Research on Optimization Design of Stereoscopic Rice Seedling Cultivation Device

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Abstract. To address the issues of extensive land occupation, inadequate utilization of space resources, and the hardship in manually replacing seedling trays in traditional rice seedling cultivation, this study put forward a seedling cultivation device and carried out its optimization. In contrast to traditional seedling cultivation equipment, this seedling cultivation device employs a rotary axis structure in combination with an eccentric wheel disc mechanism, relying on synchronous belt transmission to drive the main shaft's rotation. There are two rotating discs on the left and right sides of the device, with an eccentric wheel disc added on one side. A number of seedling cultivation trays are evenly coordinated with the rotating discs on the surface, enabling the stable rotation of the trays. This three-dimensional seedling cultivation significantly enhances seedling cultivation efficiency and fully exploits the resources within the space. The seedling cultivation tray serves as the main load-bearing component of the device, and its structure and load-bearing capacity exert a significant influence on the entire device. The seedling cultivation tray remains parallel to the ground and rotates around the central axis while rotating along with the rotating plate, achieving the balanced utilization of light, temperature, and moisture resources in the space and enhancing the utilization rate of seedling cultivation resources. The synchronous belt drive employed possesses advantages such as a suitable working environment, guaranteed transmission efficiency, and improved transmission stability. This study designed different types of tray structures and analyzed the load conditions of each tray through finite element analysis, static mechanical stress analysis, and experimental verification, and selected the optimal tray structure. The designed tray has undergone improvements in ribs and drainage holes, and the most favorable tray structure was obtained. The experimental results demonstrate that the strength and stiffness of the device proposed in this study meet the requirements.

Keywords: Rice Nursery Rack, Nursery Tray, Stress Analysis, Optimization Design.

1. Introduction

In recent years, the development of mechanized nursery cultivation in China has been quite rapid and significant [1]. The mechanization level of rice production in China is above 98% [2]. In the research and development of nursery equipment, the vertical nursery technology can fully utilize the limited resources in the space, and the efficiency of seedling cultivation is high, ensuring the quality of the seedlings, and can greatly reduce the labor intensity of workers. It is an important way to solve the problems of insufficient land and labor resources.

In recent years, both domestic and foreign researchers have conducted relevant studies on stereoscopic seedling cultivation devices. Li Guilian et al [3] studied W-type and S-type automated seedling cultivation beds, but the cultivation effect was not as good as traditional single-layer cultivation. Many et al [4] designed a cam lifting system and a stereoscopic positioning device to effectively improve the efficiency of the stacking plate in the rice factory-based seedling cultivation. Ma Xu et al [5] designed a composite tray that can be embedded with soft plastic seedling trays and an electric control system for automatically supplying soft and hard seedling trays in rice seedling cultivation. They ensured the success rate of supplying trays while meeting the technical requirements for automatically supplying seedling trays in rice seedling cultivation. Li Jingzhu et al [6] developed a stereoscopic rotating seedling stand that ensures that the seedling trays always maintain a parallel position relative to the ground and rotates around the central axis, achieving the balanced utilization of light, temperature, and air resources in the seedling cultivation greenhouse. Li Jingzhu et al [7] designed a stereoscopic movable seedling cultivation stand that has the characteristics of low cost, small land occupation, and easy operation. Jin Yifu et al [8] designed a 2B-4A self-propelled seedling cultivation machine that can complete the entire cultivation process at once, with good operating results. It can be seen that domestic seedling stands have conducted more research on stereoscopic and cyclic cultivation, which proves the effectiveness of this research direction. For the development of seedling cultivation technology abroad, because less transplantation method is used to produce rice, the United States, Australia, Italy, the Netherlands, and other Western European countries have developed very few rices seedling cultivation machinery. Japan and South Korea, which have more mature rice seedling tray cultivation line technology in Asia, are among the countries that have mastered this technology [9]. This greatly advanced the mechanization level of seedling cultivation nationwide. Japan has always been at the forefront of research in rice factory-based seedling cultivation equipment [10], it has the advantages of high automation and high efficiency, but it has not been applied and promoted domestically [11].

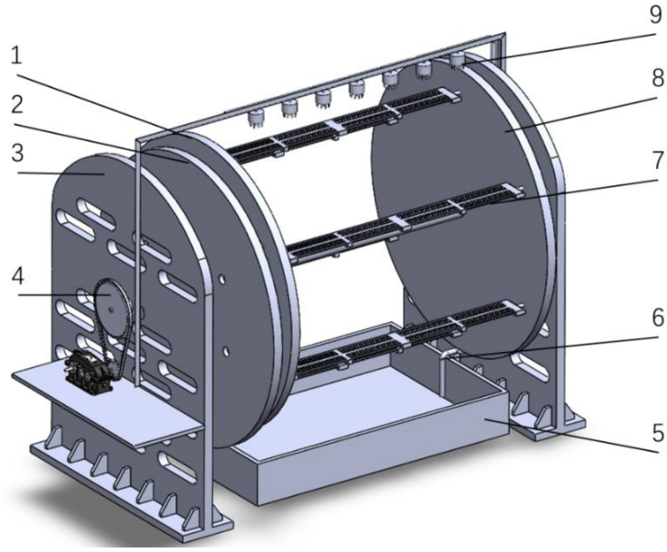
It can be observed from the research on seedling cultivation devices both domestically and internationally that some developed countries possess relatively mature seedling cultivation devices; however, they have not carried out in-depth studies on vertical seedling cultivation. The existing seedling cultivation devices in China also present several issues, such as high device costs, inability to fully exploit the limited resources in the space, difficulties in manually replacing seed trays, and challenges in guaranteeing seedling quality. These devices have not been widely applied in practical use. To address these problems, this paper proposes an automated vertical seedling cultivation device and optimizes the design of the tray structure. This device is characterized by a high degree of automation, simplicity and convenience in replacing seed trays, and full utilization of space resources. The main working component of the device, the seedling cultivation tray, has to withstand the gravitational force of the tray throughout the entire working process of the device. The optimized design of the seedling tray structure serves as a crucial factor influencing the stable operation of the seedling cultivation device. In this study, several distinct tray structures were designed, and the static mechanical analysis of each seedling cultivation tray was conducted. The stress and deformation of the seedling cultivation trays were calculated and analyzed through ANSYS experimental simulation of the actual working conditions of the device. After comparison and verification, the most outstanding seedling cultivation tray structure was obtained.

2. Establishment of the Model Structure

In this section, firstly, the composition, fundamental design concept, and design principles of the seedling cultivation device are briefly expounded. Subsequently, the design of the main components, including the seedling cultivation tray and the rotating disk, is analyzed in greater detail. Eventually, the dimensions of the key components are determined via theoretical computations.

2.1. Design Concept

In the design of the seedling cultivation rack, it is expected that seedlings can fully absorb and utilize resources, ensuring that the utilization rates of light, water, and air for each seedling fall within a suitable range to fully accomplish the accumulation of dry matter. However, within the limited space, although traditional single-layer seedling cultivation can fully utilize resources, it squanders resources in the three-dimensional space. Moreover, the utilization area within the limited space is restricted by structure and cost and cannot be increased indefinitely. The three-dimensional seedling cultivation rack can make use of resources in the space, but there exists a phenomenon of light shading, resulting in some seedlings not receiving sufficient light. To fully utilize the various resources within the limited space and from an economic perspective, to enhance the production efficiency of the greenhouse, this poses a higher demand for the structure of the entire seedling cultivation device. Hence, this study proposes the adoption of a three-dimensional stereoscopic structure for seedling cultivation. The tray rotates around the axis along with the rotating plate, combined with the eccentric wheel plate mechanism and the four-bar mechanism, preventing the tray from tilting during rotation and slipping off the tray, guaranteeing the horizontal and stable transmission of the tray. To achieve the essential irrigation operation during the seedling cultivation period, a water storage tank, a guide water pipe, and a sprinkler are added to the seedling cultivation device. The water flows from the water storage tank through the guide water pipe to the sprinkler, which then conducts the sprinkling and spraying work. The transmission device of the device employs synchronous belt transmission. This transmission method features higher transmission efficiency, and its transmission stability is superior to that of ordinary belt transmission and chain transmission. This method is also more suitable for indoor transmission work. The transmission power of the device is calculated to be no more than 1.4KW. Therefore, a motor within this power range and meeting the requirements of the working environment can be selected. In this study, the Y series motor is chosen. The overall structure of the seedling cultivation device is presented in Figure 1.

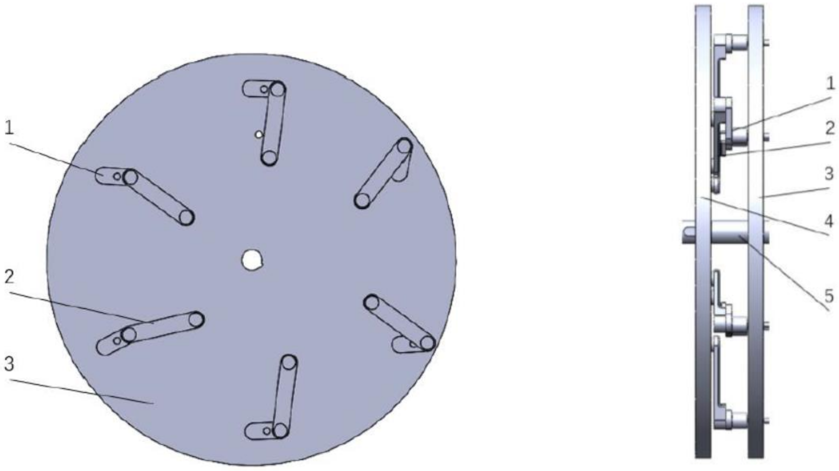


1. left turntable; 2. eccentric wheel plate; 3. frame; 4. transmission device; 5. water storage tank; 6. guidewater pipe; 7. tray; 8. right turntable; 9. sprinkler

Figure 1. General Assembly Drawing of the Seedling Cultivation Apparatus

2.2. Working Principle of the Device

This seedling cultivation rack mainly consists of rotary discs, a central rotary axis, a frame, an eccentric wheel plate, seedling cultivation trays, a watering device, a synchronous belt, a power device and other components. Once the motor is powered on, the power is transferred to the transmission device. The power is then transmitted through the synchronous belt drive to make the central rotary axis rotate, thereby driving the left and right rotary discs of the seedling cultivation rack. As shown in Figure 2, the turntable, sub-turntable, linkage, and spokes constitute a four-bar linkage. Due to the feature that the corresponding linkages in a parallel four-bar mechanism can maintain horizontal motion, it can effectively guarantee that the pallet can always rotate around the central spindle on the turntable in a horizontal posture. The application of a planar four-bar linkage ensures that the seedling tray rotates horizontally around the central axis during rotation, precluding the possibility of the tray overturning. The three-dimensional rotary seedling cultivation rack can fully utilize the spatial resources such as light, water, temperature and oxygen, and can guarantee that the seedlings of multiple layers are cultivated without low-quality seedlings. It significantly shortens the incubation period of seedlings and ensures the quality of the cultivated seedlings. It also offers convenience for workers and reduces the labor intensity, making the seedling cultivation process efficient and safe.



The frontal perspective view of the linkage mechanism The perspective view of the linkage mechanism

1. eccentric flange; 2. connecting rod; 3. left turntable; 4. eccentric plate; 5. main shaft.

Figure 2. Diagram of a linkage mechanism

2.3. Design of Main Components

2.3.1. Spinning Wheel Design

Throughout the operation of the entire apparatus, the turntable acts as the support and movement transmission component for the trays and is a crucial element in stabilizing the trays and guaranteeing smooth movement transmission. The turntable constitutes the main body of the seedling cultivation frame, and the size design of the turntable is directly associated with the size of the entire apparatus.

The seedling cultivation device designed in this paper is of a three-dimensional rotating type. Considering that it needs to leave sufficient space for the water tank and ensure that the size is not overly large, the turntable needs to have an appropriate distance from the ground. In this design, the height of the water tank is 450mm, so the minimum height of the turntable above the ground, h must be higher than 450mm, and the design stipulates that h = 500mm. Simultaneously, assuming that the seedling machine is only arranged in a single layer and not considering the case of multi-layer stacking of the device, the general height of the greenhouse, h_c will not exceed 3.8m. Thus, the maximum value is set at 4m, and the sum of the turntable diameter, D, and the distance from the ground, h must not exceed the height of the greenhouse h_c. After calculation using the formula, a more suitable diameter size is selected as D = 3000mm.

(1) The diameter of the turntable is restricted by both the height of the greenhouse and the ground clearance.

$$h + D \le h_c \tag{1}$$

2.3.2. Design of Nursery Trays

In order to insert as many seedling trays as possible on a single turntable without influencing its seedling efficiency, it is requisite to make appropriate designs for the structure of the turntable, the layout of the tray space, the quantity of arrangements, and the relative positions in the plane. A two-dimensional sketch is drawn for theoretical analysis. The trays revolve around the center point and are uniformly distributed on the turntable. This sketch is utilized to analyze the relative position relationship between tray 2 and tray 1. a and b represent the distances between the centers of tray 2 and tray 1 and the center of the circle, and α and β are the angles between tray 2 and tray 1 and the horizontal direction. As depicted in Figure 3.

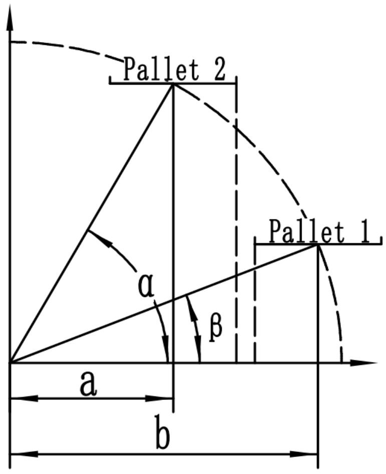


Figure 3. Relative Positioning of Nursery Trays

The designed tray is required to fulfill the condition that there is no hindrance between the trays and the seedlings during the entire rotation process. That is to say, the vertical distance between two trays should be at least greater than the height of the seedlings. The appropriate height for transplanting rice seedlings grown in nurseries is typically 130mm. Hence, this study stipulates that the vertical distance between trays h_v is 150mm.

(2) Constrain the vertical relative position of the two trays to prevent their contact.

(3) Impose constraints on the lateral relative position of pallets to preclude collisions.

$$\frac{D}{2}\sin\alpha - \frac{D}{2}\sin\beta \geq h_v \tag{2}$$

$$\frac{D}{2}\cos\beta - \frac{D}{2}\cos\alpha \geq S \tag{3}$$

The trays in this device are a crucial component for carrying seedlings, and thus they must be designed to be compatible with the various types of trays commonly utilized nowadays. To guarantee compatibility, the dimensions of the trays must be appropriate for the trays. Currently, the most frequently used trays comprise plastic mat-type trays and plastic pot seedling trays. Nevertheless, their typical dimensions in length, width, and height respectively do not exceed 595mm, 280mm, and 25mm. Considering that the trays will absorb water and expand, the length of one tray is set at 600mm, the width at 285mm, and the height at 30mm. To maximize space utilization and ensure the requirements of stable strength, the design incorporates four identical trays to form a complete tray section.

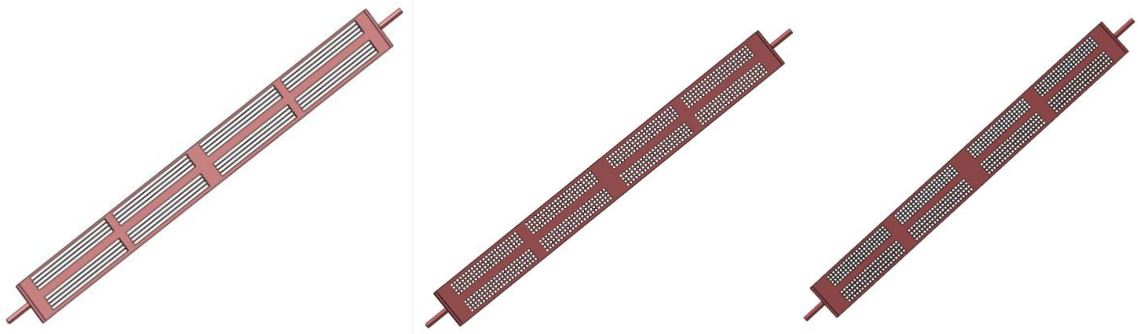
During the seedling cultivation stage, water needs to be constantly provided to the seedlings. If the water fails to circulate in time and accumulates inside the seed tray, it will cause the roots of the seedlings to rot, inflicting significant harm on the seedlings and even leading to their direct death. To address this issue, holes can be made on the seed tray. These holes not only facilitate water drainage but also promote the growth of seedling roots, and they also achieve lightweighting, reducing the usage of materials and the input of costs.

3. Simulation Analysis of Nursery Trays

This section undertakes a simulation analysis on three types of seedling trays independently. Firstly, a finite element model is established via SW. Subsequently, the model is imported into ANSYS for mesh generation. Finally, constraints are added for the solution.

3.1. The establishment of finite element models

To obtain the most appropriate seedling tray structure that complies with the requirements of strength and stiffness, this study devised three types of tray structures, namely, the circular-hole type, the square-hole type, and the groove-hole type. The hole sizes of the various types of trays are identical, and the height of a single hole is 20mm. Among them, the numbers of rows and columns of the circular-hole and square-hole types are the same. The finite element models of the three seedling trays are presented in Figure 4.

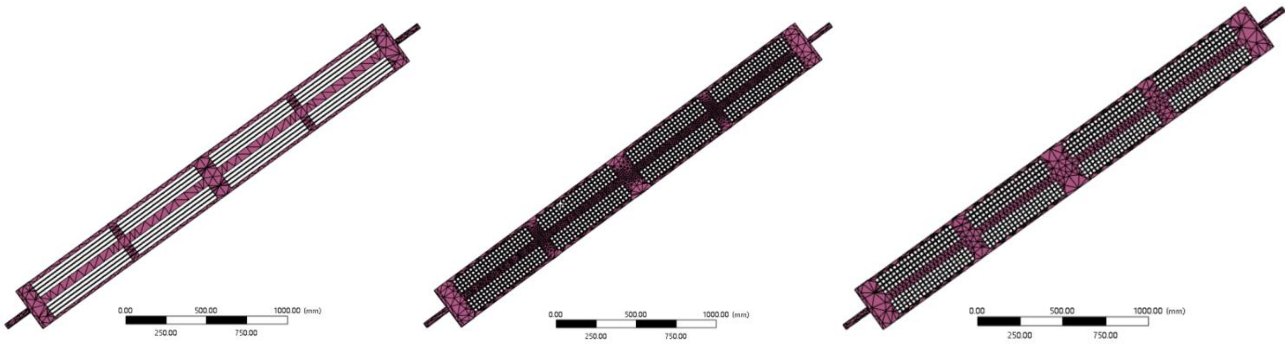


a Trough-type pallet b Round-hole pallet c Square-hole pallet

Figure 4. Three nursery trays

3.2. Discretization of the Grid

By using Solidworks, three-dimensional models of the seedling trays were established. As the circular corners and chamfers in the model have a negligible influence on the stress calculation results, they were disregarded during the modeling process. Subsequently, the model files were converted to the. x_t format and imported into ANSYS. Q235 steel is a commonly employed type of steel with moderate strength, excellent bearing capacity, plasticity, and toughness, and is widely utilized in various fields. Assuming the material is Q235, the elastic modulus is 205 GPa, the Poisson's ratio is 0.3, the shear modulus is 80 GPa, the yield strength is 235 MPa, and the density is 7850 kg/m³; the mesh divisions for the three types of trays are presented in Figure 5.



c Keyway-hole pallet b Round-hole pallet c Square-hole pallet

Figure 5. Pallet grid division

3.3. Boundary conditions

Currently, the commonly used seedling trays have a weight of less than 4kg and a load pressure of less than 250Pa, so these are used as the base data.

The pressure exerted by the seedling tray on the pallet can be expressed by formula (4).

$$P = \frac{F}{A} \tag{4}$$

Employing the data derived from the aforementioned formulas as the constraints in Ansys, we simulate its actual working condition by adding fixed supports at both ends and applying a uniformly downward distributed pressure on the surface. Subsequently, we analyze the stress, strain values, and their distribution.

4. Analysis of Simulation Results

4.1. Verifying Grid Independence

During the process of establishing a finite element model with Ansys, if the size of the mesh becomes smaller and the discretization is more refined, the calculated results will be closer to the true values. Nevertheless, as the number of mesh elements rises, the computational time cost also escalates. When the mesh is divided to a sufficiently fine degree, the calculated results will be more reliable, but the extent of improvement might be very minor. Hence, the number of mesh elements needs to be restricted to guarantee the accuracy of the calculation with the minimum computational effort. Taking the first tray as the research object, the calculated results obtained by dividing the mesh into 10mm, 1mm, and 0.1mm are presented in Table 1.

Table 1. The maximum calculated result divided into a grid with 10mm, 1mm, and 0.1mm resolution

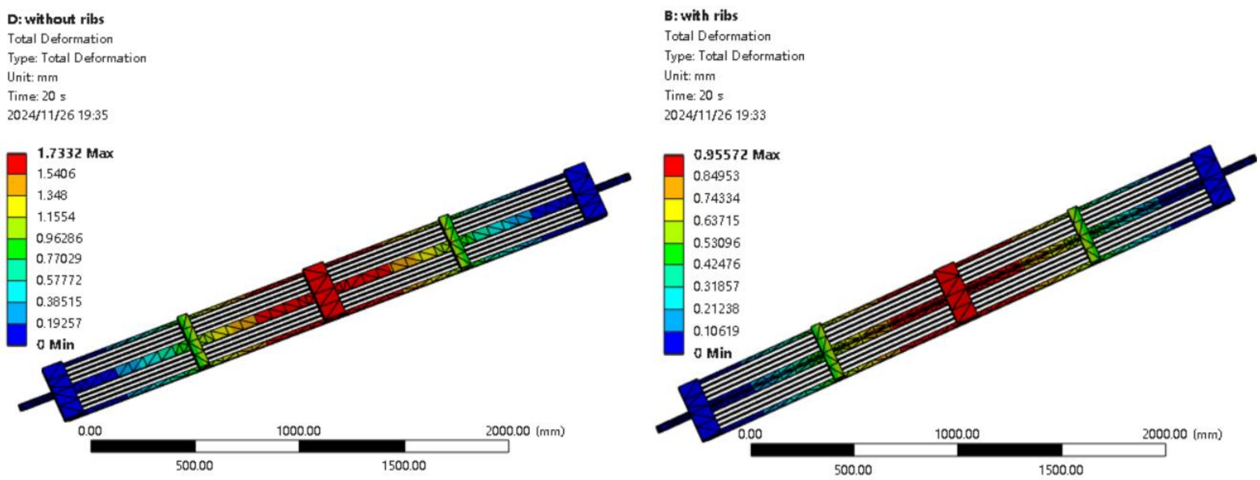
Grid size	10mm	1mm	0.1mm
Equivalent Stress (MPa)	11.389	11.493	11.493
Equivalent Elastic Strain (mm)	5.6994×10^{-5}	5.7531×10^{-5}	5.7531×10^{-5}
Total Deformation (mm)	3.8345	0.95572	0.95572

The experimental outcomes demonstrated that the size of the grid division exerted a negligible influence on the results, and a grid division of 1mm was adequate for the requisite level of precision. Consequently, the subsequent computations were conducted using grid divisions of 1mm.

4.2. Different Pallet Design Solutions and Result Analysis

4.2.1. Analysis of the Conditions with Ribs and without Ribs

Taking the first type of keyway-hole pallet as the research subject, the stress and strain conditions in both the cases with and without ribs were analyzed and compared. The deformation analysis is presented in Figure 6. It can be discerned from the figure that the deformation distribution is more concentrated in the case with ribs, and the major deformation is distributed over the ribs. The surface of the pallet does not undertake the main deformation. The deformation in the case with ribs is improved more favorably than that in the case without ribs.



without ribs　　　　with ribs

Figure 6. The deformation distribution of keyway hole pallets with and without ribs

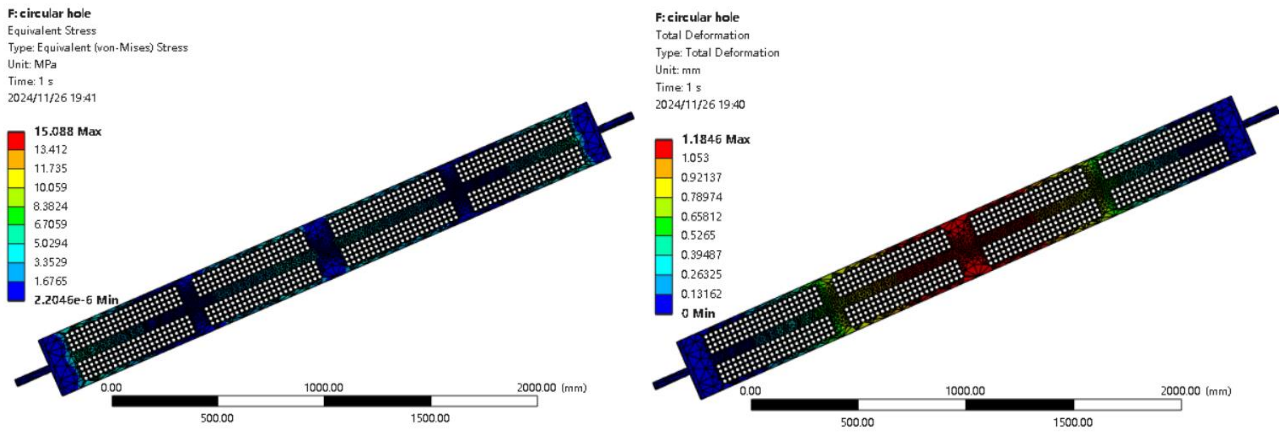
Table 2. Maximum values of the data calculated with and without ribs

	Equivalent Stress (MPa)	Equivalent Elastic Strain (mm)	Total Deformation (mm)
with ribs	11.493	5.7531×10^{-5}	0.95572
without ribs	11.364	5.698×10^{-5}	1.7332

By comparing the stress and strain values of the two cases, with and without ribs, although the difference is minor, the deformation of the case without ribs is nearly twice that of the case with a tray. Through the observation of the pictures, the stress in the case without ribs is more uniformly distributed on the surface of the tray. In the case with ribs, the maximum stress is directly distributed on the ribs, while in the case without ribs, the maximum stress is directly distributed on the tray surface. There is no maximum stress on the surface of the tray, effectively protecting the tray from being affected by the main stress and maintaining its function. Therefore, the carrying capacity of the tray with ribs is superior, with a total deformation of less than 1mm and a stronger bearing capacity.

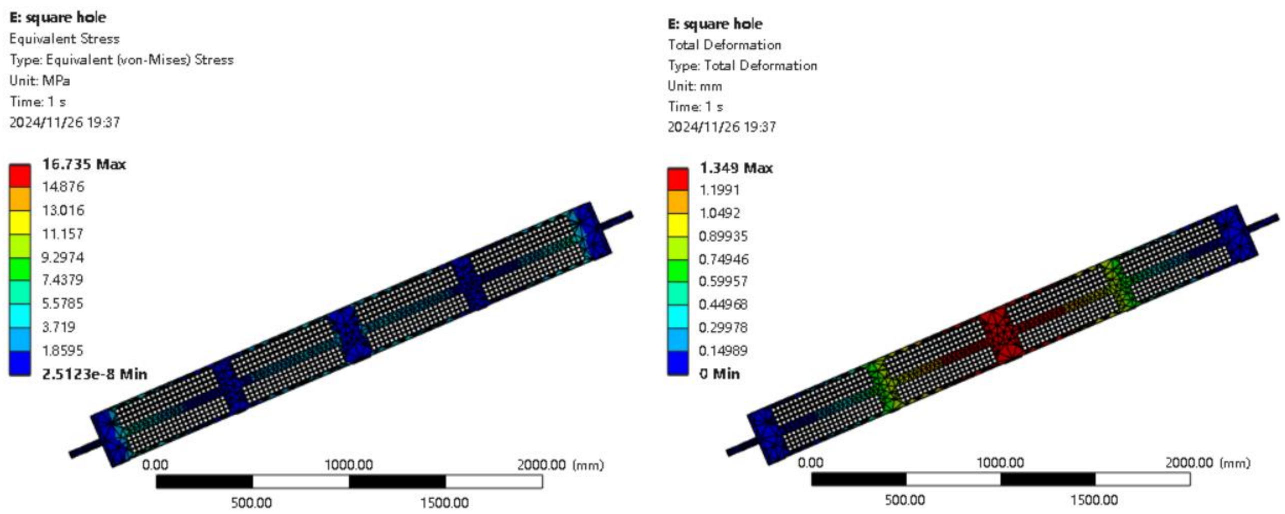
4.2.2. Analysis of Different Hydrophobic Pore Shapes

Load the second and third pallets separately to compute the stress, strain, and deformation values. The results are presented in Figure 7-8. Based on the figures, the deformation and stress distributions of circular hole trays and square hole trays can be acquired. The main deformation of both types of trays is situated in the middle of the model, and the main stress is located on the backside of the model. The detailed solution data are presented in Table 3.



Equivalent Stress Total deformation

Figure 7. Circular Hole Deformation and Equivalent Stress Diagrams



Equivalent Stress Total deformation

Figure 8. Square Hole Deformation and Equivalent Stress Diagrams

Table 3. Comparison of Three Pallets

Indicator name	Keyway Hole	Circular Hole	Square Hole
Equivalent Stress(MPa)	11.493	15.088	16.735
Equivalent Elastic Strain(mm)	5.7531×10^{-5}	7.5604×10^{-5}	8.4199×10^{-5}
Total Deformation(mm)	0.95572	1.1846	1.349

It can be observed from the data in Table 3 that the maximum stress, strain, and deformation of the keyway hole tray are all the lowest, and the keyway hole type also holds an advantage in water repellency in comparison with other types. Hence, the keyway hole is the more preferable structure.

5. Conclusion

This paper proposes a three-dimensional rotary seedling-growing mechanism, which possesses numerous advantages such as high efficiency, full utilization of resources, and reduction of working intensity. The three tray structures proposed for optimizing the device were analyzed through simulation and static mechanics analyses to obtain the most satisfactory tray structure that meets the usage requirements.

(1) The stereoscopic seedling cultivation device proposed in this research significantly enhanced the seedling cultivation efficiency, made full use of the resources in space, and the growth condition of rice seedlings was outstanding. It also decreased the labor intensity of workers and guaranteed safe production.

(2) The main components of the device, namely the trays, were analyzed in detail, and three distinct types of seedling trays were designed. After experimental and simulation analyses, the maximum stress value of the keyway hole tray was 11.493 MPa, and the maximum deformation was 0.95572 mm. All the data were superior to those of the other types and met the strength design requirements. Thus, the keyway hole structure was the optimal one.

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