EXPERIMENTAL STUDY ON CUTTING CHARACTERISTICS OF CORN SEEDLING SEPARATOR WITH PAPER POT

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玉米纸钵盘分苗机构切割特性试验研究

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ABSTRACT

Seedling picking is important in corn transplantation and can directly influence the efficiency of transplanters. To avoid high injury rate caused by the seedling picking system to separate seedlings and the pot, a pot separator that can cooperate with tube transplanters was designed. First, design requirements of the pot separator were proposed according to corn transplantation demands and the characteristics of the paper pot. Second, based on the transplantation technology of paper potted cultivation, 35-day potted corn seedlings were chosen as test materials. Finally, the cutting characteristics of the paper pot were experimentally studied using a home-made cutting device and a microcomputer control electronic universal testing machine. Results showed that soil with 60%–67% soil moisture content is more suitable for potted corn seedlings. Single paper pot cutting in the shearing mode had the highest integrity and the damage rate was lower than 5%. The conditions to obtain the minimum cutting force of the paper pot were: 63%–67% soil moisture content, 500 mm/min cutting speed, and 30° cutting angle. The cutting force decreased with the increase of soil moisture content, and the maximum cutting force decreased with the increase of cutting speed. Research results provide reference for future optimization of the pot separator and are significant for promoting the development of fully automated corn transplanters.

摘要

取苗是玉米移栽过程中的重要工序，直接影响移栽机的工作效率。为了避免取苗机构将秧苗和钵盘分离导致伤苗率高等问题，设计了一款可与导管式移栽机配合使用的分钵机构。首先，根据玉米移栽农业要求和纸钵盘特点，提出分钵机构的设计要求。其次，基于纸质钵育移栽技术，培育苗龄 35 天左右的玉米钵苗为试验材料。最后，利用自制的切割装置和微机控制电子万能试验机等设备对纸钵盘切断特性进行了试验研究。结果表明：含水率在 60%-67%之间的育秧土更适宜培育玉米移栽钵苗；剪切方式切割玉米纸钵盘后的单钵完整度高，破损率低于 5%；玉米纸钵苗切断力最小的条件：含水率为 63%—67%，切割速度为 500mm/min，切割角度为 30°；切割力随着含水率的升高而减小，切割力最大值随着切割速度的增大而减小。研究结果为以后分钵机构的优化提供了参考，对推进全自动玉米移栽机的发展具有重要意义。

INTRODUCTION

Corn is not only considered a main grain crop but also an important raw material for chemistry, fuel, and other industries. Compared with direct sowing, transplantation increases accumulated temperature that can accelerate the sowing time, prolong the growth period of crops, and increase corn yield and quality (*Xiang W, et al., 2015; Lu Y T, et al., 2011*). Most corn transplanters are semiautomatic (*Cui W, et al., 2015; Yu X X, et al., 2014; Xu B X, et al., 2015*) and require manual cultivation of seedlings, which is labor intensive and has low efficiency. The existing fully automated transplanters (*Shi T, 2015*) have complicated structures and are expensive, which prevents the large-scaled promotion and application of mechanized transplantation.

Seedling picking mechanism is an important component of fully automated transplanters and distinguishes the fully automated transplanters from the semi-automatic ones. Fully automated transplanters mainly have the pick-up and push-out types. In foreign countries, Kumar designed a double row vegetable transplanter for paper pots, which was highly customizable and had an 81% working efficiency (*Kumar G, et al., 2011*). Tian S B designed a fully automated transplanter for vegetables and flowers based on the PLC system (*Tian S B, et al., 2010*). Some studies have studied the law of motion of planetary gear trains in the seedling separator and navigation control algorithm of the transplanting robot.

They found that the structure was relatively complicated (*JOVAN D, et al., 2011; Tong-jie Li, et al., 2012; Zhou Z Y, et al., 2014; Li S, et al., 2014; Zheng F Y, et al., 2016*). Mao Hanping et al. designed a seedling picking mechanism, but the mechanism failed to integrate the mechanical structures of the pot (*Mao H P, et al., 2011*). In China, Yu Gaohong (*YU G H, et al., 2011*) designed an incomplete intermittent driving planetary gear system with a non-circular gear, which realized the non-uniform velocity rotation of the planet gear relative to the planet carrier. Li Hua (*Zhang L, et al., 2014*) developed an automatic control system for a clamp plug-seedling picking mechanism by a single chip. Zhang Min (*Zhang M, et al., 2014*) simplified the overall structure, and designed a crank sliding push-out device with a connecting rod without a seedling delivery system. Liu Weixiang (*Liu W X, et al., 2016*) et al. designed a push-out and pick-up automatic seedling picking system, which resulted in a seedling picking rate of 98.44% and a matrix loss ratio of 36.67 %. Yan Xiaoyue et al. developed a row seedling picking transplanter based on cucumber seedlings (*Yan X Y, et al., 2013*), which increased the automation and efficiency of the transplanter. Liao Qingxi et al. designed a potted seedling separator with a conveyer belt for grape seed oil (*Liao Q X, et al., 2015*) and conducted a pot integrity test under different extrusion modes; seedling separation efficiency was at 90%. Yu Lei et al. designed a double row fully automated corn transplanter with a paper pot (*YU L, et al., 2015*), which had a planting missing rate of less than 3%. However, this transplanter had high standardization requirements on the seedling container. All of these machines have to pick up seedlings from the pot and the seedling separator has to contact with the matrix, which can damage the matrix and the seedling root system to different extents.

To avoid damages to pot and seedlings caused by the machine, a pot separator that directly cuts pots was designed. The cutting characteristics of the paper pot separator were studied using the mechanical engineering research method. Research results provided references for the succeeding optimization design of the seedling separator.

MATERIAL AND METHOD

Overall design of the seedling separator

The seedling separator could transplant potted corn seedlings without separating the pot and seedling, which increases efficiency and ensures the high survival rate of seedlings. According to the service conditions and agricultural requirements, the following technological requirements were proposed to the seedling separator:

(1) Replace manual seedling separation to reduce labour intensity and increase production efficiency.

(2) Meet the requirements of corn transplantation by cutting a single row of paper potted seedlings into single potted seedlings and orderly delivering it to the seedling guide tube.

(3) Avoid the seedling pot separator and protect the corn root system to increase the survival rate of transplanted corn seedlings.

To accomplish pot separation and deliver single pots to the seedling guide tube orderly, the overall design of the seedling separator was proposed according to these technological requirements. The seedling separator consists of a cutter, a transporter, and a rack (Figure 1). The cutter is the main part of the seedling separator and the object of this study.

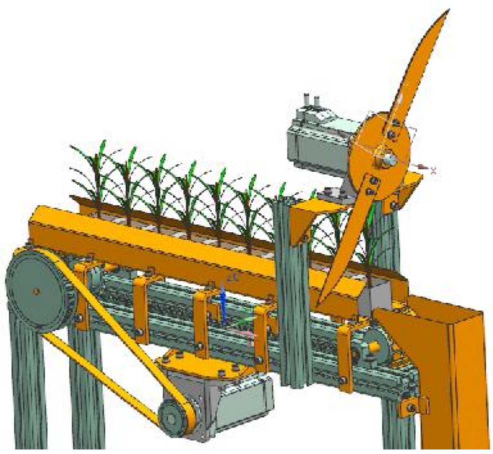


Fig. 1 - Three-dimensional assembly map of the seedling separator

The disc cutter cuts the paper pots at a uniform rotation speed. The conveying chain makes intermittent movements. It stops moving when cutting paper pots and delivers cut paper pots to the seedling guide tube. The disc cutter is above the transporter end and consists of a disc cutterhead and two symmetric cutting edges. The cutting edges are connected to the cutterhead by bolts. During the cutting rotation, each cutting edge passes through the space between the conveyer belt end and the inclined gusset plate.

Finite element analysis on the cutting edge

The finite element analysis on the cutting edge was performed by UG. The cutting edge was made of 65 MN steel, and the applied force was 100 N. Deformation and deformation displacement of the cutting edge are shown in Figure 2. The deformation was recorded at <0.099 mm, which is small and negligible. This datum provides the reference for the next experimental verification.

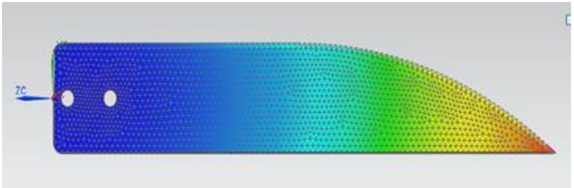


Fig. 2 - Finite element analysis of the cutting edge

Test materials

The square paper pots used in the experiment were designed by the Heilongjiang Bayi Agricultural University. They are made by the compaction of paper and thin film with 10 connected pots in one row (Figure 3). Paper pots ensure material biodegradability, low injury rate to seedlings, and high survival rate of transplanted seedlings. Compared with plant pots, paper pots are easier to cut and consume less dynamics. Square pots have smaller intervals than columnar ones, which is beneficial for the root growth of seedlings because of the uniformity in water distribution and their larger matrix capacity.

Fig. 3 - Paper pot

Fig. 4 - Paper potted seedlings

Paper pots are degradable and have excellent strength. Pot sizes are listed in Table 1. In this experiment, about 35-day paper potted seedlings were chosen as test materials (Figure 4).

Table 1

Size parameters of corn paper pots

Name	Numerical value
Overall size (Length*Width*Height) [mm]	500*38*38
Single pot Size(Length*Width*Height) [mm]	45*38*38
Holes	10
Rows	1
Cutting wall thickness [mm]	5

Experimental equipment

Soil moisture content was tested by a drying oven and a balance. The paper pot cutting test was done using the universal testing machine and the home-made cutting device. Consistent initial cutting position was maintained under the assistance of scale calibration. Experimental equipment used are as follows:

(1) Pot cutter device. Figure 5 is the bending cutter device that cuts pots by applying stress on the upper pot surface through the press cake. Figure 6 is the shearing cutter device that cuts pots using the cutting edge.

(2) WDW-200E microcomputer control electronic universal testing machine. The maximum test force was 200 KN.

(3) JD series multifunctional electronic balance with an accuracy of 0.001 g.

(4) Scale with an accuracy of 1 mm.

(5) DGG-9070B electric heating constant temperature air dry oven.

Fig. 5 - Bending cutter device

Fig. 6 - Shearing cutter device

Test method

Soil moisture content measurement by drying method

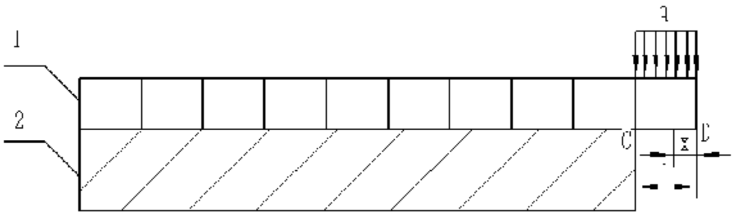
Soil samples were dried in the 105°C dry oven with constant weight. Carbonization of the organic matter in soil is easily obtained over high temperature. Soil samples were then placed into a dry glass container and covered to cool to room temperature. Soil moisture content was calculated. Soil moisture content was obtained from a single-factor experiment as presented in this calculation formula:

$$P(\%) = \frac{B - C}{C - A} \times 100 \tag{1}$$

where P is soil moisture content, A is the weight of aluminum specimen box (g), B is the weight of wet aluminum specimen box (g) and C is the weight of dry aluminum specimen box (g).

Bending cutting of corn paper pots

Pots are placed on the platform during bend cutting, while the waiting pot for cutting is suspended out of the platform. This process provides a uniform load from the universal testing machine until the pot is damaged completely (Figure 7). The initial descending position was kept constant by using a straight ruler.



1. Paper pots 2. Platform

Fig. 7 - Bending cutting of corn paper pots

In the bending failure experiment, pots on the platform bear no stress, and the suspending pot is equal to the cantilever with a uniform load. According to the bending stress analysis of the cantilever, shearing force and bending moment on any section of the suspending pot can be presented as:

$$\mathrm{F}(x) = qx(0 \le x < 1) \ \ [\mathrm{N}] \tag{2}$$

Where q is uniformly distributed load, [N/m]; x - extended length, [m]

$$\mathrm{M}(x) = -\frac{qx^2}{2}(0 \le x < 1) \ \ [\mathrm{Nm}] \tag{3}$$

where point C has the largest shearing force, $F=ql$, and the largest bending moment, $M_{max} = ql^2/2$.

Thus, point C is considered a dangerous section and the suspending pot can break at point C.

The positive bending stress on any section of a single suspending pot is:

$$\sigma = \frac{M_x}{W_z} \qquad (4)$$

σ is bending normal stress, [N/m²];

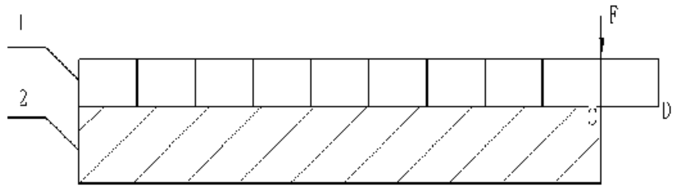
M_x — bending moment of the section whether point *X* is in [Nm];

W_z — coefficient of the bending section [m³]

Pots are uniform and W_z is a fixed value. Pots are cut when point C reaches the critical positive bending stress.

Shear cutting of corn paper pots

In the shear cutting experiment, pots are placed on the testing platform and the pot lined up for cutting is suspended out of the platform (Figure 8). Applied loads are concentrated at the pot located on the platform edge, that is, the section where point *C* is in, thus stress at point *C* quickly increases to the critical positive stress. The pot breaks at point *C*, thus completing the cutting process.



1. Paper pots 2. Platform

Fig. 8 - Shear cutting of paper pots

Orthogonal test

According to the orthogonal test, soil moisture content, cutting speed, and cutting angle (the angle between the interface of two paper pots and the plane of cutting edge) were considered the influencing factors. Corn paper pots were numbered in sequence. Soil moisture content, cutting speed, and cutting angle of each paper potted seedling are shown in Table 2.

Table 2

Levels of test factors

Factors	**Levels**		
	1	**2**	**3**
Soil moisture content A [%]	60–63	63–67	67–70
Cutting speed B [mm/min]	200	350	500
Cutting angle C [°]	10	20	30

RESULTS

Effect of cutting mode on pot integrity

Figure 9 shows the bending failed pot. The pot has serious deformation failures and random breakage position, which is inappropriate for transplanting. The shear failed pot is shown in Figure 10. The potted seedling retains high integrity, regular cutting section, and an injury rate that is lower than 5%. Therefore, shear cutting shall be adopted.

Fig. 9 - Potted seedling after bending failure

Fig. 10 - Potted seedling after shear failure

Effect of soil moisture content on cutting force

Based on agricultural requirements, soil moisture content for corn transplantation should be kept at 60–70%. Potted seedlings were cultivated under three different soil moisture contents. Each of moisture content was tested three times, and the mean was obtained. The variation curve of the cutting force with time is shown in Figure 11. According to the test data, the pots with 67–70%, 63–67%, and 60–63% soil moisture content require a cutting form of 48 N, 53 N, and 58 N, respectively, which indicates that cutting force is negatively correlated with soil moisture content. This decrease in cutting force is due to the reduction of soil cohesion as the thickness of the water film surrounding soil particles increases when soil moisture content increases.

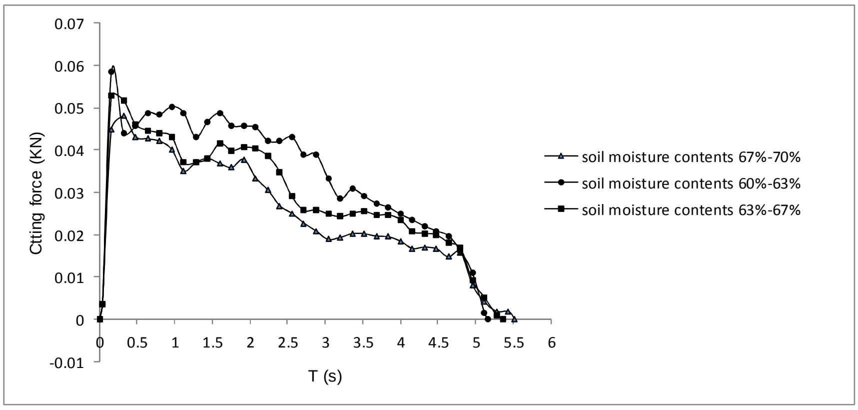


Fig. 11 - Variation of cutting force with time under different soil moisture contents

After cutting, potted seedlings with 60–67% soil moisture content showed the lowest injury rate, and cut pots maintained high pot integrity. The potted seedlings with 67–70% soil moisture content reached an injury rate of 10% because of the high soil moisture content and high porosity, which prevents high pot integrity after cutting. Based on the results, corn pots with 60–67% soil moisture content are appropriate for cultivation of corn seedlings.

In general, cutting force increased first and then decreased as the cutting depth of the pot increased. The maximum cutting force was between 50–70 N, while the maximum cutting force loaded by the cutter in the finite element analysis was smaller than 100 N. This result confirmed that the cutter design was reasonable. The cutting force reached the extreme value at 0.5 s of contact between the cutter and the pot. The desired cutting force gradually declined until the failure process ended.

Effect of cutting speed on maximum cutting force

The variation of the maximum cutting force with the cutting speed is shown in Figure 12. Maximum cutting force decreased to some extent with the increase of cutting speed. With the increase of cutting speed, the time for contact deformation of the pot shortened and the cutting force decreased, which also decreased the maximum cutting force.

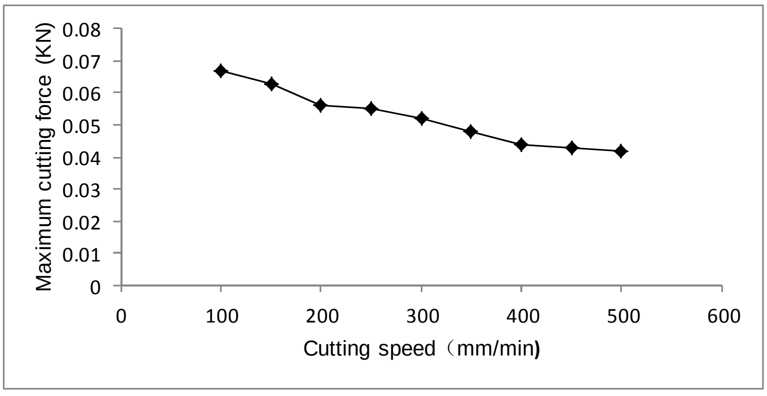


Fig. 12 - Variation of maximum cutting force with cutting speed

Orthogonal test results

According to the factors and levels selected, a three-factor, three-level orthogonal test was carried out. The test plan and results are shown in Table 3.

Table 3

Test plan and results of the three factors and three levels

Test No.	Factors			Integrity η (%)	Cutting force F (N)
	A (%)	B (mm/min)	C (°)		
1	1 (60-63)	1 (200)	1 (10)	96	62
2	1 (60-63)	1 (200)	1 (10)	95	62
3	1 (60-63)	2 (350)	2 (20)	97	57
4	1 (60-63)	2 (350)	2 (20)	96	59
5	1 (60-63)	3 (500)	3 (30)	96	52
6	2 (63-67)	3 (500)	1 (10)	97	52
7	2 (63-67)	1 (200)	1 (10)	96	60
8	2 (63-67)	2 (350)	2 (20)	96	57
9	2 (63-67)	3 (500)	2 (20)	97	50
10	2 (63-67)	3 (500)	3 (30)	96	46
11	3 (67-70)	1 (200)	1 (10)	90	48
12	3 (67-70)	1 (200)	1 (10)	91	50
13	3 (67-70)	2 (350)	2 (20)	90	47
14	3 (67-70)	2 (350)	2 (20)	89	49
15	3 (67-70)	3 (500)	3 (30)	90	46

As shown in Table 3, cutting speed is the most important influencing factor of cutting force. Conditions to achieve the minimum cutting force of corn paper pot are A2B3C3: 63–67% soil moisture content, 500 mm/min cutting speed and 30° cutting angle. This data coincides with the single-factor test results and confirms the reasonability of the design angle (30°) of cutting edges in the seedling separator.

CONCLUSIONS

Cutting characteristics of paper pots are experimentally studied to address high seedling injury rate and low efficiency of existing seedling separators. Based on the results, a seedling separator that can directly cut paper pots is designed. We can conclude that soil moisture content for potted corn seedling should be controlled between 60–67% to meet the agricultural requirements and maintain the integrity of a single potted seedling after the cutting process. Shear cutting is superior to bend cutting for corn paper pots, and the injury rate of seedlings is lower than 5%. The maximum cutting force decreases with the increase of cutting speed. The minimum cutting force of the corn paper pot is achieved under 63–67% soil moisture content, 500 mm/min cutting speed, and 30° cutting angle. A cut single pot is delivered to the seedling guide tube. This seedling separator can lessen labor intensity and increase transplantation efficiency. In this design, two cutting edges are installed on the cutter head. In future research, installing four cutting edges on the cutter head can be done to further study seedling separation efficiency.

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