ISSN: 2414-1895 DOI: 10.6919/ICJE.202506_11(6).0031

Development of Small-Sized Cabbage Harvesting Equipment for Smallholder Farmers

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Abstract

As one of the most important edible vegetables in China, cabbage is mostly grown by smallholder farmers. At present, cabbage harvesting typically involves two methods: manual harvesting and large-scale cabbage harvesting equipment. The former is inefficient and labor-intensive, while the latter is highly efficient but expensive, offering extremely low cost-performance for smallholder farmers. The market lacks low-cost and effective cabbage harvesting equipment tailored for smallholder farmers. Through investigating and analyzing the process of manual cabbage harvesting by farmers, a small-sized cabbage harvesting equipment has been designed. The equipment incorporates a cabbage maturity sensing mechanism with a multi-link structure, which uses the volume of cabbage as the criterion for determining maturity. Meanwhile, the mechanism for removing outer leaves simulates the technical process of farmers selectively removing large outer leaves of Chinese cabbage during the picking process. This harvesting equipment has been put into practice and is being batch-trialed in cooperation with local farmers. Compared with existing large-scale cabbage harvesting equipment, the cost of this equipment is reduced by approximately 1/8. Compared with manual harvesting, its harvesting efficiency is increased by at least 1.8 times.

Keywords

Smallholder; Small Cabbage Harvesting Equipment; Multi-link Mature Sensing Mechanism; Leaf Trimming Module.

1. Introduction

In China, Chinese cabbage (Brassica rapa subsp. pekinensis) has a cumulative planting area of 40 million mu. Characterized by low cost, delicious taste, and broad consumer acceptance, it remains one of the most important edible vegetables in the country[1].

As a major agricultural nation, smallholder farmers account for over 98% of China's farming population. This group primarily consists of agricultural producers with fragmented farmland, small-scale operations, and low technological adoption rates, managing cultivated land that accounts for 70% of the total cultivated land area in China[2].

Cabbage harvesting constitutes approximately 40% of the total workload in its cultivation process. Currently, the main harvesting methods are manual labor and large-scale mechanical harvesting.

Existing solutions include simple-to-operate but single-function auxiliary equipment for small-scale picking[3-4], as well as automated and high-efficiency cabbage harvesters. However, the latter are only suitable for large-scale cabbage fields, with prohibitively high machine costs. Additionally, the harvested cabbages still require manual removal of outer leaves. Given the dominant presence of smallholder farmers in China, such equipment offers extremely low cost-performance[5-9].

Volume 11 Issue 6, 2025
DOI: 10.6919/ICJE.202506_11(6).0031

Manual harvesting is inefficient and labor-intensive: harvesting 150 cabbages typically requires 3 to 5 people working for one hour. In contrast, large-scale mechanical harvesting is highly efficient and automated, completing the same task in approximately 0.3 hours. However, the high purchase cost of large machines, coupled with challenges such as required storage space and maintenance expenses, makes them cost-prohibitive for smallholder farmers.

In summary, there is a notable gap in the market for small-sized cabbage harvesting equipment tailored to the needs of smallholder farmers.

2. Overall Design of Small-Sized Cabbage Harvesting Equipment

2.1 Module Functional Configuration of Small-Sized Cabbage Harvesting Equipment

2.1.1 Sub-section Headings

Based on on-site farmer surveys and combined with actual harvesting conditions, the functional configuration of the Small-Sized Cabbage Harvesting Equipment (hereinafter referred to as the "harvesting equipment") is set as follows:

Cutting Module: This module is responsible for two processes: inspection of cabbage maturity qualification and cutting of qualified cabbages.

Leaf Trimming Module: Considering factors such as pesticide residue and quality preservation during actual picking, farmers typically remove large outer leaves from freshly cut cabbages. To address this, an innovative module is designed to complete the initial leaf-trimming processing simultaneously with harvesting. This reduces subsequent picking steps for farmers and alleviates labor intensity.

2.2 Overall Design of the Harvesting Equipment

The equipment is designed by integrating the defined functional modules, with 3D modeling conducted using SolidWorks software. The three-dimensional model of the designed harvesting equipment is shown in Figure 1. The equipment integrates functions such as maturity sensing, cutting, leaf trimming, and storage. Its external dimensions are: 1743 × 980 × 695 mm (length × width × height).

Figure 1. 3D Design Schematic Diagram of Harvesting Equipment

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3. Design of Key Components for Harvesting Equipment

3.1 Multi-Link Maturity Sensing Mechanism

The harvesting equipment is manually pushed forward by operators. During the pushing process, cabbages in the soil first come into contact with the cutting module at the front end of the equipment. As shown in Figure 2, the cutting module consists of two main components: the maturity sensing mechanism and the cutting mechanism, with their respective functions being cabbage maturity detection and root cutting harvesting.

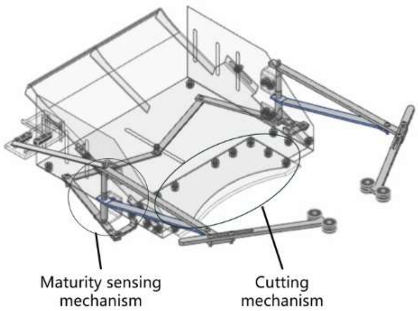

Figure 2. Cutting Module

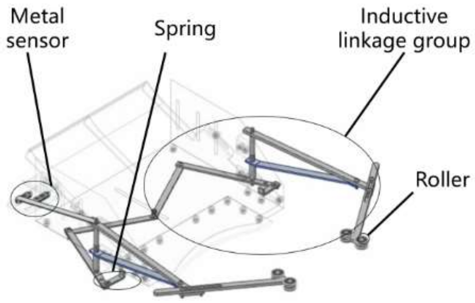

Figure 3. Multi-State Schematic Diagram of Multi-Link Maturity Sensing Mechanism

The size of cabbages (often assessed by diameter) is not only one of the criteria for determining cabbage maturity but also an important factor for consumers when purchasing cabbages. Therefore, the mechanism's determination of the diameter of cabbages to be harvested serves as the principle basis for the maturity sensing mechanism in the harvesting equipment.

3.1.1 Working Principle of the Mechanism

As shown in Figure 3, the Multi-Link Maturity Sensing Mechanism was designed with the principle of minimizing the use of sensors and electrical control components during the initial design stage. This approach aims to drastically reduce energy consumption, complying with the national design principle of energy conservation and emission reduction. Meanwhile, reducing the use of electronic components also helps cut down farmers' maintenance and operation costs.

This mechanism is composed of two sets of symmetrical four-bar linkages, rollers, springs, and metal sensors. The rollers aid in the smooth contact process with cabbages. The connecting rods serving as sensing transmission components are each connected by bolted joints, placed symmetrically on the left and right to form a spatial linkage mechanism. Meanwhile, the linkages utilize spring force to give the mechanism mechanical retraction characteristics, with sensors determining the position of the linkages.

The Multi-Link Maturity Sensing Mechanism judges cabbage maturity based on cabbage diameter, as cabbage size is one of the important criteria for purchasers to determine cabbage maturity. Since cabbages of different sizes can cause displacement of the sensing linkages, different displacement amounts produce different linkage effects on the sensors. The length of each linkage in this mechanism is shown in Figure 4(a). Combined with two metal sensors, it can exhibit the following three states:

State 1: As shown in Figure 4(b), when the cabbage does not contact the mechanism, it remains in its initial state.

State 2: As shown in Figure 4(c), if the maximum diameter of the cabbage is less than 150mm, it is immature. The three-color light turns red, prompting operators not to harvest this cabbage.

State 3: As shown in Figure 4(d), if the cabbage diameter is between 150mm and 200mm, it is mature. The three-color light turns green, indicating that operators can harvest it.

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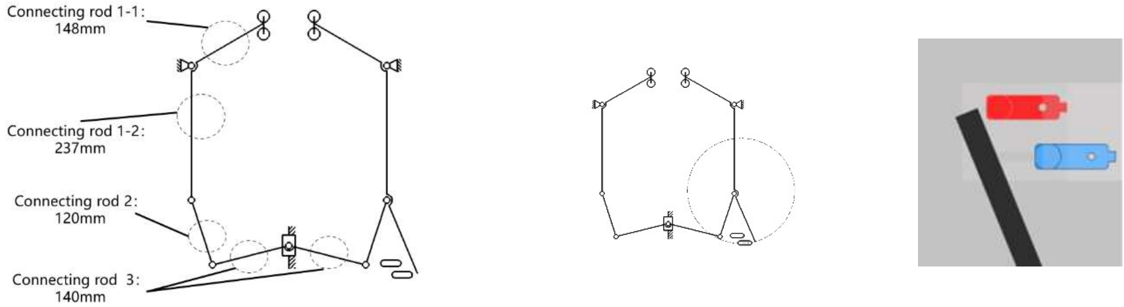
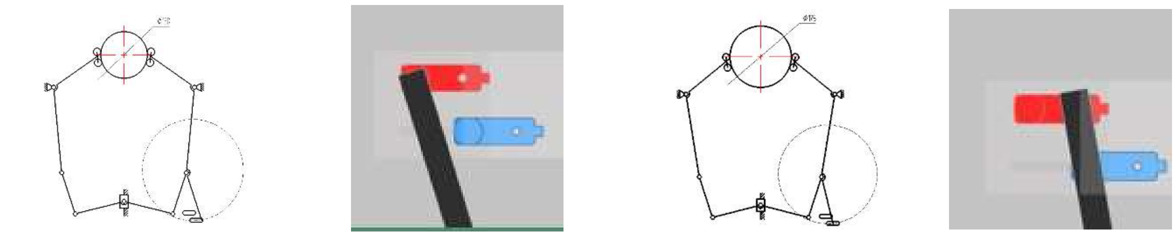
Through the transformation of these three states, the mechanism can assist operators in screening Chinese cabbages of different maturities.



(a) Dimensions of Each Linkage in Maturity Sensing Linkage Mechanism

(b) State 1: Status of Linkages and Sensors When Not in Contact with Cabbage



(c) State 2: Status of Linkages and Sensors for Unqualified Cabbages

(d) State 3: Status of Linkages and Sensors for Qualified Cabbages

Figure 4. Multi-State Schematic Diagram of Multi-Link Maturity Sensing Mechanism

3.1.2 Mechanism Optimization

The linkage mechanism of the maturity detection module is one of the core components of the overall transmission system and harvesting execution system. As it needs to be continuously driven under complex field working conditions, to avoid failures such as linkage fracture or deformation caused by sudden changes in dynamic loads or material fatigue during operation, ANSYS simulation analysis is required. The analysis focuses on verifying the stress distribution and deformation of the mechanism under extreme loads, ensuring that the maximum equivalent stress of the linkages is lower than the material yield strength, and the deformation displacement at key hinge positions does not exceed the allowable motion tolerance range. This ensures the accuracy of harvesting actions and the long-term operational reliability of the equipment. The linkage mechanism before optimization is shown in Figure 5.

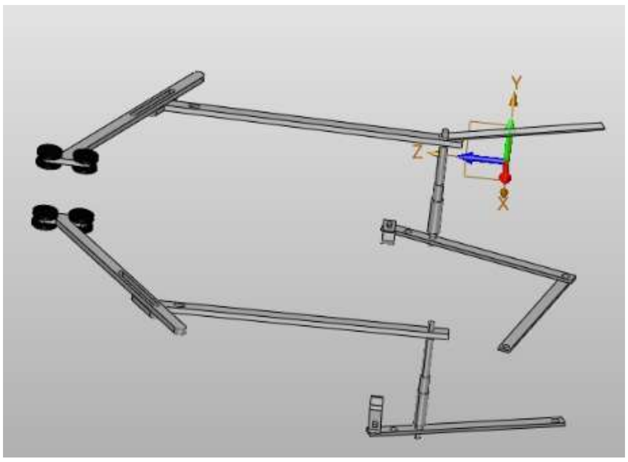


Figure 5. Schematic Diagram of the Linkage Mechanism Before Optimization

ISSN: 2414-1895 DOI: 10.6919/ICJE.202506_11(6).0031

The linkage mechanism of the maturity detection module, as a core component for power transmission and action execution, must maintain high reliability, light weight, and durability under complex field working conditions (such as vibration and impact, soil erosion, and continuous alternating loads). Considering the actual needs of agricultural machinery, the 7050-T7451 high-strength aluminum alloy is primarily selected for analysis as the hub material, and its performance parameters are shown in Table 1.

Table 1. Material Properties of Linkage

Poisson's Ratio	Young's Modulus	Density	Yield Strength
0.33	71 GPa	2810 kg/m3	462 MPa

Mesh Generation is a critical step in model preprocessing. Generally, finer meshes lead to more accurate computational results, but overly dense meshes significantly increase computational costs. In this study, first-order tetrahedral elements were selected for mesh generation. The mesh generation results of the linkage mechanism are shown in Figure 6, with a uniform mesh size of 2 mm.

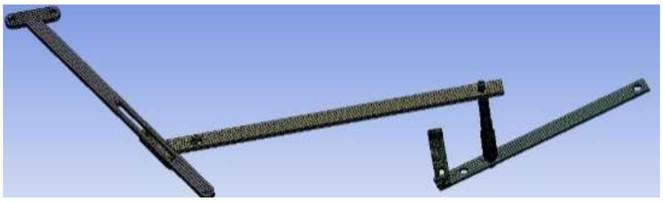


Figure 6. Harvesting Module (Left) - Linkage Mechanism Finite Element Model

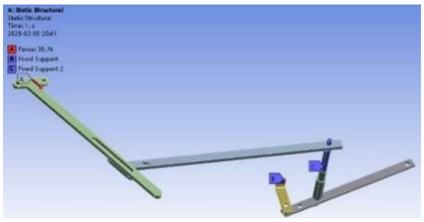


Figure 7. Harvesting Module (Left) - Linkage Mechanism Constraints and Loads

The lugs of the linkage mechanism are connected to the harvester body by bolted joints, and the linkages rotate around a circular shaft. Therefore, fixed constraints are applied at the connection points between the lugs and the body, as well as at the circular shaft. During cabbage harvesting, due to mechanical vibration and the necessary torque for picking, the end of the linkage mechanism is subjected to a load of approximately 20-30N. Thus, a 30N force is applied at the end, directed perpendicular to the contact surface between the linkage and the cabbage. The constraint and load diagram is shown in Figure 7.

After applying the constraints and load specified in Section 1.3 to the linkage mechanism model, ANSYS was used to perform the analysis. The stress and strain analysis results are shown in Figures 8 and 9.

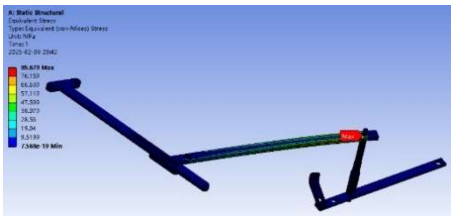


Figure 8. Stress Analysis Results of Left Linkage Mechanism

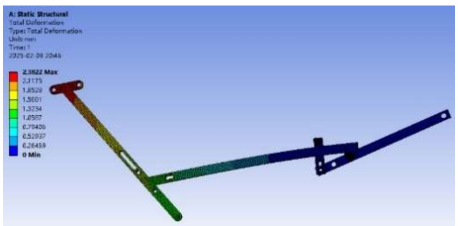


Figure 9. Strain Analysis Results of Left Linkage Mechanism

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According to the simulation analysis results, the maximum strain of the linkage mechanism occurs at the end of the linkage, with a maximum value of 2.382 mm, which will not affect the operation and function of the mechanism. The maximum stress of the linkage mechanism appears at the junction between the middle linkage and the circular shaft, reaching 84.679 MPa, which is far below the yield strength of the material, indicating relatively safe performance but still with room for improvement. Therefore, a strengthening design was carried out on Linkage 1-2 in Figure 4, as shown in Figure 10.

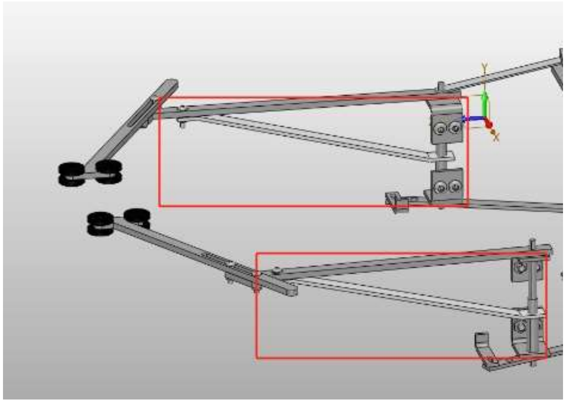

Figure 10. Schematic Diagram of Strengthened Linkage

After the strengthening design, simulation analysis was performed under the same constraint and load conditions. The simulation results of stress and strain are shown in Figures 11 and 12.

The maximum strain of the improved linkage mechanism decreased by 1.31 mm, and the maximum stress decreased by 38.607 MPa.

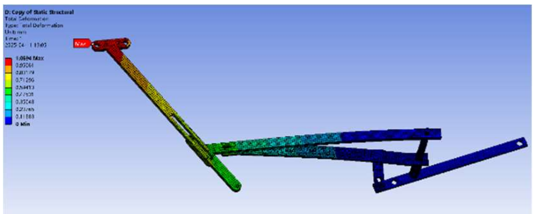

Figure 11. Strain Analysis Results of Strengthened Linkage Mechanism

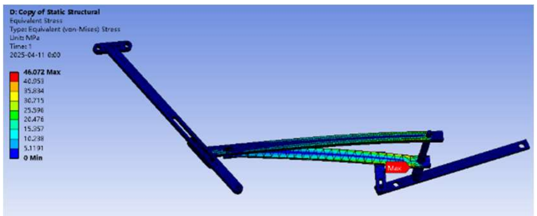

Figure 12. tress Analysis Results of Strengthened Linkage Mechanism

3.2 Leaf Trimming Module

During the cabbage harvesting process, farmers typically remove the outer large leaves that are unusable and take up transportation space. Based on the actual manual leaf selection action of farmers for outer large leaves, the mechanism of the simulated design leaf selection module is shown in Figure 13.

After the cabbage is cut from the root and separated from the soil by the cutting module, it falls into the leaf selection module. Through the combined rotation of a pair of rollers with blunt blades of opposite rotation directions, helical transportation of the cabbage is achieved. Meanwhile, as the double rollers rotate in the direction opposite to that of their own blunt blades, during the transportation of the cabbage, the outer large leaves that are not firmly attached to the main cabbage body are rolled out. The rolled-out large leaves can directly fall into the farmland and be used as field fertilizer.

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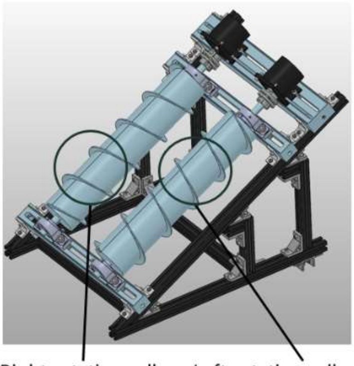

Figure 13. Schematic Diagram of Roller Outer Leaf Removal Mechanism

3.3 Physical Display of Equipment

As shown in Figure 14, the overall design and fabrication of the small-scale cabbage harvesting equipment were carried out around the above two key component modules. After design, research, and fabrication, the equipment has been produced in small batches for collaborative use with surrounding small-scale farmers.

Figure 14. Physical Photograph of Small-Scale Cabbage Harvesting Equipment

As shown in Table 2, the equipment was compared with manual harvesting in cabbage fields with harvesting areas of approximately 40 m^2 and 70 m^2. Although the harvesting speed of the equipment decreases as the area increases, its efficiency is 1.8 to 2.5 times that of manual harvesting, still representing a significant improvement.

Table 2. Comparison of Actual Field Harvesting Performance of Equipment

Harvesting Speed of Equipment (pcs/min)	Harvesting Area(m^2)	Manual Harvesting Speed (pcs/min)
5.8	About 40	3.1
5.2	About 70	2

4. Conclusion

The harvesting equipment introduced in this paper achieves low-cost cabbage harvesting through a mechanism-based design, incorporating both maturity sensing and leaf selection functions. Compared with large-scale harvesting equipment, this equipment features low cost, simple maintenance, and

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convenient storage. Its cost is approximately one-eighth that of large-scale harvesting equipment, while its efficiency is 1.8 to 2.5 times more efficient than manual harvesting. The equipment's leaf selection and automatic cabbage maturity recognition functions are extremely farmer-friendly, further reducing the labor burden on operators. Thus, it holds broad application prospects for small-scale farmers and represents a cost-effective cabbage harvesting solution suitable for smallholders.

Acknowledgments

The author would like to express heartfelt gratitude to Wenzhou Vocational and Technical College for the financial support provided by the "14th Five-Year Plan" General Teaching Construction and Teaching Reform Research Project (WZYYB202427) during the 2023-2024 academic year.

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