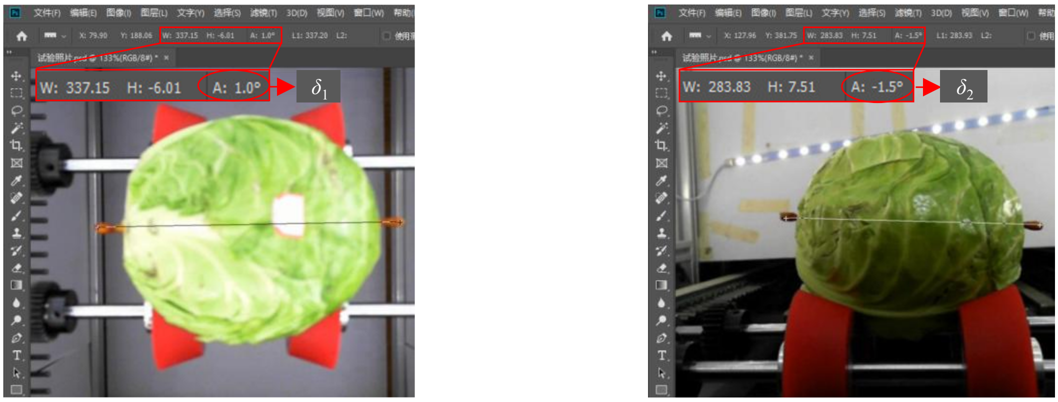
The taper angle of the conical tread orientation roller was adjusted by replacing custom-made rollers with different taper angles, where the inner diameter and thickness of the rollers were fixed at 70 mm and 30 mm, respectively. The axial clearance was measured and adjusted using a digital vernier caliper, while the linear velocity of the conveyor chain was regulated by measuring the angular velocity of the sprocket with a laser tachometer. Each experimental group consisted of 30 cabbages, and each group was repeated three times; the average value was taken as the final experimental result.

Table 1

Orthogonal Test Factors and Levels for Conical Tread Orientation

Levels	Factors		
	Taper angle (°)	Axial clearance (mm)	Linear velocity of chain (mm/s)
1	10	40	225
2	20	50	300
3	30	60	375

The experimental indicators, including the orientation angle and orientation success rate of postharvest cabbage, were calculated based on the calibration results of the angle between the central axis of postharvest cabbage and the axis of the rollers, which were obtained from the top-view and side-view images using Photoshop software. This measurement method was consistent with that reported by *Cui et al., (2020)*, as illustrated in Figure 5.



(a) Included angle from top-view δ_1 (b) Included angle from side-view δ_2

Fig. 5 - Method for determining the orientation angle of postharvest cabbage on a conical tread orientation roller

The calculation methods for the cabbage angle and orientation success rate are shown in Eqs. (13) and (14).

$$\delta = \arcsin\sqrt{\frac{\tan^2\delta_1 + \tan^2\delta_2}{1+\tan^2\delta_1 + \tan^2\delta_2}} \tag{13}$$

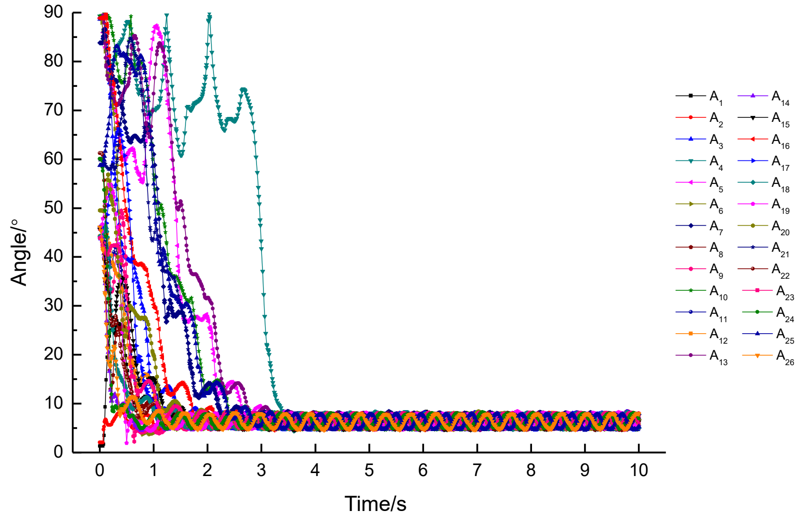
$$\eta_o = \frac{n_o}{N} \times 100\% \tag{14}$$

where: η_o is postharvest cabbage orientation success rate, [%]; n_o is number of postharvest cabbage achieving successful orientation (rotating around their central axis at a relatively small and stable angle), [heads]; N is total number of postharvest cabbage, [heads].

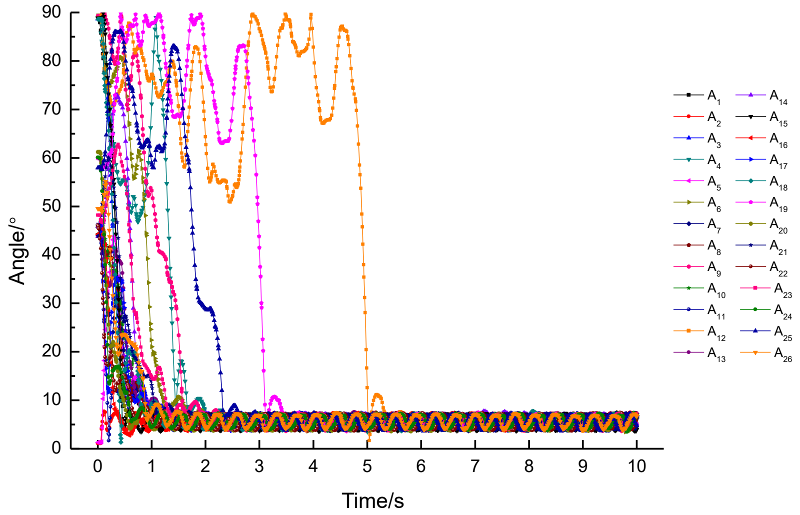
RESULTS

Analysis of the Simulation Results on the Orientation Movement of Postharvest Cabbage on Conical Tread Surfaces

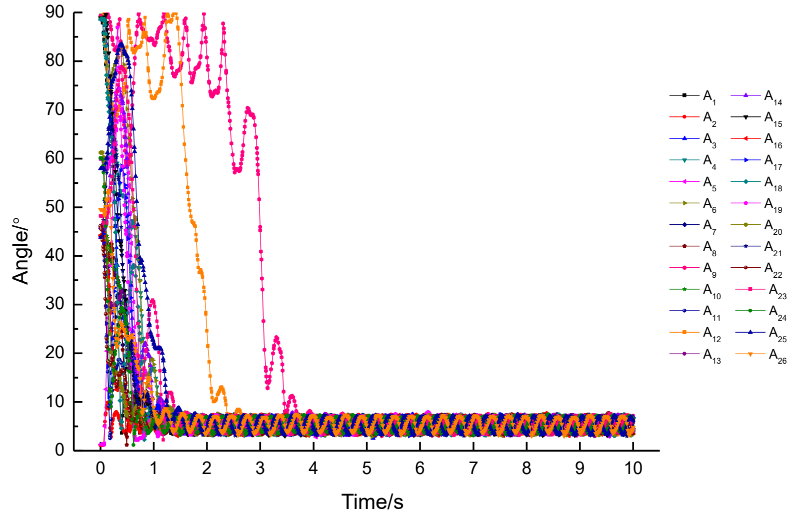
The pattern of angular variation during the automatic orientation of postharvest cabbage on the conical tread orientation roller group is illustrated in Figure 6.



(a) Roller angular velocity: 12.00 rad/s.



(b) Roller angular velocity: 15.00 rad/s.



(c) Roller angular velocity: 18.00 rad/s

Fig. 6 - Pattern of Angular Movement Between the Central Axis of Postharvest Cabbage and the Axis of the Conical Orientation Roller

Specifically, as shown in Figure 6(a), the angle stabilizes at 6.62 ± 0.12° when the roller's angular velocity is 12.00 rad/s. The longest time required for angular stabilization is 3.52 seconds (for initial pose A_4). For initial poses A_{13} and A_5, the time required for angular stabilization decreases gradually, while the remaining postharvest cabbage poses take no more than 2.50 seconds to achieve angular stabilization.

Similarly, as shown in Fig. 6(b), the orientation angle of postharvest cabbages stabilized at 5.90 ± 0.07° when the angular velocity reached 15.00 rad/s. The maximum stabilization time was 5.42 s, which was observed for the initial pose A_{12}. For the initial poses A_{19} and A_3, the stabilization time decreased in turn, whereas the orientation angles for all other initial poses stabilized within 2.08 s. As depicted in Fig. 6(c), at an angular velocity of 18.00 rad/s for the conical tread orientation roller group, the orientation angle of postharvest cabbages stabilized at 5.74 ± 0.13°. The maximum stabilization time was 3.76 s for the initial pose A_9; the stabilization time for A_{12} was relatively shorter, and that for all other initial poses did not exceed 1.44 s.

It is worth noting that in the above cases, the initial poses of postharvest cabbages (A4, A12 and A9) that required the longest angular motion stabilization time all corresponded to rotational motion about a principal axis of inertia other than the central axis. Nevertheless, no orientation failure was observed, and all initial poses were successfully oriented. In comparison with the orientation accuracy of cylindrical orientation rollers (6.72 ± 1.23°; *Cui et al., 2020*), the conical tread-based automatic orientation and conveying structure for postharvest cabbages thus exhibits superior orientation performance and efficiency.

Analysis of the experimental results on the performance optimization of automatic orientation based on conical treads

As shown in Table 2, range analysis indicated that the experimental factors affecting the orientation angle of postharvest cabbages were ranked by significance as follows: axial clearance > taper angle > linear velocity of the conveyor chain. The optimal parameter combination for achieving the target orientation angle was determined as $A_2B_3C_3$. Similarly, for the orientation success rate, the factors were ranked by significance in the order of taper angle > axial clearance > linear velocity of the conveyor chain, with the optimal parameter combination identified as $A_2B_3C_2$.

Table 2

Results of Postharvest Cabbage Cone Tread Orientation Orthogonal Experiment

Test number	*A*	*B*	*C*	Orientation angle (°)	Orientation success rate (%)
1	1	1	1	8.39	80.00
2	1	2	2	7.54	81.11
3	1	3	3	5.51	87.78
4	2	1	2	6.63	94.44
5	2	2	3	6.78	90.00
6	2	3	1	6.17	96.67
7	3	1	3	7.72	82.22
8	3	2	1	7.07	90.00
9	3	3	2	5.88	92.22
$k_{\delta 1}$	7.15	7.58	7.21		
$k_{\delta 2}$	6.53	7.13	6.68		
$k_{\delta 3}$	6.89	5.85	6.67		
R_{δ}	0.62	1.72	0.54		
$k_{\eta 1}$	82.96	85.56	88.89		
$k_{\eta 2}$	93.70	87.04	89.26		
$k_{\eta 3}$	88.15	92.22	86.67		
R_{η}	10.74	6.67	2.59		

Note: A is the taper angle of conical roller, B is the axial clearance, C is the linear velocity of the chain.

A comparison of the optimal parameter combinations for the orientation angle and orientation success rate of postharvest cabbages shows consistency in the operational parameters for the taper angle and axial clearance of the conical orientation rollers: specifically, the taper angle at A_2 and axial clearance at B_3. In contrast, a variation was observed in the linear velocity of the conveyor chain.

Notably, the orientation success rate was relatively high at conveyor chain linear velocity C_2, and the orientation angle achieved at this velocity was essentially identical to that obtained at C_3. For this reason, conveyor chain linear velocity C_2 was selected, yielding the overall optimal parameter combination of $A_2B_3C_2$ for the conical orientation of postharvest cabbages.

Meanwhile, analysis of variance (ANOVA) was performed on the test results to judge whether the effect of each factor possessed statistical significance. Specifically, the ANOVA results for orientation deflection angle are listed in Table 3. The F-values of the three factors followed the order axial clearance > taper angle > linear velocity of the conveyor chain, which was entirely consistent with the factor sequence obtained from range analysis. Nevertheless, all F-values were far lower than the critical value at the significance level of 0.05. This indicated that within the parameter range selected for the test, none of the three factors induced statistically significant differences in the orientation angle. This phenomenon could be attributed to the compensation effect among different factor levels a smaller axial clearance can make up for the insufficient lateral friction torque for automatic orientation generated by rollers with a small taper angle, which restrains drastic fluctuations of cabbage orientation deflection angle as a whole and ultimately weakens the statistical discrimination ability of a single factor.

Table 3

ANOVA Results of Orientation Angle

Factors	Sum of squares	Freedom	*F* value
A	0.582	2	0.293
B	4.814	2	2.421
C	0.569	2	0.286
Error	5.965	6	

The ANOVA results for orientation success rate are presented in Table 4. The sequence of F-values follows taper angle > axial clearance > linear velocity of the conveyor chain, consistent with the ranking derived from range analysis. The surface structure of conical rollers directly determines the lateral friction torque for automatic orientation that corrects the posture of cabbages, so the roller taper angle always acts as the dominant control variable to achieve stable orientation. However, the F-values of all factors remain below the critical value corresponding to the significance level of 0.05. This implies that within the parameter range set in this study, none of the factors exhibited a significant regulatory effect. Subsequent research can appropriately expand the value interval of factor levels and add more gradient levels to further explore their underlying influence rules.

Table 4

ANOVA Results of Orientation Success Rate

Factors	Sum of squares	Freedom	F value
A	173.091	2	2.009
B	73.591	2	0.854
C	11.786	2	0.137
Error	258.468	6	

Optimal parameter combination trial validation

Sixty randomly selected Zhonggan 15 cabbages were used as experimental samples to verify the postharvest orientation performance of the conical tread orientation and conveying device for postharvest cabbages, which was operated at a taper angle of 20°, an axial clearance of 60 mm, and a linear velocity of 300 mm/s for the conveyor chain. The experimental results are summarized in Table 5.

Table 5

Postharvest Cabbage Cone Tread Orientation Validation Test Results

Test number	Number of cabbage successfully orientated (piece)	Orientation success rate (%)	Orientation angle (°)
1	59	98.33	5.37
2	59	98.33	5.14

Test number	Number of cabbage successfully orientated (piece)	Orientation success rate (%)	Orientation angle (°)
3	60	100	4.53
4	59	98.33	5.39
5	59	98.33	5.92
6	60	100	4.81
7	60	100	5.47
8	59	98.33	5.04
9	58	96.67	5.2
10	59	98.33	4.89
Standard	59.20	98.67	5.18
Deviation	0.63	1.05	0.39

The results demonstrate that under this optimal parameter combination, the orientation success rate of postharvest cabbages reaches 98.67±1.05%, with the orientation angle at 5.18±0.39°. Further analysis on the processing capacity of the prototype indicates that the rack length of the rack-and-pinion pair is 1 m, namely the actual effective length of the orientation section is 1 m. At the optimal chain linear velocity of 300 mm/s, the corresponding cabbage residence time for orientation section is approximately 3.33 s, which provides sufficient duration to complete automatic orientation. For individual cabbages with occasional orientation failure, they can be identified, rejected and circulated back into the orientation mechanism for secondary posture adjustment. Meanwhile, the uniform feeding spacing between adjacent cabbages is set to 150 mm, and the calculated theoretical hourly throughput reaches 7200 cabbages per hour, which satisfies the demand for large-scale commercial processing of cabbages. There exists a trade-off between orientation performance and processing capacity. If higher production efficiency is required in practical application, the conveying speed can be moderately increased at the cost of reduced orientation accuracy. For precision rhizome cutting scenarios with extremely strict requirements on trimming quality, the chain conveying speed can be reduced to extend the residence time for orientation, sacrificing partial throughput to acquire more stable orientation performance. These findings further enhance the orientation performance of postharvest cabbages and provide more favorable technical conditions for subsequent commercial processing operations, such as root and stem trimming.

CONCLUSIONS

(1) Based on the moment of inertia and the principle of minimum action, this study develops an automatic conveying and orientation device for postharvest cabbages equipped with conical tread rollers. The axially variable-diameter tread surfaces of conical rollers generate lateral friction torque acting on cabbages, counteracting orientation deviation caused by non-homogeneous mass distribution and axial offset of the mass center, and guiding cabbages to rotate steadily around their minimum inertia axis to achieve automatic orientation. Meanwhile, ADAMS dynamic simulation results reveal that cabbages with 26 types of initial poses can all complete automatic orientation on this device, with the maximum posture stabilization convergence time reaching 5.42 s, which further verifies the superiority and feasibility of the conical tread orientation mechanism.

(2) Range analysis and analysis of variance (ANOVA) of orthogonal tests indicate that the significance order of experimental factors affecting the orientation deflection angle of postharvest cabbages is axial clearance > taper angle > linear velocity of the conveying chain. The significance order of factors influencing orientation success rate is taper angle > axial clearance > linear velocity of the conveying chain. Within the parameter range set in this study, none of the experimental factors exerted a statistically significant regulatory effect on the orientation deflection angle or orientation success rate of postharvest cabbages. Future research can appropriately expand the value range of factor levels and add more gradient levels to further explore their underlying influence rules.

(3) The optimal combination of operating parameters was determined as follows: taper angle of 20°, axial clearance of 60 mm, and conveying chain linear velocity of 300 mm/s. Under this working condition, the orientation success rate reaches 98.67±1.05%, the average orientation deflection angle is 5.18±0.39°, and the theoretical processing throughput is 7200 cabbages per hour, which can basically meet the requirements of postharvest commercial treatment of cabbages. Nevertheless, all performance tests in this paper were only

carried out with the cabbage cultivar "Zhonggan No.15" as the research object, which brings certain limitations to this study. Follow-up research will investigate the automatic orientation adaptability of flatter, elongated and highly asymmetrical cabbage cultivars.

(4) Test results of the prototype performance reveal that occasional orientation failures are inevitable during long-term continuous orientation operation. Excluding failures caused by cabbage jamming due to oversized dimensions or cabbage slipping through roller gaps, all remaining failures stem from insufficient residence time for orientation. Cabbages rotating around non-central principal axes with large moments of inertia cannot complete automatic orientation within the limited available duration. To address the above problems, our research team plans to conduct follow-up studies on cabbage size grading and orientation posture recognition based on machine vision. Specifically, cabbages will be classified by size grading prior to orientation and delivered to dedicated orientation production lines matching their respective dimensions, so as to eliminate orientation failures induced by mismatches between cabbage size and structural parameters of the orientation device. After orientation, machine vision posture recognition will judge the orientation quality. Cabbages identified as orientation failures will be separated and recirculated into the orientation mechanism for secondary adjustment, thereby improving the orientation success rate for cabbages of various sizes.

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REFERENCES

[1] Bennedsen BS. , Peterson DL., Tabb A. 2005. Identifying defects in images of rotating apples. *Computers and Electronics in Agriculture*, 48(2): 92-102 Kearneysville/West Virginia,DOI:10.1016/j.compag.2005.01.003

[2] Cui G P., Wang Z J., Wen S T., Wei Y Z., Cui Y J., Niu Z J. 2021. Design and Experiment of Post-Harvest Cabbage Individual Sorting and Orientation Conveying Device (采后甘蓝单体排序定向输送装置设计与试验). *Transactions of the Chinese Society for Agricultural Machinery,* 52 (6): 351-360 Yangling/Shaanxi, China. DOI: https://doi.org/10.6041/j.issn.1000-1298.2021.06.037

[3] Cui G P., Zheng X M., Cui Y J., Wang Z J., Shi Y G., Fu L S. 2020. Research on Automatic Orientation Method of Postharvest Cabbage Based on Moment of Inertia (基于转动惯量的采后甘蓝自动定向方法研究). *Transactions of the Chinese Society for Agricultural Machinery*, 51 (11): 183-195 Yangling/Shaanxi, China. DOI: https://doi.org/10.6041/j.issn.1000-1298.2020.11.020

[4] Cui Y J., Wang M H. (2023). Analysis of Research Progress in Automatic Orientation Technology in the Agricultural Field (农业领域自动定向技术研究进展分析). *Transactions of the Chinese Society for Agricultural Machinery*, 54 (04): 1-20 Yangling/Shaanxi, China. DOI: https://doi.org/10.6041/j.issn.1000-1298.2023.04.001

[5] Du D., Wang J., Xie L., Deng F. 2019. Design and field test of a new compact self-propelled cabbage harvester. *Transactions of the ASABE*, 62(5): 1243-1250 Hangzhou/Zhejiang, China. DOI: https://doi.org/10.13031/trans.13327

[6] FAOSTAT. 2026. Production of cabbages and other brassicas in 2024 [DB/OL]. Retrieved from http://www.fao.org/faostat/en/#data, 2026-1-11

[7] Kang N B., Qiang F., Wu L G., Wang S G., He J G. 2017. Design and Experiment of Fresh Jujube Grading Machine Based on Electromagnetic Synchronous Actuator (基于电磁式同步执行机构的鲜枣分级机设计与试验). *Transactions of the Chinese Society of Agricultural Engineering*, 33 (7): 254-260 Yinchuan/Ningxia, China. DOI: https://doi.org/10.11975/j.issn.1002-6819.2017.07.033

[8] Kang N B., Shang M Y., He J G., Liu G S., Wang S L., Wu L G. 2017. Design of a Chain Pneumatic Punching Automatic Seed-removing Machine for Dried Red Dates (链式气动冲切自动化干红枣去核机设计). *Transactions of the Chinese Society of Agricultural Engineering*, 34 (22): 19-26 Yinchuan/Ningxia, China. DOI: https://doi.org/10.11975/j.issn.1002-6819.2018.22.003

[9] Lefcourt AM., Narayanan P., Tasch U., Kim MS., Reese D., Rostamian R., Lo YM. 2009. Orienting apples for imaging using their inertial properties and random apple loading. *Biosystems Engineering*, 104(1): 64-71 Baltimore/Maryland, USA. DOI: https://doi.org/10.1016/j.biosystemseng.2009.06.002

[10] Lefcourt AM., Narayanan P., Tasch U., Rostamian R., Kim MS., Chen YR. 2008. Algorithms for parameterization of dynamics of inertia-based apple orientation. *Applied Engineering in Agriculture*, 24(1): 123-129 Beltsville/Maryland, USA. DOI：10.13031/2013.24152

[11] Li C Y., Ma X Z., Cheng H S., Chen Z. 2014. Design and Testing of a Lychee-Specific Pitting and Shelling Machine (荔枝定向去核剥壳机设计与试验). *Transactions of the Chinese Society for Agricultural Machinery*, 45 (8): 93-100 Guangzhou/Guangdong, China. DOI: https://doi.org/10.6041/j.issn.1000-1298.2014.08.015

[12] Li J., Zhang D X., Liu B. 2009. Design of Conveying and Tilting Mechanism for Apple Grading Machine (苹果分级机输送与翻转机构设计). *Transactions of the Chinese Society for Agricultural Machinery*, 40 (5): 158-161+157 Beijing, China.

[13] Lin J., Holmes M., Vinson R., Ge CR., Pogoda FC., Mahon L., Gentry R., Seibel GE., Chen X., Tao Y. 2017. Design and testing of an automated high-throughput computer vision guided waterjet knife strawberry calyx removal machine. *Journal of Food Engineering*, 211: 30-38 College Park/Maryland, USA. DOI: https://doi.org/10.1016/j.jfoodeng.2017.05.002

[14] Liu X D., Liang Q A., Li S., Liu X L., Zhang J. 2012. Design and Experiment of Single-channel Apricot Cutting and Pitting Machine (单通道杏切分去核机的设计与试验). *Xinjiang Agricultural Mechanization*, (6): 5-7 Urumqi/Xinjiang, China. DOI:10.13620/j.cnki.issn1007-7782.2012.06.013

[15] Liu X D., Wang X N., Wang C Y., Liu X L., Yang H M., Gan L X. 2016. Design and Experiment of a Differential Three-Channel Dynamic Orientation Conveying Device for Fresh Apricots (差速式三通道鲜杏动态定向输送装置设计与试验). *Transactions of the Chinese Society for Agricultural Machinery*, 47 (10): 35-43 Shenyang/Liaoning, China. DOI: https://doi.org/10.6041/j.issn.1000-1298.2016.10.005

[16] Mizushima A, Lu R. 2013. A low-cost color vision system for automatic estimation of apple fruit orientation and maximum equatorial diameter. Transactions of the ASABE, 56(3): 813-827 East Lansing/Michigan, USA. DOI:https://doi.org/10.13031/trans.56.9343

[17] Ren ZS., Sun SG., Xie G. 2010. A method to determine the two-point contact zone and transfer of wheel–rail forces in a turnout. *Vehicle System Dynamics,* 48(10): 1115-1133 Beijing, China. DOI: https://doi.org/10.1080/00423110903337281

[18] Wang X Y., Zhu S., Li X Q., Li T X., Wang L L., Hu Z X. 2020. Design and Experiment of a Potato Seed Tuber Cutter with Oriented Arrangement and Vertical-Horizontal Cutting (定向排列纵横切分马铃薯种薯切块机设计与试验). *Transactions of the Chinese Society for Agricultural Machinery*, 51 (6): 334-345 Zibo/Shandong, China. DOI: https://doi.org/10.6041/j.issn.1000-1298.2020.06.036

[19] Wang Z J., Cui G P., Zheng X M. 2021. Analysis of Motion and Damage in the Cabbage Flipping and Unloading Process Based on EDEM (基于 EDEM 的甘蓝翻转卸料过程运动与损伤分析). [J] *Journal of Agricultural Mechanization Research*, 43 (02): 16-22+77 Yangling/Shaanxi, China. DOI: https://doi.org/10.13427/j.cnki.njyi.2021.02.003

[20] Xiong W., Zhou L C., Yu H. 2025. Research Progress and Prospect of Sorting Technology and Equipment for Thin-Skinned Fruits and Vegetables (薄皮果蔬分选技术与设备研究进展与展望). [J] *Transactions of the Chinese Society for Agricultural Machinery*, 56 (08): 665-683

[21] Zheng X M., Cui G P., Wang Z J. 2021. Design and Experiment of Automatic Orientation Adjustment Device for Postharvest Trimming System of Cabbage (甘蓝采后整修系统自动调向装置设计与试验). *Journal of Agricultural Mechanization Research*, 43 (02): 64-70 Yangling/Shaanxi, China. DOI: https://doi.org/10.13427/j.cnki.njyi.2021.02.011

[22] Zheng X S., Wang C Y., Tang W B., Guo Y P., Lu F. 2015. Design of Orientation Conveying Mechanism for Chili Seed Removing Machine (辣椒去核机定向输送机构的设计). *Journal of Agricultural Mechanization Research*, 37 (10): 112-115 Urumqi/Xinjiang, China. DOI: https://doi.org/10.13427/j.cnki.njyi.2015.10.024

[23] Zhong X B., Tao G A., Luo Y Y., Yi X L. 2016. Optimisation Method for the Tread Profile of Independently Rotating Wheels (独立旋转车轮踏面外形优化设计方法). *Journal of Sichuan University of Science & Engineering (Natural Science Edition)*, 29 (3): 33-38 Zhuzhou/Hunan, China. DOI: https://doi.org/10.11863/j.suse.2016.03.08