

# Seedling-growing tray made of rice straw for maize seedling transplantation and its shear mechanics test

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**Abstract:** The plant-made seedling-growing tray cultivation technique is an effective way to improve maize yield and quality in China's cold northern area. However, the corn seedling nursery carrier and tray cultivation technique has been proved poor in adaptability. After comparing several nursery carriers, a design for a plant-made seedling-growing tray that is suitable for maize transplantation was proposed in which rice straw was used as the primary raw material. The preparation method, processing and structural dimensions of the tray were investigated and designed, five types of plant-made seedling-growing trays with different formulations were proposed. The shear mechanical properties and the shear strength of the plant-made seedling-growing trays were tested to determine the shear force needed for cutting through trays prepared with increasing mass ratios of rice straw and the effect of the shearing rate on the shear strength. The results showed that at a shearing rate of 100 mm/min, the maximum shear force decreased gradually as the mass ratio of straw was increased and that the hardness of the tray decreased as its shear strength decreased. Under three shearing rates (100 mm/min, 200 mm/min and 500 mm/min) and a blade displacement of 10 mm, the shear force was the highest at the point at which the tray was cut through; the required shear force to cut through the tray then gradually decreased. Trays with the same straw composition showed no significant influence of shearing rate on the tray's shear strength at shearing rates of 100 mm/min, 200 mm/min or 500 mm/min. This study describes a multi-tray, single-strip nursery carrier for use in plant-made seedling-growing tray cultivation and proposes a theoretical basis for the design of a rotary transplanting device, the key part of a maize plant-made seedling-growing tray transplanter.

**Keywords:** maize seedling transplanting, seedling-nursery tray, preparation, shear force, shear strength, rice straw, mixing ratio  
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## 1 Introduction

With the ever-decreasing amount of arable land per capita, the sustainable growth of food production has become a top priority for China's development<sup>[1]</sup>. In

2012, the corn acreage in China was 35 million hm<sup>2</sup>, and the total corn production was 20.81×10<sup>6</sup> t, which surpassed rice production to become No.1 grain crop in China<sup>[2]</sup>. As a result, the issue of phased and structured oversupply has been proposed. To solve this problem, in 2016, the Ministry of Agriculture implemented a policy that focuses on reducing corn acreage to promote the adjustment of planting structures. To improve the quality and yield of maize in a single cropping system, reduce production costs, improve quality and efficiency and achieve green development, it is necessary to develop suitable technologies and equipment. Pot seedling cultivation and transplanting mechanization are effective means for improving the maize yield in the single cropping system for the current high-yielding situation<sup>[3]</sup>, especially for improving the yield and quality of corn in China's frigid northern regions.

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The origin of the pot seedling cultivation technique dates to the early 20th century in Western countries. Since the beginning of the 1950s, some European countries began to investigate the production techniques of seedling cultivation and transplanting of crop plants using pots made of compressed soil. In the 1980s, pot-making, seedling cultivation and transplanting formed a complete system of mechanized operation that could be extensively applied in the transplanting of crops, such as cereals and vegetables (tomatoes and peppers)<sup>[4,5]</sup>. Currently, Japan is the international leader in pot seedling cultivation technology<sup>[6]</sup>, with the core technology of manufacturing plastic seedling cultivation trays<sup>[7-9]</sup>. Although Japan has achieved a significant yield improvement in rice using the rice seedling tray cultivation technique, the issues of corn seedling cultivation have rarely been addressed. China has conducted numerous studies of corn seedling cultivation and transplanting. In the 1970s, the first 4-row hanging style corn transplanting machine was successfully developed in Beijing<sup>[10]</sup>; however, it did not been placed into production. In the 1990s, to improve the yield and quality of corn, considerable attention was paid to corn seedling cultivation and transplanting. Despite numerous investigations in China, the automatic transplanting machine has not been implemented for practical use because the corn seedling cultivation and transplanting techniques lagged behind other methods, the supporting trays exhibited poor performances, and the requirements of automated transplanting were not satisfied<sup>[11]</sup>.

The study of seedling tray cultivation techniques requires the development of a carrier for seedling cultivation and an understanding of its critical quality characteristics. Since the 1970s, numerous investigators around the world have examined the carriers for seedling tray cultivation. Currently, the carriers used in seedling cultivation mainly include plastic trays, paper trays and nutrient pots.

(1) The plastic seedling trays are often replaced with paper trays in developed countries. Although they have better air permeability and standing properties, paper trays are costly, produce a significant amount of pollution

during upstream pulp production and cannot be processed into a shaped seedling cultivation tray that is suitable for a high-humidity seedling growing environment. Thus, it cannot support the automatic, accurate and orderly feeding of seedlings for transplanting.

(2) The plastic trays are commonly used in China because of their low cost, light weight and superior water retention capability, but they have many disadvantages, such as poor water permeability. Due to the electrostatic interaction of plastic sheets, plastic trays often stick together, and they are too soft to stand up and usually filled with soil, also, they cannot degrade well in soil. Thus, they are not conducive to plant root growth. Plastic tray waste pollutes the soil, while transplanting without the trays tends to damage the root system of plants and affect seedlings' survival rates<sup>[8]</sup>.

(3) Nutrition pots are usually individually filled with one seedling per pot. The seedlings are transplanted to the field, where they do not have a rejuvenation period. In addition, the nutrition pot (block) has a low forming rate. If the pot is too small, the roots of the seedlings will become entangled, whereas the consumption of nutrition soil is significant if the pot is too large, which is difficult for mechanized operations.

The previously described seedling cultivation carriers, which have insurmountable problems, have been primarily employed in the seedling cultivation and transplantation of rice or cash crops but are rarely used for field crops such as corn. In recent years, a number of research institutes and manufacturing enterprises in China developed various seedling cultivation methods, such as soilless seedling cultivation, seedling cultivation on matrix and micro-pot seedling cultivation<sup>[12-15]</sup>, and have made a series of achievements. Wang et al.<sup>[16]</sup> and Zhang et al.<sup>[17]</sup> developed seedling cultivation trays by mixing and compressing crushed crop straws with adhesive and successively, as well as paper-made seedling cultivation carriers while rationally recycling the straws. However, the seedling cultivation carriers were specifically developed for rice, vegetables or cash crops. Paper-made seedling cultivation carriers for corn plant transplanting have been rarely investigated, and their application in a large area has not been reported.

Given the previously mentioned problems in seedling cultivation techniques and the status of studies on the development of the paper-made corn seedling cultivation carrier, this research aimed to develop a multi-pot, single strip paper-made corn seedling cultivation tray, propose viable design ideas and determine the manufacturing method and processing procedure to provide well-performing seedling cultivation carriers for corn. The forming ratio of the tray-making materials, the shear mechanical properties and the changes in the shear strengths of the trays were investigated to provide a theoretical basis for the design of key components of the supporting machine using the corn paper-made seedling cultivation trays. The parameters in farm machinery design, which including estimates that empirically obtained without scientific, rigorous and quantitative analyses<sup>[18]</sup>, were disregarded to resolve the most important issues in the development of a seedling cultivation carrier and the analysis of the key characteristics of the tray in the seedling tray cultivation technique.

## 2 Design of the maize plant-made seedling-growing tray

Previous studies have demonstrated that plant-made seedling-growing trays primarily consisting of crop stalks are breathable and water-permeable, easy for seedling roots to penetrate, conducive to seedling growth and development, can be transplanted together with the seedlings and will degrade naturally after transplanting. After such degradation, the decomposition of the straw used in the construction of the seedling-growing trays was shown to significantly improve the physical and chemical properties of the soil<sup>[19,20]</sup>, which serving as a fertilizer to increase soil organic matter content. In high-humidity environments, plant-based trays also have strong shape retention capability. Therefore, crop stalks are considered the primary composite material for the production of maize plant-made seedling-growing trays. The factors that were taken into account in the design of the plant-made seedling-growing tray, the requirements imposed by each specific factor and the design ideas used in this study are shown in Figure 1.

Crop stalks were used as the main raw material. To this material, strengthening matrix and biological starch

glue were added; the components were mixed thoroughly and molded into a form at room temperature, then sterilized and solidified under dry conditions at high temperature to produce a multi-tray, single-strip seedling nursery carrier that can be separated by cutting when transplanting.

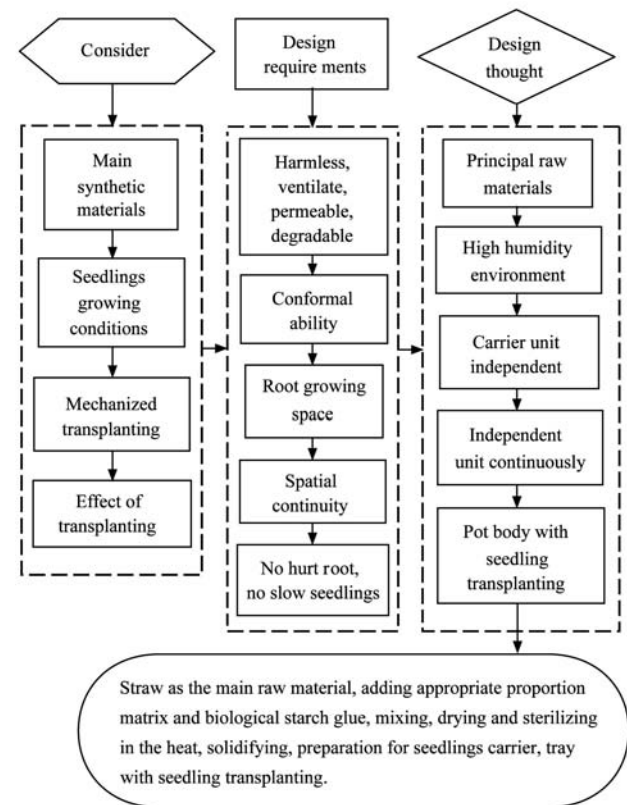


Figure 1 Design ideas for the plant-made seedling-growing tray

## 3 Structural design of the maize plant-made seedling-growing tray

### 3.1 Individual pot on the tray

#### 3.1.1 Volume of the individual pot

Maize is a dry-land crop, to ensure that maize seedlings grow robustly at the nursery stage, the individual pot for single plant in the tray must be large enough. After market research, the most widely used trapezoidal-shaped plastic pots were chosen, as shown in Figure 2. The large-size pot has an upper opening of 45 mm × 45 mm, a bottom area of 23 mm × 23 mm and a height of 48 mm; the small-size pot has an upper opening of 38 mm × 38 mm, a bottom area of 19 mm × 19 mm and a height of 41 mm. Their volumes are 55 cm<sup>3</sup> and 33 cm<sup>3</sup> respectively; thus, the volume of the plant-made individual pots of the seedling-growing tray falls within the range of 33-55 cm<sup>3</sup>.

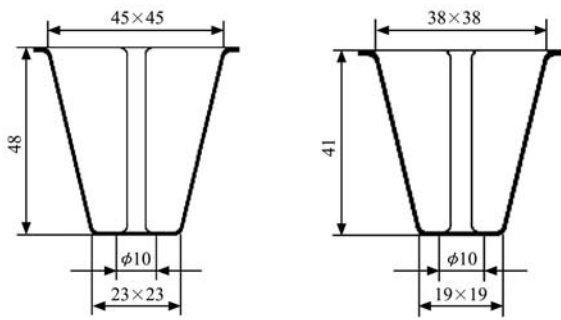


Figure 2 Two different sizes of plastic pots were selected as test objects

### 3.1.2 Depth of the pot

According to the agronomic requirements of maize seedling cultivation, a layer of subsoil 4-5 mm thick is placed in the bottom of the pot; the seeds are then sown using supporting devices and precision maize-sowing technology. One seed is sown in each pot and is covered with soil to a depth of 20-40 mm so that a germination rate of nearly 100% is assured. Therefore, the depth of the pot should be no less than 25 mm. Preliminary experiments verified that with increasing pot height, the molding rate decreased and that when the height of the maize plant-made seedling-growing tray reached 35 mm, the molding rate of pots with different compositions was consistent. However, when the pot height reached 40 mm, the molding rate of the pots was unstable and followed a significant downward trend. Therefore, the height of the plant-made seedling-growing tray was set at 35 mm. The pot depth is the pot height after subtraction of the thickness of the pot bottom.

### 3.1.3 Section of single plant pot in the seedling-growing tray

To reduce production cost and achieve mass production of the pots, molding of the pots was performed by exerting pressure on raw materials of different compositions using a mold mounted on a press at room temperature so that separation and plastic deformation were attained. Ultimately, a pressure processing method was established for the production of the desired pot. From the perspective of mold press processing in general, when round, square, or rectangular holes are produced, the overall dimension is kept constant and the side wall of the pot is maintained at the same thickness; the volume of square holes is thus greater, providing a larger growth space for the maize seedling. Therefore, a square hole

was chosen as the cross-section of each single plant pot.

### 3.2 Thickness of the pot bottom

When corn seedlings reach the 3-leaf stage, the nutrients stored in the seed are exhausted; at this point, the seedling has reached the first turning point in its life cycle and turns from autotrophy to heterotrophy. From the 3-leaf stage to the jointing stage, maize plants undergo growth of roots and leaves and differentiation of stem nodes. To ensure that the plant was exposed to favorable conditions during the transition from autotrophy to heterotrophy and that there was no restriction of root growth, it was decided that in the plant-made pot cultivation technique, the corn seedlings would be transplanted at the growth stage of three leaves and one shoot. At the same time, it was required that the root systems of seedlings with 4-5 leaves are able to penetrate the pot bottom so that after the seedlings were transplanted to the field together with the pots, the growth of their root systems would not be impeded. The growth of a potted maize plant at the stage of 4-5 leaves and one shoot is shown in Figure 3. It was confirmed through experimental observation that the intactness rate of pots with a thickness of 3.5 mm after the pot nursery stage was ideal, that the strength of the tray met the requirements for transportation and mechanized transplanting and that the roots could penetrate the pot bottom and grow normally. Based on these requirements, the thickness of the pot bottom was set at 3.5 mm, and the pot depth was set at 31.5 mm.



Figure 3 Root system of maize seedlings grown to 4 or 5 leaves per core penetrating the plant-made seedling-growing tray

### 3.3 Thickness of side wall and separation wall of the pot

During the seedling period, the effect of maize seedling root growth on the pot bottom was more

significant than its effect on the pot side walls and separation wall. When the pot bottom was set at 3.5 mm, the pot was able to meet the requirements for pot tray formation and seedling cultivation; therefore, the thicknesses of the side wall and the separation wall of the pot were also set at 3.5 mm, which also served well for the desired seedling strength.

### 3.4 Longitudinal and lateral dimensions of the pot tray

#### 3.4.1 Longitudinal dimension of the pot tray

The longitudinal dimension of the pot tray represents the width of a single strip of pots. Based on the sizes of many commercially available plastic nursery pots and on advice from agriculture experts, the longitudinal dimension of the pot tray was set at 42 mm.

#### 3.4.2 Lateral dimension of the pot tray

At present, rice seedling pot cultivation techniques are the most highly developed, and the supporting transplanting equipment is also the most advanced. Therefore, in developing the maize plant-made seedling-growing tray, the advanced structures of the rice transplanter were borrowed to develop a supporting automated transplanter for use with the maize plant-made seedling-growing tray. The maximum lateral dimension of the seedling box of the most widely used commercially available rice transplanter is 285 mm<sup>[21]</sup>; ignoring the processing error and the slight error caused by deformation during use and taking into account only the expansion deformation that occurs in the hot and humid environment of a plastic greenhouse nursery, the maximum lateral dimension for pot tray transplantation, i.e., the length of a single strip of the pot tray, is given by the following formula:

$$B_H \leq \frac{285}{1 + \delta} \quad (1)$$

where,  $B_H$  is the length of a single strip of the pot tray, i.e., the maximum lateral dimension, mm;  $\delta$  is the largest longitudinal expansion rate of a single strip of the pot tray, %.

Given that the maximum length of a single strip of the pot tray should not exceed 285 mm and the volume range of the individual pots, which was previously determined, six pots were continuously assigned to a single strip of the pot tray. The dimensions of the tray and the

conveying device are shown in Figure 4.



Figure 4 Dimensional coordination of the plant-made seedling-growing tray conveying appliance

Through tests and calculations, when the length of a single strip of the pot tray was 276.5 mm, the maximum longitudinal expansion rate of the tray was 3.07%; by integrating this value into the above formula, it can be found that the calculated value (276.5) is not more than 276.511. Therefore, the maximum lateral dimension of the tray was set at 276.5 mm.

### 2.5 Dimensions of a single pot within the tray

The pot tray width was 42 mm, and the thickness of its side wall was 3.5 mm, yielding a longitudinal side length of 35 mm for the single pot tray. Let the lateral side length of the single pot tray be  $L_{DH}$ , then, the formula for its calculation is as following:

$$L_{DH} = \frac{B_H - 7 \times 3.5}{6} \quad (2)$$

where,  $B_H$  is the length of a single strip of the pot tray, i.e., the maximum lateral dimension of the tray, mm; digit 7 represents the number of separation walls between the pots; digit 6 represents the number of pots; and digit 3.5 represents the thickness of the separation wall.

The volume of the single plant pot was finalized at  $35 \times 42 \times 31.5 = 46.305 \text{ cm}^3$ , the median of the volume range of the single plant pot that was initially designed; thus, this volume was reasonable. The dimensions of the maize plant-made seedling-growing tray designed in this study are shown in Figure 5.

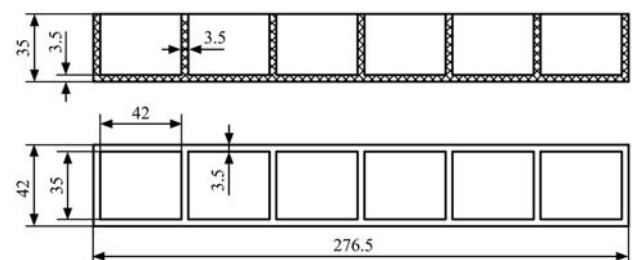


Figure 5 Overall dimensions of the seedling-growing tray

## 4 Pot tray manufacturing materials and methods

### 4.1 Pot tray raw materials

(1) Rice straw: rice straw was air-dried, maintaining its moisture content at approximately 15% (a moisture content of 14%-16% measured using the oven-drying method was appropriate). The dried straw was cut into small pieces with 100-150 mm in length<sup>[22]</sup> and milled into straw powder with the longest straw length between 5- 10 mm.

(2) Soil for the pot tray: the soil was composed of matrixes A and B at a fixed ratio; matrix A was mainly SiO<sub>2</sub>, the main components of matrix B were S and Ca, which were similar with phosphogypsum.

(3) Adhesive (biological starch glue) was provided by the Plant-made Pot Seedling Cultivation Technology Research Group of Heilongjiang Bayi Agricultural University.

(4) Water: an appropriate amount of water was used.

### 4.2 Main equipment

The main equipment and devices used in the preparation and testing of the pots are as follows:

(1) Pot tray forming machine: manufactured by Xiangyang Machinery Plant, Taizhou, Zhejiang, China (Model YJ-1000, nominal pressure 1000 kN, working stroke 300 mm).

(2) Pot tray forming mold: the mold that produced multiple pots in the single strip plant-made tray was self-designed and worked together with the pot tray forming machine. The mold was 3-D designed using UG software. In this process, the interference between the components was determined using motion simulation and the structural dimensions of the pot tray were optimized using finite element analysis. The strength and deformation of the material frame and the mold stripper were measured at 10 times the maximum load pressure. The simulation results showed that the strengths of the material block and stripper plate met the requirements and that the maximum variation in pot tray wall thickness caused by small deformations of the material box and stripper did not exceed 1.96%, ensuring

that the designed mold could effectively produce multiple pots and single strip plant-made seedling-growing trays with the desired shape and structural dimensions. The 3-D model and the 3-D simulation of the core parts of the mold are shown in Figure 6 and Figure 7, respectively.

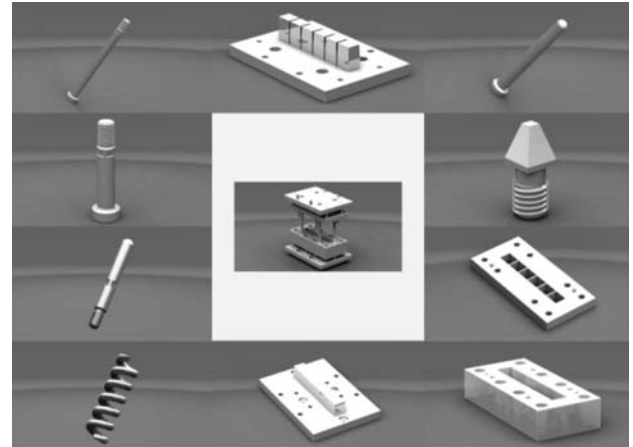


Figure 6 Three-dimensional model of the plant-made seedling-growing tray mold

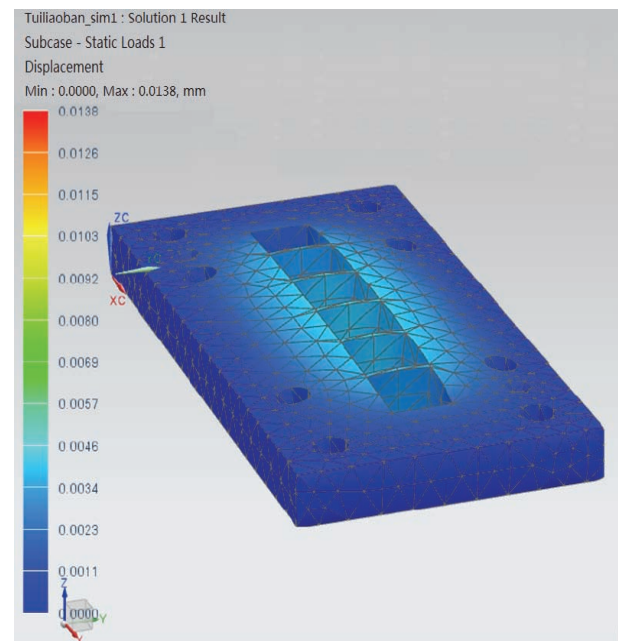


Figure 7 Simulation of the core part of the plant-made seedling-growing tray mold

(3) Self-designed sterilization, drying and solidifying devices: the highest steam temperature was 120°C.

(4) Microcomputer (Model WDW-1) controlled multi-purpose electronic testing machine: equipped with a measurement and control system (WinWdw1.6) for data acquisition and analysis.

(5) Hammer mill, mixers and other equipment

### 4.3 Preparation method

The self-developed single strip plant-made maize pot

tray forming mold was mounted to the press; the raw materials for the pot tray were thoroughly mixed using the mixer, weighed and introduced into the mold box formed by the molding press. This method was used to produce five types of maize plant-made pot trays with straw compositions of 6%, 10%, 15%, 20% and 25% under a forming pressure of 20 MPa. After sterilization, drying and solidifying, the pot trays were tested in corn seedling cultivation. Seedlings with three leaves and one shoot were used as the test material for the shear test. The process flow of manufacturing the plant-made seedling-growing tray is shown in Figure 8. The raw material mixing and the pot tray manufacturing process are shown in Figures 9a and 9b.

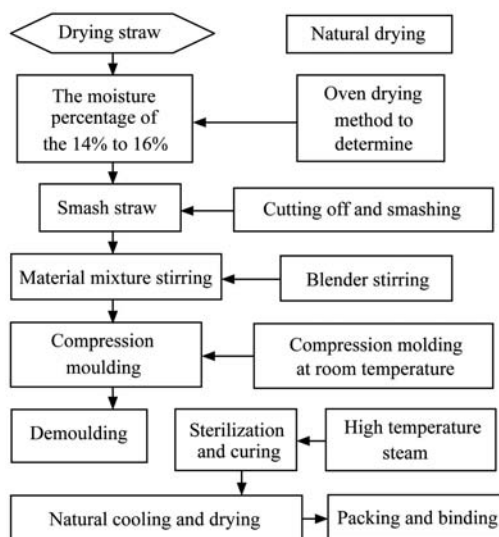


Figure 8 Preparation processing of the seedling-growing tray



a. Mixing the materials for the seedling-growing tray

b. The seedling-growing tray after molding, drying and solidifying

Figure 9 Material mixing and the final plant-made seedling-growing tray

#### 4.3.1 Determination of the amount of adhesive to be used in construction of the pot tray

Without addition of the self-developed starch glue in the molding process of the plant-made seedling-growing tray, the press molding rate of the pots was 95.1%; however, the pot trays thus produced were prone to cracking and fracturing. This occurred in approximately

30% of the pot trays (fracturing accounted for 10.5%, and cracking accounted for approximately 30%); the actual value was 25.6% after the trays were exposed to the warm and humid environment required for seedling cultivation. After adding the biological glue, fracturing and cracking were effectively eliminated; when the mass ratio of the biological glue to the pot tray raw materials was gradually increased from 0.01% to 0.04%, the press molding rate of the pots reached over 95.6%. The pot trays containing 0.04% starch glue had a fracturing rate of 0.73% after drying and solidifying, and the intactness rate of these pot trays after seedling cultivation was greater than 95%. Therefore, the concentration of the starch glue was set at 0.04%.

#### 4.3.2 Determination of the molding pressure to be used in construction of the pot tray

The molding pressure used to prepare the pot tray was determined by measuring the specific tensile strength, i.e., the ratio of tensile strength to density. This parameter was measured as follows: a 40 mm sample was collected from the side wall of an individual pot of the plant-made seedling-growing tray; the sample width was the 40 mm side wall width, and the thickness of the sample was determined by averaging the thicknesses at three spots on the pot tray. The tensile strength test was performed on a microcomputer-controlled multi-purpose electronic testing machine at a tensile rate of 5 mm/min.

The formula for calculating the tensile strength of the maize plant-made seedling-growing tray is as following:

$$\sigma_B = \frac{P_{Y_{\max}}}{B_Y H_Y} \quad (3)$$

where,  $\sigma_B$  is the tensile strength, MPa;  $P_{Y_{\max}}$  is the maximum load value at the destruction of the sample, N;  $B_Y$  is the sample width, mm;  $H_Y$  is the sample thickness, mm.

The specific tensile strength of the maize plant-made seedling-growing tray increased with increasing pressure. When the pressure reached 10 MPa, the specific tensile strength of the tray began to stabilize and then slightly decreased, primarily because the bonding between the rice straw fibers and between the fibers and the pot matrix was strengthened by the increasing pressure. In this way, the structure of the formed pot tray was tightened, and its

strength increased accordingly. When the pressure reached 20 MPa, the bonding between the particles of the pot tray-forming raw materials was very tight, and they could be even further compressed by the increasing pressure, leading to a rather stable specific tensile strength. Therefore, the molding pressure of the maize plant-made seedling-growing tray was set at 20 MPa in this study.

The strength properties of pot trays molded under a molding pressure of 20 MPa were tested in the seedling cultivation experiment. The results showed that in the humid environment of the plastic greenhouse, the strength properties of the pot trays containing the growing seedlings were excellent, yielding an intactness rate of greater than 95%, as shown in Figure 10.

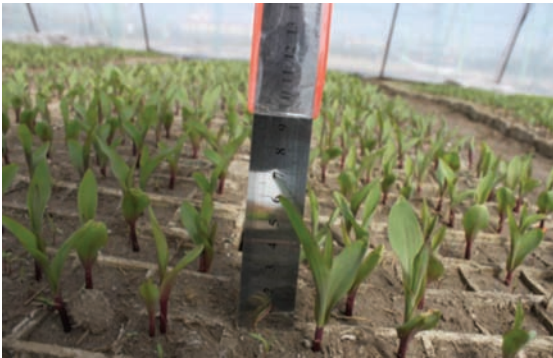


Figure 10 Seedling-growing trays in use

## 5 Analysis of shear mechanical properties of the pot tray

### 5.1 Test method

When 95% of the seedlings cultivated in the plant-made pot trays had put forth three leaves and one shoot, watering of the plants was suspended for 2 d, and the pot trays were tested. In the test, the trays were treated as an idealized model with continuity, uniformity and isotropy, and the property changes caused by non-uniform mixing of the raw materials, uneven addition of the filling materials, uneven distribution of pressing pressure, etc. were ignored. For testing, the pot tray was placed on a self-developed shearing platform, and the cutter plane was kept perpendicular to the pot tray to be tested; in each test, one pot tray was projected forward horizontally without support from beneath, and the cutters on the two sides were aligned to the side walls of the pot tray in the longitudinal direction and pressed against the separation wall of the two sides of the pot tray. At the

beginning of testing, seedlings in five types of plant-made seedling-growing trays with rice straw percentages of 6%, 10%, 15%, 20% and 25% were placed on the platform as described above and aligned with the cutters. After setting the cutting rate, load was applied at a uniform rate to generate a force-displacement curve. Each test was repeated three times, and the average value was calculated. The results of cutting testing of the pot trays are shown in Figure 11.



Figure 11 Performing the cutting seedling-growing tray experiments

### 5.2 Test results and analysis

#### 5.2.1 Changes in the force-displacement curve of the pot tray under the same loading rate

At a cutting rate of 100 mm/min, the shear performances of the five types of pot trays with different mass ratios of straw were measured. The force-displacement curves obtained from these experiments are shown in Figure 12.

Figure 12 shows that the starting point of the curve is not zero; this is because the initial force was set at 0.02 kN. The test data were recorded only after the cutters made contact with the pot tray and the shear force reached 0.02 kN; this ensured that prior to the test, the adjustment of the vertical distance between the cutters and the pot tray did not affect the test. From the starting point, the load on the pot tray was then increased rapidly to 0.086-0.087 kN. This resulted in only a small plastic deformation because when the shear force began, the pot tray was first compressed by the shear force; then, under the action of the force in the range of 0.086-0.087 kN, the cutters further compressed the pot tray while the shear force remained unchanged and the pot tray entered the stage of plastic deformation. When the displacement reached approximately 4 mm, the load increased rapidly because the pot tray then broke due to squeezing by the



cone-shaped cutting region of the cutters, which tore off the pot tray; the shear force then destroyed the binding forces among the raw materials of the pot tray, and the two sides of the blade of the cutter started to generate friction at the cut region of the pot tray. As the depth of cutting increased, the friction also increased; thus, the shear force produced by the shear increased gradually. The shear force reached its maximum value at the peak of the curve when the pot tray was cut through, the shearing process was completed, and the system began to unload.

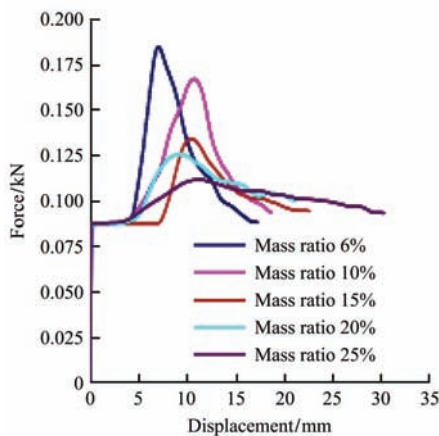


Figure 12 Force-displacement curves of plant-made seedling-growing trays with different straw content at a cutting rate of 100 mm/min

At a cutting speed of 100 mm/min, with the increase in the mass ratio of rice straw in the pot tray, the maximum shear force required for cutting through the pot tray gradually decreased, and the hardness of the pot tray became increasingly small, as did the anti-shearing strength. Based on the analysis, the regression model for the maximum shear force variation was  $Y = -0.188X + 0.2017$ . The maximum shear force curves of the five types of pot trays with different mass ratios of rice straw are shown in Figure 13.

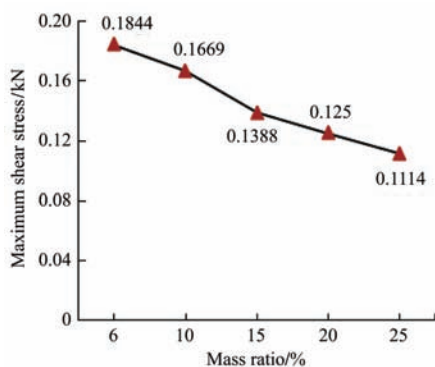


Figure 13 Maximum shear force change curves of five types of plant-made seedling-growing trays at a cutting rate of 100 mm/min

### 5.2.2 Changes in shear strength of the pot trays under the same loading rate

The shearing properties of the pot trays produced using five different mass ratios of rice straw were tested at a cutting rate of 100 mm/min. The resulting shear strength curves are shown in Figure 14.

Figure 14 shows that with an increasing mass ratio of straw, the overall shear strength followed a declining trend. However, when the mass ratio was increased from 15% to 20%, the shear strength gradually increased, indicating that an increase in the straw mass ratio over this range contributed to the hardness of the pot tray. Considering the straw-decomposing capability permitted by the climate and soil conditions, straw mass ratios in this range were ideal for the hardness and shear strength of the pot tray.

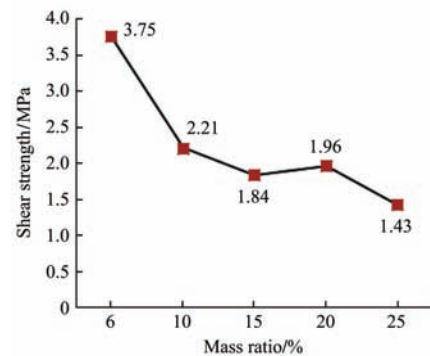


Figure 14 Shear strength change curves of five types of plant-made seedling-growing trays at a cutting rate of 100 mm/min

### 5.2.3 Changes in force-displacement curves of pot trays with the same rice straw mass ratio under the same loading rate

The shearing properties of pot trays with the same rice straw mass ratios were measured at cutting speeds of 100 mm/min, 200 mm/min and 500 mm/min. The force-displacement curves obtained in these experiments are shown in Figure 15.

At all three cutting rates, when the shear displacement was approximately 5 mm, the pot tray entered the stage of plastic deformation, and the shear force increased rapidly; when the displacement reached approximately 10 mm (in the range of 8-12 mm), the shear force on the pot tray was maximal. After the pot tray was substantially cut through, the required shear force gradually decreased. However, after the pot tray with a straw mass ratio of 25% achieved the maximum shear force, the shear force

required for the cutting process did not show a significant decreasing trend relative to the maximum shear force value because with the increase in the straw mass ratio, the longer straws could not be cut through

instantaneously and were pushed downward by the cutters, generating the stacking of a small amount of straw and leading to an insignificantly decreasing trend in the shear strength.

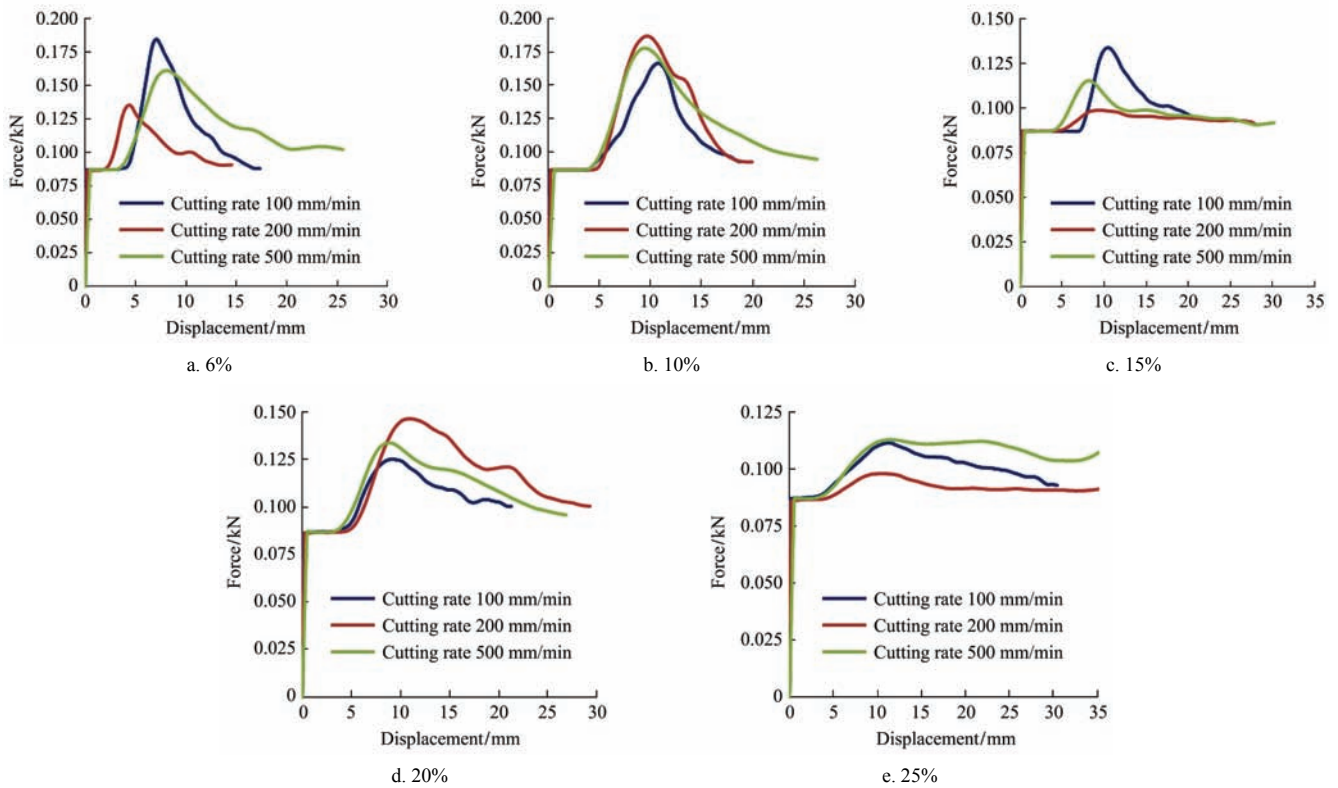


Figure 15 Force-displacement curves of plant-made seedling-growing trays with different straw content at three cutting rates

#### 5.2.4 Effect of loading rate on the shear strength of the pot tray

At cutting speeds of 100 mm/min, 200 mm/min and 500 mm/min, shearing tests were performed on pot trays with five different straw mass ratios. The tests were repeated three times; the shear strengths of the pot trays with different straw mass ratios under different loading rates are shown in Table 1.

Linear regression analysis of the shear strengths of pot trays with the same rice straw mass ratio under different cutting rates was conducted using SPSS software. The results showed that the statistical significance of the loading rate ( $x_1$ ) was 0.793, i.e., the effect of the loading rate on the shear strength of the pot tray was not significant ( $p > 0.05$ ). This provides a theoretical basis for the selection of the rotation velocity parameters of the rotors used in the actual transplant operations, i.e., when determining the movement speed of the rotor, the effect of the cutting rate on the shear strength of the pot tray can be ignored.

**Table 1 Average shear strength of plant-made seedling-growing trays with different straw contents at three cutting rates**

| Speed/mm·min <sup>-1</sup> | Straw/% |      |      |      |      |
|----------------------------|---------|------|------|------|------|
|                            | 6       | 10   | 15   | 20   | 25   |
| 100                        | 3.75    | 2.21 | 1.84 | 1.96 | 1.43 |
| 200                        | 4.45    | 2.75 | 1.56 | 1.90 | 1.40 |
| 500                        | 2.80    | 2.74 | 2.02 | 2.16 | 1.44 |
| Average value              | 3.67    | 2.57 | 1.81 | 2.01 | 1.42 |

**Table 2 Linear regression coefficients (a)**

| Model      | Nonstandard coefficients |            | Standardized coefficients | <i>t</i> | Sig.  |
|------------|--------------------------|------------|---------------------------|----------|-------|
|            | B                        | Std. error |                           |          |       |
| 1 Constant | 3.209                    | 0.340      |                           | 9.429    | 0     |
| $x_1$      | 0.034                    | 0.128      | 0.043                     | 0.268    | 0.793 |
| $x_2$      | -0.373                   | 0.073      | -0.830                    | -5.121   | 0     |

## 6 Conclusions

1) In this paper, the design principles, method of preparation and manufacturing process for a seedling cultivation carrier that is suitable for use with the maize plant-made pot tray seedling cultivation technique are presented, and the structural dimensions of the pot tray

are determined. The volume of the individual pot was set at 46.305 cm<sup>3</sup>; the pot height was set at 35 mm; the thicknesses of the pot bottom, its side wall and the separation wall were all 3.5 mm; the longitudinal and lateral dimensions of the pot tray were 42 mm and 276.5 mm, respectively; the overall dimensions (length × width × height) were 276.5 mm × 42 mm × 35 mm. Maize plant-made pot trays of five different compositions, i.e., 6%, 10%, 15%, 20% and 25% rice straw, were prepared to provide a seedling cultivation carrier that is well suited for use in the maize seedling pot cultivation technique.

2) The shear force properties and shear strengths of the plant-made pot trays were tested. The results showed that during the shearing process at a loading rate of 100 mm/min, the required maximum shear force required to cut through the pot tray followed a gradual declining trend as the rice straw mass ratio increased. The regression model of the maximum shear force variation curve was  $Y=-0.188X+0.2017$ . During shearing at loading rates of 100 mm/min, 200 mm/min and 500 mm/min, the statistical significance of the loading rate ( $x_1$ ) of the pot tray with the same straw mass ratio was 0.793 ( $p>0.05$ ), i.e., the effect of the loading rate on the shear strength of the pot tray was not significant. This provides a theoretical basis for the design of the rotation velocity parameters of the rotors that will be used in the actual transplant operations.

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