Design of the filling device for citrus seedling pot based on turnover box

Qinchao Xu[1,2,3], Haoyi Chen[1,2,3], Chuanxin Liu[1,2,3], Jiating Zhu[1,2,3], Shanjun Li[1,2,3*], Meiqi Ye[1,2,3]

(1. *College of Engineering, Huazhong Agricultural University, Wuhan 430070, China*;
2. *Key Laboratory of Agricultural Equipment in Mid-lower Yangtze River, Ministry of Agriculture and Rural Affairs, Wuhan 430070, China*;
3. *Citrus Mechanization Research Base of the Ministry of Agriculture and Rural Affairs, Wuhan 430070, China*)

Abstract: In China, soft plastic pots are the predominant container used for the cultivation of citrus seedlings. However, due to their soft characteristics, manual operation is the primary method of pot filling and placement, which significantly impedes production efficiency. In order to resolve this issue, a solution for filling citrus seedling pots based on a turnover box was proposed. By analyzing the movement status of the turnover box unloading mechanism, the length of each component was calculated, and the specific structure of the turnover box was designed. The substrate lifting rate of the conveyor belt was analyzed and the structural parameters of the lifting mechanism were determined. Through theoretical analysis of the substrate trajectory during the dispersion process, the inlet position of the splitter mechanism was determined, and the specific structure of the splitter mechanism was designed to control the uniformity of the substrate distribution. A seedling pot filling process simulation model was constructed using discrete element software. The operating parameters of the filling device were evaluated, and the filling effect was analyzed. The test prototype was processed and three loading tests were carried out. The results show that the prototype runs stably, with a loading time of 8 s for 16 pots. The unloading mechanism of the turnover box is reliable, and the seedling pots are neatly arranged after unloading. The maximum weight among the 16 pots in the turnover box is 2.00 kg, while the minimum weight is 1.88 kg. The mean weight is 1.94 kg, with a coefficient of variation of 2.47%. The excess substrate mass scraped on the turnover box is 0.83 kg, accounting for 2.67% of the total mass of the 16 pots. The prototype design is reasonable, with good filling uniformity and high efficiency. The research results can provide reference for the development and optimization of citrus seedling pot filling and transportation equipment in the future.

Keywords: agricultural machinery, citrus, seedling pot, turnover box, filling, EDEM
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1 Introduction

With the development of seedling cultivation technology, container seedling technology has been widely used because of its considerable advantages[1-3]. Concurrently, factory seedling equipment based on container seedling technology is developing rapidly[4-6], especially in the main parts of the process such as substrate filling, transplanting, and transporting[7-9]. However, the predominant production processes for citrus container seedling in China are currently manual and labor-intensive[10-13]. Especially during the substrate filling process, the small diameter-to-depth ratio soft plastic pot cannot be placed stably, which makes it difficult to fill mechanically. It is therefore imperative to develop equipment for filling the soft plastic pot to improve the overall efficiency of seedling production.

Presently, after long-term technological accumulation, the factory seedling equipment in developed countries has reached a relatively high degree of automation, and is capable of completing the primary seedling processes on a conveyor line with minimal reliance on manual labor[14,15]. The automatic tray seeder line, developed by Visser in the Netherlands, adopts a needle-type pneumatic seeding method and can be utilized as an independent part or integrated with other seedling parts, exhibiting a high degree of automation. TM 2700 pot seedling production line of Mayer Company in Germany integrates automatic pot taking, substrate filling, hole pressing, and automatic conveying. It also has different replacing parts that can match pot containers of different sizes, with good adaptability[16-18]. In general, factory seedling equipment in developed countries is large in size, expensive in price, large in power requirements, and difficult in maintenance[19-22]. However, the development of factory seedling equipment in China is relatively late, especially in the citrus seedling industry. There is no unified standard for seedling substrates and containers, and the main seedling processes still have no machines available. Some seedling equipment has a low degree of automation and poor universality[23-27].

Based on the aforementioned considerations, a turnover box-based citrus seedling pot filling scheme was proposed. The structural parameters of the key components were determined. The experimental prototype was developed and operational performance tests were conducted to verify the rationality of the determined parameters. This device can be used as an independent filling part or placed on the seedling production line, which provides a reference for the development and optimization of citrus seedling production lines.

2 Structure and working principle of the filling device

2.1 Overall structure

The filling device consists of three primary components: a turnover box, a substrate filling device, and a substrate lifting

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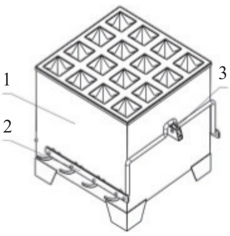
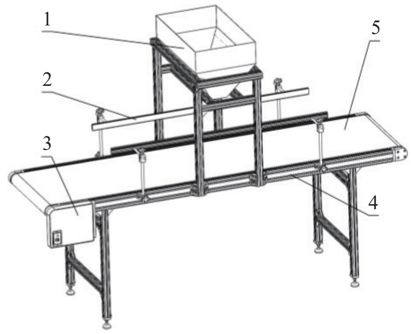
Biographies: Qinchao Xu, PhD, Associate Professor, research interest: orchard machinery, Email: hlxqc@mail.hzau.edu.cn; **Haoyi Chen**, MS, research interest: orchard machinery, Email: 282905159@qq.com; **Chuanxin Liu**, MS, research interest: orchard machinery, Email: 1902305743@qq.com; **Jiating Zhu**, MS, research interest: orchard machinery, Email: 3252605113@qq.com; **Meiqi Ye**, Undergraduate, research interest: orchard machinery, Email: 1789156569@qq.com.
***Corresponding author: Shanjun Li**, PhD, Professor, research interest: orchard machinery. College of Engineering, Huazhong Agricultural University, Wuhan 430070, China. Tel: +86-27-87288638 , Email: shanjunlee@mail.hzau.edu.cn.

device. The turnover box includes the box frame, unloading mechanism, and locking mechanism. The substrate filling device comprises the conveyor line, position-limit mechanism, flow guiding bin, power system, and frame. The substrate lifting device comprises a splitter mechanism, a storage bin, a feeding conveyor, a flow limiting plate, a lifting conveyor, a base, and a frame. The specific structure of the device is illustrated in Figure 1, and the parameters of the entire machine are listed in Table 1.



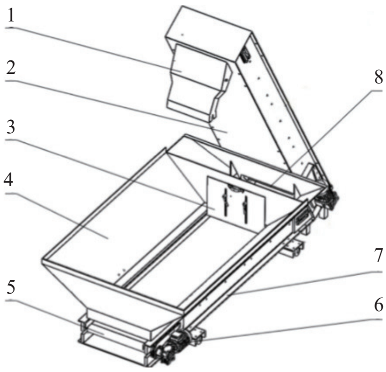
1. Box frame; 2. Unloading mechanism;
3. Locking mechanism

a. Turnover box



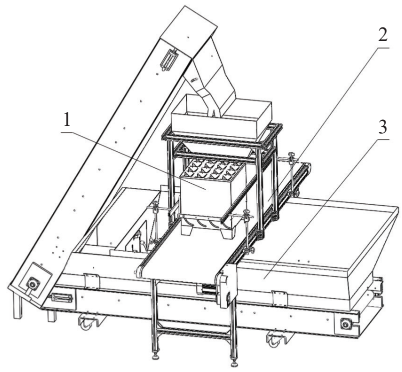
1. Flow guiding bin; 2. Position-limit mechanism;
3. Speed control motors; 4. Conveying line;
5. Frame;

b. Substrate filling device



1. Splitter mechanism; 2. Lifting mechanism;
3. Flow limiting plate; 4. Storage bin;
5. Feeding conveyor; 6. Feeding conveyor motor;
7. Feeding conveyor frame; 8. Scraper belt

c. Substrate lifting device



1. Turnover box; 2. Substrate filling device;
3. Substrate lifting device;

d. Overall of seedling pot filling device

Figure 1 Schematic diagram of seedling pot filling device

Table 1 Main parameters of citrus seedling production line seedling pot filling device

Parameter index	Numerical value
Overall dimensions (length×width×height)/mm	2870×2500×2500
Filling quantity (pots per time)	16
Filling time/s	<10
Filling capacity per pot/kg	1.8-2.2
Variation coefficient of filling uniformity/%	<5
Qualification rate/%	>95

2.2 Working principle

At the stage of preparation for filling, the cover of the turnover box should be opened, the seedling pots placed into each compartment of the turnover box, and the cover closed. When the conveyor line is operational, the turnover box enters the preset filling position via the position-limit mechanism. Upon reaching the position of the flow guiding bin, the substrate in the storage bin is lifted. Subsequently, the substrate is diverted through the splitter mechanism and flows evenly into the first row of seedling pots via the guide bin. The conveyor line drives the turnover box forward at a constant speed, with the substrate successively filling the back seedling pots. To ensure the filling effect, a scraper is installed at the bottom of the guide bin. The scraped substrate naturally falls into the storage bin. Once the filling process is complete, the turnover box can be stacked and transported to the nursery by forklift or other transfer equipment. The locking mechanism on the turnover box can then be opened, allowing the seedling pots to be unloaded in an orderly manner to the designated location. The unloaded turnover box can then be transported to the filling position for reuse.

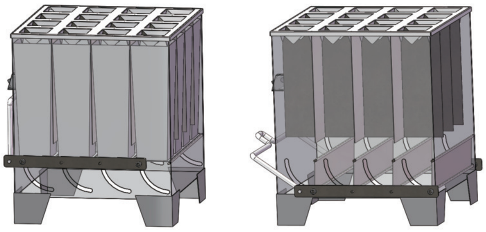
3 Design of key components of filling device

3.1 Turnover box design

The turnover box is primarily utilized to guarantee the stable placement and unloading of the 16 seedling pots at a time, so its overall size should be equivalent roughly to the volume of the 16 seedling pots (the size of a single seedling pot is 100 mm×100 mm×300 mm). To facilitate and maintain stability and transportation, the device employs a linkage flap mechanism for unloading. The transition between loading and unloading is accomplished by rotating the flap through the action of a connecting rod, as shown in Figure 2.

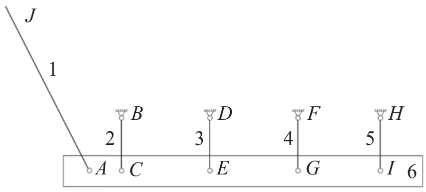
In order to ascertain the structural parameters of the unloading mechanism, a diagram of the linkage mechanism is illustrated in Figure 3. When in the unloading state, lever 1 is unlocked, and flaps 2, 3, 4, and 5 are in a vertical position. Conversely, when in the filling state, lever 1 is lifted to the locking mechanism and locked.

The connecting plate drives the flap into motion, with the result that the connecting plate 6 and the flaps 2, 3, 4, and 5 all move into a horizontal position. The unloading mechanism in the two positions is illustrated in Figure 3b.

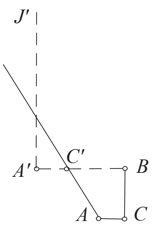


a. Loading condition b. Unloading condition

Figure 2 Schematic diagram of linkage flap mechanism



a. Kinematic diagram of the linkage mechanism



b. Different positions of the linkage mechanism

1. Driving link; 2-5 are flipping plates; 6. Connecting plate

Figure 3 Schematic diagram of unloading mechanism

In the unloaded state, the point J position of the control lever must be outside the box frame to ensure that the unloading mechanism does not interfere with the frame. This means the length of the lever must exceed that of the flap.

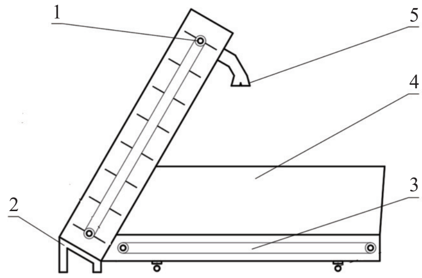
$$JA \geq BC \tag{1}$$

The length of BC should be suitable for the bottom size of the seedling pot, which is determined to be 75 mm. In consideration of the spatial requirements of the flaps and connecting plates within the box, as well as the installation dimensions of the external box frame, AC is determined to be 35 mm and JA is 199.6 mm.

3.2 Lifting mechanism design

The main function of the lifting mechanism is to stably lift and transport the substrate to the guide hopper. The specific structure is illustrated in Figure 4. The horizontal conveyor belt is affixed to the frame at the base of the storage bin, and the frame is equipped with casters at the bottom for convenient movement. The lifting conveyor belt is affixed to the frame at a certain angle, which is used in conjunction with the horizontal conveyor belt. Considering the overall weight and size requirements, a scraper is used for material lifting, with a total of 16 scrapers installed on both sides.

The structural parameters of the conveyor belt have a significant impact on the substrate lifting rate. During the process of lifting the substrate with a scraper, the shape of the substrate on the scraper can be approximated as a triangular prism, ignoring the flow loss of the substrate during the lifting process. The schematic diagram is illustrated in Figure 5.



1. Lifting conveyor; 2. Frame; 3. Feeding conveyor; 4. Storage bin; 5. Splitter mechanism

Figure 4 Structure of lifting mechanism

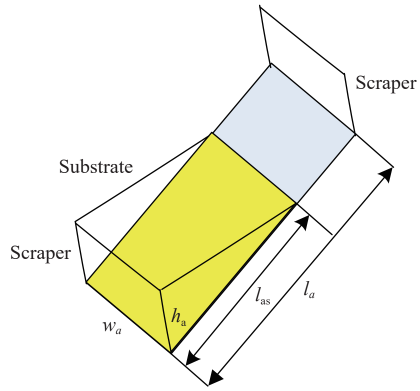


Figure 5 Schematic diagram of single-lift substrate scraper

The quality of the substrate between the two scrapers m_{as} is calculated as follows:

$$m_{as} = \frac{l_{as} \cdot w_a \cdot h_a}{2} \cdot \rho_s \tag{2}$$

where, w_a is the width of the conveyor belt, m; h_a is the height of the conveyor belt scraper, m; l_{as} is the length of the substrate between the two conveyor belt scrapers, m; ρ_s is the substrate density, kg/m³.

The approximate mass flow rate of the lifting substrate q_{ma} is calculated as follows:

$$q_{ma} = \frac{m_{as} \cdot v_a}{l_a} \tag{3}$$

where, l_a is the distance between the two scrapers of the lifting conveyor, m; v_a is the operating speed of the lifting conveyor, m/s.

The approximate mass flow rate of the filling substrate q_{mf} is calculated as follows:

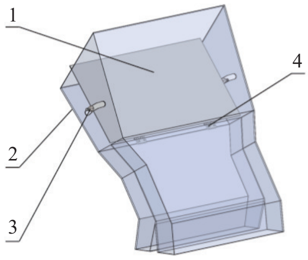
$$q_{mf} = \frac{m_{fs} \cdot v_f}{l_f} \tag{4}$$

where, m_{fs} is the filling mass of the turnover box substrate, kg; l_f is the length of the turnover box, m; and v_f is the speed of the horizontal conveyor belt, m/s.

The mass flow rate of the lifting substrate should be matched with the mass flow rate of the filling substrate. The turnover box is filled with 16 pots, with an average weight of 2 kg. The conveyor belt width is selected to be 0.5 m, and the scraper height is 0.08 m. Considering the installation inclination angle of the lifting conveyor belt and the substrate sliding angle, it is determined that the length of the substrate-conveying part between the two scrapers of the conveyor belt l_{as} is about 0.2 m, and the distance between the two scrapers of the conveyor belt l_a is 0.3 m. It can be determined that the speed ratio of the conveyor belt to the horizontal conveyor belt is 5:1.

3.3 Splitter mechanism design

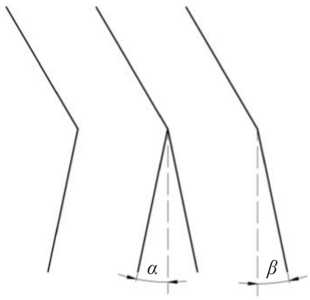
The substrate falling is one of the key stages in the entire filling process. The distribution of falling substrate has a direct effect on the uniformity of seedling pot filling. The main function of the splitter mechanism is to regulate the distribution of the substrate during the filling process to ensure a consistent and uniform filling. The specific structure is illustrated in Figure 6.



1. Adjustable partition plate; 2. Splitter tube; 3. Locking mechanism; 4. Hinge

Figure 6 Schematic diagram of splitter mechanism

The substrate particles are redirected by the adjustable partition plate of the splitter mechanism and enter the left and right channels of the splitter tube. It is essential to adjust the position of the adjustable partition plate to ensure that the mass of the substrate entering the left and right channels is equal. By designing the angle of the left channel wall and vertical direction, it is possible to guarantee uniform filling of the entire row of seedling pots, as illustrated in Figure 7.



1. Angle α between left channel and vertical direction; 2. Angle of right channel with vertical β

Figure 7 Schematic diagram of angles between splitter walls and vertical direction

Due to assembly requirements, the size of the feeding port of the splitter mechanism should correspond to the size of the outlet of the lifting conveyor. In order to determine the size of the outlet of the conveyor, it is necessary to analyze the trajectory of the substrate during the feeding process. When lifting the conveyor belt scraper to the roller section, the scraper will move in a circular motion around the roller, and the substrate on the belt will detach from the belt and the substrate on the scraper will detach from the scraper due to inertia and be ejected along a certain trajectory due to inertia, as shown in Figure 8. To simplify the calculation, the effects of sliding and adhesion between the particles of the substrate are disregarded.

The position of substrate particle P at the highest point on the scraper was investigated. The diagram shows the position where the particle separates from the scraper. The motion trajectory of substrate particle P after separation is as follows:

$$\begin{cases} x_p = v_p \cdot \cos\theta \cdot t_p \\ y_p = v_p \cdot \sin\theta \cdot t_p - \dfrac{1}{2} g t_p^2 \end{cases} \tag{5}$$

where, x_p is the horizontal displacement of the substrate particle P, m; y_p is the vertical displacement of the substrate particle P, m; t_p is the movement time of the substrate particle P, s; v_p is the speed of the substrate particle P when it separates from the belt, m/s; θ is the installation angle of the lifting conveyor belt and the frame, rad; and g is the acceleration of gravity, taken as 9.8 m/s^2.

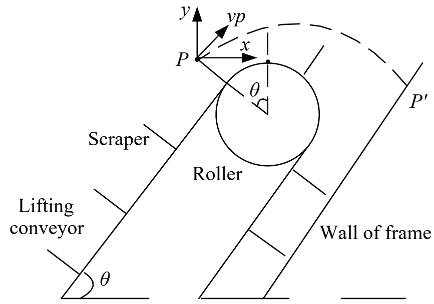


Figure 8 Trajectory diagram of substrate dispersion

The initial velocity of the substrate particles (P) is identical to that of the lifting conveyor belt, which is 0.5 m/s. The angle of the conveyor belt and the frame is 60°. According to the structural dimensions of the device, the substrate particles (P) make contact with the frame wall at a point 0.122 m horizontally from the point of departure. The position of point P' relative to point P can be determined based on the horizontal and vertical displacement of the substrate particles (P). This enables the location of the substrate outlet to be ascertained in the region below point P' on the frame wall, with dimensions of 175 mm × 500 mm (length × width).

EDEM simulation experiments were carried out on the splitter mechanism, and the substrate particle parameters are shown in Section 3. The mass of the substrate flowing into each pot in a row was adjusted by changing the angles α and β. The overall mass of particles generated on the feeding port of the splitter mechanism is 8 kg. The ranges of angles α and β are 11°-15° and 5°-9°, respectively, for the simulation test. The model of the EDEM simulation experiments is shown in Figure 9, and the average values of the results of five repeated experiments are listed in Table 2.

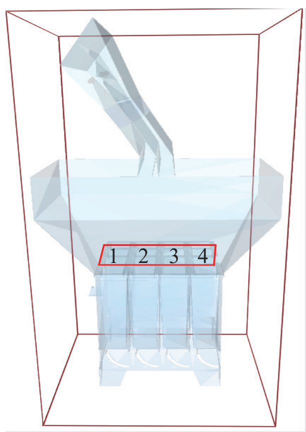


Figure 9 Simulation model of splitter mechanism

Table 2 Simulation experiment results of splitter mechanism

α/(°)	β/(°)	Substrate mass/kg			
		Pot 1	Pot 2	Pot 3	Pot 4
11	5	1.535	2.154	2.164	1.679
12	6	1.956	2.016	2.106	1.813
13	7	2.055	1.856	1.968	2.035
14	8	2.154	1.679	1.858	2.079
15	9	2.164	1.545	1.624	2.103

Table 2 illustrates that when α is 12° the mass difference between the seedling pots 1 and 2 is the smallest, while when β is 7° the mass difference between the seedling pots 3 and 4 is the smallest. Therefore, it is determined that the optimal angle combination of α and β is 12° and 7°.

4 A discrete element simulation of operating parameters based on the EDEM

4.1 Three-dimensional substrate model

The substrate for citrus seedlings is composed of loess, wood ash, perlite, and vermiculite in a specific ratio. The particle size distribution of the substrate was determined using a standard round-hole sieve, and the proportions of the substrate distributed in the range of 0-0.1 mm, 0.1-1 mm, 1-2 mm, and greater than 2 mm were found to be 25.51%, 12.52%, 50.27%, and 11.70%, respectively. Particles were randomly selected from the substrate, and their shapes were observed using a super-depth-of-field microscope[28]. The particles exhibited a predominantly rounded, square, or elongated morphology. In the Particle module of the EDEM software, three corresponding particle models were constructed, as illustrated in Figure 10.

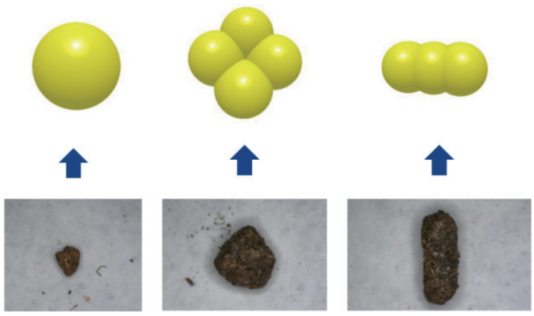


Figure 10 Models of three types of particles

In order to achieve effective simulation, it is necessary to simplify the model of the machine. The non-frame parts should be removed from the 3D model created in Solidworks, while the overall frame, conveyor belt, lifting belt, scraper belt, splitter mechanism, and main components of the turnover box are retained. The simplified result is shown in Figure 11.

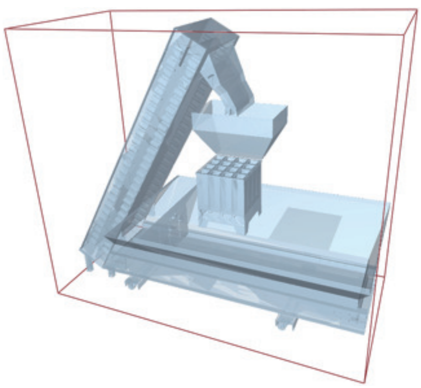


Figure 11 Simulation model of filling device

4.2 Determination of simulation parameters

Due to the viscous nature of the substrate particles, the Hertz-Mindlin with JKR Version 2 contact model is employed to simulate the sliding and adhesion between the particles[29]. Surface energy represents a significant parameter in characterizing the mutual cohesion and adhesive contact between substrate particles. The surface energy of the substrate was calibrated using a combination of experiments and simulations[30,31], with the result that the surface energy of the filled matrix was found to be 4.92 J/m². The values of the characteristic parameters and contact parameters are listed in Tables 3 and 4[32].

Table 3 Material characteristic parameters

Material	Density/ kg·m^{-3}	Modulus of elasticity/Pa	Shear modulus/ Pa	Poisson ratio
Substrate	1526	2.808×10^6	1.080×10^6	0.30
PVC belt	1282	1.056×10^7	4.000×10^6	0.32
Q235 Steel	7830	7.270×10^{10}	1.963×10^{11}	0.35

Table 4 Material contact parameters

Contact object	Collision recovery coefficient	Static friction coefficient	Rolling friction coefficient
Particle and particle	0.45	0.89	0.43
Particle and metal	0.20	0.30	0.03
Particle and PVC belt	0.50	0.50	0.01

4.3 Simulation test method

The proportion of single-spherical, multi-spherical, and columnar-spherical substrate particles is set at a ratio of 4:4:3, with the particle size distribution scaled accordingly. The generation rate of substrate particles in the storage bin is 20 kg/s, and a total of 100 kg is generated. The substrate particles in the conveying silo are produced at a rate of 20 kg/s, for a total of 100 kg. The total mass of the particles is 100 kg. The speed of the conveyor belt in the storage bin is set to 0.5 m/s, the lifting conveyor belt speed is set to 0.5 m/s, and the speed of the conveying line is set to 0.075 m/s.

In order to determine the operational parameters of the device and analyze the filling effect, the filling quality, filling uniformity, and substrate mass scraped by the scraper were evaluated. The calculation area was set up according to the evaluation needs, and the measurement tool module provided by EDEM was used to measure.

The coefficient of variation for filling is calculated as follows:

$$CV_{ij} = \frac{S_{ij}}{\overline{m_{ij}}} \times 100\% \tag{6}$$

$$\overline{m_{ij}} = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} m_{ij}}{mn} \tag{7}$$

$$S_{ij} = \sqrt{\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}(m_{ij} - \overline{m_{ij}})^2}{mn-1}} \tag{8}$$

where, S_{ij} is the standard deviation of the test; $\overline{m_{ij}}$ is the average filling mass of the test, kg; m_{ij} is the mass of the seedling pot in the i row and j column of the test, kg; m is the number of rows of seedling pots in the test, m=4; n is the number of columns of seedling pots in the test, n=4.

4.4 Simulation results and analysis

The simulation results of EDEM are shown in Figure 12 and Table 5.

As illustrated in Figure 12, after stable operation of the conveyor belt, the single-lift mass of the scraper is 5.5315 kg, while the calculation result in Section 2.2 is 6 kg, with a difference of 8.3%. The simulation outcome is consistent with the design lifting amount.

As illustrated in Table 5, the maximum filling mass of the 16 seedling pots in the turnover box is 1.930 34 kg, which is 0.0696 kg less than the tested value (Table 6), with an error of 3.61%. The minimum filling mass is 1.855 47 kg, which is 0.024 53 kg less than the tested value, with an error of 1.37%. The average filling weight of the 16 seedling pots is 1.897 50 kg, which is 0.0425 kg less than the tested value, with an error of 2.24%. From the comparison of simulation and experimental results, it can be seen that the two are basically consistent, which verifies the correctness of the simulation model. The average filling weight of the 16 seedling pots is 1.897 50 kg, with a coefficient of variation of 1.08%, indicating good filling uniformity.

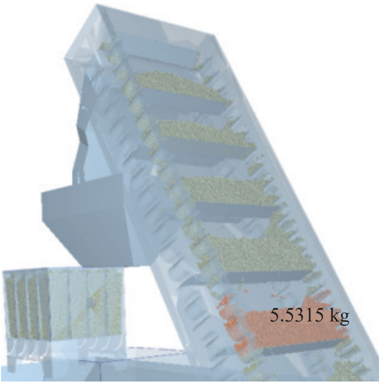


Figure 12 One scraper lifts the mass of substrate

Table 5 Filling simulation results

No.	Filling quality of different rows of seedling pots/kg				Scrape off excess substrate/kg
	1	2	3	4	
1	1.884 76	1.897 13	1.909 83	1.887 78	1.129 51
2	1.917 76	1.908 89	1.930 34	1.860 78	
3	1.915 74	1.907 51	1.906 24	1.875 17	
4	1.893 44	1.903 33	1.9058	1.855 47	

Table 6 Filling experiment results

No.	Filling quality of different rows of seedling pots/kg				Scraped off excess substrate/kg
	1	2	3	4	
1	1.91	1.97	1.96	1.90	0.83
2	1.89	2.00	1.98	1.93	
3	1.88	1.99	1.96	1.88	
4	1.89	1.96	2.00	1.91	

When the 16 seedling pots within the turnover box were filled, the excess substrate mass scraped off was 1.129 51 kg, accounting for 3.72% of the total mass of the 16 seedling pots. This indicates that during the process of filling the seedling pots, the amount of substrate lifted is basically consistent with the weight of the substrate filled in the seedling trays. When the speed of the substrate lifting conveyor belt is 0.5 m/s and the speed of the conveyor line is 0.075 m/s, the filling speed of the substrate matched well with the advancing speed of the turnover box.

5 Prototype testing

According to the design results of the key components of the filling device, a prototype was developed and is shown in Figure 13. The reliability and stability of the filling process were evaluated through practical filling tests, and the quality of each seedling pot after filling was weighed to assess the filling effect.

The test used plastic seedling pots with dimensions of 10 cm×10 cm×30 cm (length×width×height). The substrate ratio, material parameters, and operating speed of the prototype were consistent with those described in Section 3.3. The filling test was repeated three times, and the results after filling and unloading are shown in Figures 14 and 15. An electronic scale (with a measuring accuracy of one gram and a measuring range of 30 kg) was used to weigh and record the individual seedling pots and the excess substrate scraped off for each test. The test results are listed in Table 6.

Figure 13 Test prototype of filling device

Figure 14 Filling test results

Figure 15 Unloading results

Table 6 illustrates that the maximum filling mass of the 16 seedling pots in the turnover box is 2.00 kg, the minimum filling mass is 1.88 kg, and the average filling weight of the 16 seedling pots is 1.94 kg. The difference between the maximum and minimum filling masses of the seedling pots is 0.12 kg. The coefficient of variation of the 16 seedling trays is 2.47%, indicating good uniformity of filling.

Three filling tests were conducted, and the filling device operated stably. The unloading mechanism of the turnover box was reliable. There were no detached seedling pots, and the seedling pots were neatly arranged after unloading. The difference between the maximum and minimum filling weights of the seedling pots was 0.12 kg, and the coefficient of variation for the 16 seedling pots was 2.47%, indicating good uniformity of filling.

The average amount of excess substrate scraped off was 0.83 kg in three filling tests, accounting for 2.67% of the total weight of 16 seedling pots, indicating that the filling speed of the substrate matched well with the advancing speed of the seedling turnover box.

The citrus seedling pot filling device, which is based on the turnover box, does not account for the time required for placing the empty pots. The time required to fill a single box with 16 pots is approximately 8 s. This is considerably less than the time required for manual filling, which has an efficiency of only 60 to 80 pots per hour.

6 Conclusions

1) A citrus seedling pot filling device based on a turnover has been developed, which can effectively improve the quality and efficiency of filling. The device can be used as an independent filling part or integrated with other seedling parts on the production line, which can enhance the overall automation level of citrus seedling machinery.

2) The prototype test shows that the machine runs stably and the running speed matches well between each part. When the pots in the turnover box were filled, the excess substrate scraped off accounts for 2.67% of the total weight of the 16 seedling pots, and the coefficient of variation of the filling mass is less than 5%, indicating a high level of precision and consistency in the filling process. The even distribution of the filling further supports the high efficiency of the prototype.

3) The structure of the turnover box is rather complex, and it is heavy, which is inconvenient for transportation. Therefore, the structure of the transfer box can be optimized subsequently.

The research results can provide reference for the development and optimization of citrus seedling pot filling and transportation equipment in the future.

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