Design and operational parameters optimisation of a citrus substrate filling and transporting machine

Qinchao Xu, Shanjun Li, Haibing Pan, Qian Yang, Jian Zhang, Xuedong Lu, Cheng Shan

Key Laboratory of Agricultural Equipment in Mid-lower Yangtze River, College of Engineering, Huazhong Agriculture University, Ministry of Agriculture and Rural Affairs, Wuhan, China

Abstract

Aiming to address the problem of low mechanisation of filling and transporting citrus seedling pots in China, a new type of pot filling and transporting machine with 120 pots at a time was designed. Based on the study of flow characteristics of the seedling substrate, key components of the filling and transporting machines, such as the hopper component, transmission mechanism, flip mechanism, and steering mechanism, were designed. The effects of the opening width of the hopper, the rotating speed of the stirring shaft, the moisture content of the seedling substrate, and the forward speed of the transporting device on the filling effect of the seedling pot were studied by the experimental method, and the optimal operation parameters were determined. The prototype tests were repeated 3 times with the best combination of parameters. The test results indicate that the machine was in good condition for loading and unloading. The number of filling pots was 120 once, and the average filling time was 40 s. The average filling mass was 1.881 kg, 0.006 kg different from the predicted value of 1.887 kg, and the relative error was 0.32%. The coefficient of variation of the mass was 2.97%, which was 0.12% different from the predicted value of 2.85%, and the relative error was 4.0%. This designed machine can provide a reference for developing and optimising the citrus substrate filling and transporting machine.

Correspondence: Qinchao Xu, College of Engineering, Huazhong Agriculture University, Key Laboratory of Agricultural Equipment in Mid-lower Yangtze River, Ministry of Agriculture and Rural Affairs, Wuhan 430070, China.
E-mail: hlxqc@mail.hzau.edu.cn

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Introduction

Virus-free container seedling technology has been widely used in citrus seedlings. At present, the mechanisation degree of citrus container seedlings in China is low, mainly relying on manual operation, which is time-consuming and challenging to achieve standardised production (Shan, 2008; Liu *et al*., 2014; Du and Du, 2014; Gao *et al*., 2015; Han *et al*., 2019). Especially in filling and transporting seedling pots, the labour intensity is high, and the production efficiency is low, which has become a significant obstacle to the development of the citrus industry. Therefore, citrus seedling pot filling and transporting machines can effectively improve the quality and efficiency of citrus seedling cultivation, which is of great significance for accelerating the development of the citrus industry in China.

Substrate filling equipment in developed countries has been developed and optimised for over 40 years. It has a high degree of automation and works reliably, which has been widely used in many large-scale protected horticulture enterprises in the world (Gu *et al*., 2012; Gu *et al*., 2013; Lantin, 2016; Dian and Soranat, 2018; Liu *et al*., 2018; Zhang *et al*., 2018). The automatic seedling production line produced by Visser in the Netherlands can complete filling, seeding, soil covering, and transplanting at once and transport seedling containers by all kinds of transporters, such as electric transporters, hydraulic transporters, and forklift transporters. Standard-type flowerpot substrate filler manufactured by JAVO Company of the Netherlands has high efficiency of 6000 pots per hour and strong adaptability. SMART flowerpot substrate filler, developed by Demtec in Belgium, and TM2600 flowerpot substrate filler, developed by Mayer in Germany, all have high working efficiency. There is still a certain gap in the research and development of substrate-filling equipment between China and developed countries. The flower pot substrate filling machine developed by Yang *et al*. (2013) can adapt to different sizes of flowerpots, and the flowerpots and substrate can fall automatically, but the inclined flowerpots need to be set up right manually. TLZ-400 substrate filling machine developed by Wei *et al*. (2013) can continuously complete the tray filling, scraping and excess substrate recovery. It uses the electrical control system to adjust the substrate conveying capacity to adapt to the actual production. Liu *et al*. (2016) designed an intelligent seedling machine for vegetable seedling trays, which adopted a PLC control system to realise rapid filling and sowing operation and can meet the requirements of modern seedling factories. The biomass nutritive cube-making machine developed by Liu *et al*. (2015) uses crop straw as the substrate material, which can accurately control the amount of output and has a high degree of automation. The automatic substrate filling machine developed by Cai (2017) is suitable for a polyethylene plastic soft pot, which uses a linkage mechanism with a negative pressure sucker to open the pot and uses a PLC system to automatically control the amount of substrate dropped. In general, substrate filling and transporting machines are mostly suitable for standardised seedling trays and hard plastic pots, which are unsuitable for the seedling pot filling process with soft plastic pots. Due to the poor placement stability of soft plastic pots, there are relatively few machines for filling and transporting this type of pot (Li et al., 2016; Qi *et al*., 2017; Zhang *et al*., 2020; Xu *et al*., 2020). In this paper, based on the agronomic requirements of citrus seedling (Xu *et al*., 2020), a new type of seedling pot filling and transporting machine with 120 pots at a time was designed, and the operation parameters were optimised.

Materials and Methods

Composition and working principle

The citrus seedling pot filling and transporting machine comprises a filling device and a transporting device, as shown in Figure 1. The filling device evenly fills the substrate into the seedling pot, mainly composed of a filling mechanism, drive mechanism, frame, and power system. The transporting device is used for transporting and unloading the seedling pots, mainly composed of the frame, the power system, the unloading mechanism, the flip mechanism, and the steering mechanism.

The filling device and the transporting device are used together. The parameters of the machine are shown in Table 1. The working process of the machine is mainly divided into three stages: filling, transporting, and unloading. Before filling, the cover plate is lifted, the pots are put into the compartments, and the cover plate is closed. During filling, the transporting device is moved to the lower part of the filling device, then the hopper is opened, the motor is turned on simultaneously, the stirring shaft rotates, and the transmission mechanism drives the transporting device forward. Scrapers are installed at the bottom of the hopper to scrap while filling. After filling, the transporting device moves to the specified location, then the unloading mechanism work and the seedling pots fall from nursery compartments neatly.

Flow characteristics of the substrate

The flow characteristics of the substrate determine the substrate accumulation form in the hopper and the flow performance, which is also an important basis for the structural design of the hopper. The main parameters that characterise flow, and friction characteristics are the repose and sliding angles (Liu *et al*., 2018). In order to measure the flow characteristics of the substrate in different relative humidity conditions, the substrate, which is the combination of loess, plant ash, perlite, and vermiculite with the portion of 5:3:1:1 was prepared. The accumulation shape of the substrate in the natural state is a cone shape, and the angle between the horizontal plane and cone surface is the repose angle (Jia *et al*., 2014), as shown in Figure 2. The calculation of the repose angle is as Eq.1.

$$\theta_a = \frac{2h_a}{d_a} \tag{1}$$

where, θ_a is the repose angle (rad); h_a is the height of the substrate (mm); d_a is the bottom diameter of the substrate (mm). The sliding angle is the inclination angle between the inclined plate and the horizontal plane, measured by lifting the flat plate, as shown in Figure 3 until the substrate starts to slide (Jiacong *et al*., 2019). Each test was repeated 3 times, and the average value was used to determine the substrate flow characteristic parameters, as shown in Table 2.

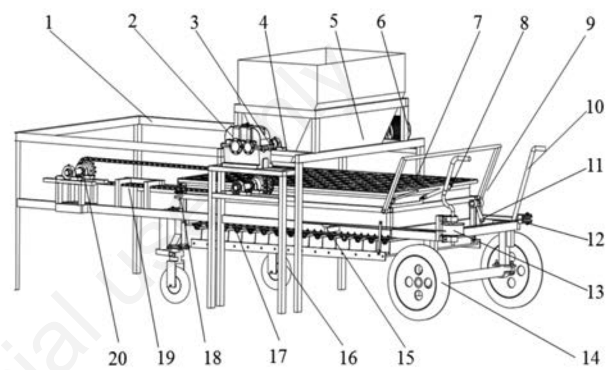

Figure 1. Structure of filling and transporting machine. 1) Frame; 2) gear reducer; 3) coupling; 4) bearing pedestal; 5) silo; 6) electric machinery; 7) cover plate; 8) gas spring; 9) discharge mechanism; 10) steering handle; 11) unlocking mechanism; 12) pulley; 13) rope drum; 14) driving wheel; 15) guide wheel; 16) steering wheel; 17) nursery compartment; 18) pull rod; 19) chain; 20) chain wheel.

Figure 2. Diagram of substrate accumulation.

Table 1. Parameters of filling and transporting machine.

Item	Parameters or form
Overall shape size	2245×1444×1458 mm (width × length × height)
Filling number	120 pots (15×8)
Filling time	40 s
Drive mode	Electric drive
Speed	1.2 m/s

Design of key components

Design of hopper component

The hopper component is used for uniform and continuous flow of the substrate, mainly composed of a hopper, agitating shaft, bottom plate, and electric motor, as shown in Figure 4. The bottom plate controls the falling of the substrate through opening and closing, and the agitating shaft prevents the substrate from arching and accumulating in the hopper through rotation.

The hopper shall not only meet the volume requirements of the filling but also prevent arching and accumulation of substrate to ensure smooth flow. The substrate is placed on the groundand exposed to the air before filling into seedling pots, and the moisture content is determined by the relative humidity of the air and the time exposed to the air. So, the moisture content of the substrate exposedto the air is less than 22.6%. As shown in Table 2, the maximum repose angle of the substrate is not more than 30.35°, and the maximum sliding angle is not more than 42.34° in the natural moisture content condition. When the sliding angle is between 40° and 45°, the substrate is difficult to flow and easy to adhere to, which will cause the outlet of the hopper to be blocked (Wu, 1998). In order to ensure the flow of the substrate, the angle between the hopper wall and the horizontal plane was determined to be 60°. Meanwhile, a stirring shaft was set in the middle of the hopper to prevent substrate arching.

The hopper length was designed as 1000 mm, and the length of the stirring shaft was 960 mm. When the stirring shaft works, there is friction between the substrate and the stirring shaft, and the torque on the stirring shaft drives the transporting device (refer to the structure shown in Figure 5). So the main parameters of the stirring shaft were determined as Eq. (2-4) (Jiacong *et al*., 2019):

$$d_s = \left(\frac{16P_s}{\tau_T \cdot n_s}\right)^{\frac{1}{3}} \quad (2)$$

$$D_s = (0.2\text{~}0.5)B_s \quad (3)$$

$$L_s = \frac{1}{2}\left(D_s\text{-}d_s\right) \quad (4)$$

where, d_s is the diameter of the stirring shaft (m); P_s is the power transmitted by the stirring shaft (W); n_s is the rotating speed of the stirring shaft (rad/s); τ_T is allowable torsional shear stress of the stirring shaft (Pa); D_s is the length of the stirring range (m); B_s is the width of the hopper (m); L_s is the length of the stirring shaft (m).

Design of drive mechanism

The function of the drive mechanism is to drive the stirring shaft and move the transporting device simultaneously. It is mainly composed of an electric motor and transmission system. The structure is shown in Figure 5. The pull rod fixed on the drive chain

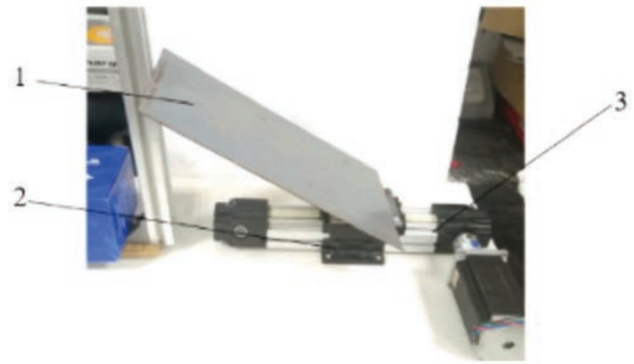

Figure 3. Measuring device of friction angle. 1) Steel plate; 2) slider; 3) linear guide rail.

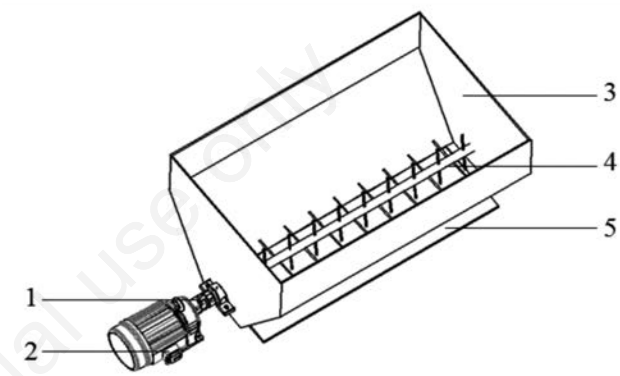

Figure 4. Structure of hopper component. 1) Coupling; 2) electric motor; 3) hopper; 4) stirring shaft; 5) bottom plate.

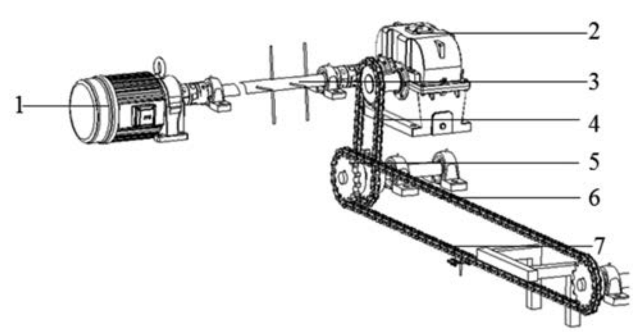

Figure 5. Structure of drive mechanism. 1) Electric motor; 2) gearboxbox; 3) stirring shaft; 4) drive chain; 5) conveyor chain wheel; 6) conveyor chain; 7) pull rod.

Table 2. Test results of substrate characteristics.

Moisture content of substrate, %	Repose angle, °	Sliding angle, °
13.6	20.36	30.72
16.6	23.95	33.80
19.6	26.90	37.20
22.6	30.35	42.34

cooperates with the fixed rod on the transporting device. When the last row of seedling pots is full, the pull rod moves in a circular motion around the conveyor wheel, the pull rod is disengaged from the fixed rod, and the transfer device stops moving forward.

According to the conveying distance of 1510 mm, the centre distance of the two conveying wheels was determined to be 1450 mm. The power required to drive the transporting device was calculated as follows:

$$P_d = T_c \cdot n_c \tag{5}$$

$$T_c = F_c \cdot R_c \tag{6}$$

$$F_c = \mu_t m_t g \tag{7}$$

where, P_d is the power required to drive the transporting device (W); n_c is the rotating speed of the chain wheel (rad/s); T_c is the resistance torque of the conveyor chain wheel (N·m); μ_t is the friction coefficient between the wheel of the transporting device and ground, μ_t=0.1; F_c is the friction force between the wheel of the transporting device and the ground (N); R_c is the radius of the chain wheel (m); m_t is the total weight of the transporting device when fully loaded (kg); g is the gravity acceleration, g=9.81 m/s^2.

Design of the flip mechanism

The cover plate is an auxiliary part of the transporting device, and the funnel-shaped hole on the plate corresponds to the seedling pot compartment. In order to get enough operation space, the cover plate should be able to flip, move back, and stop in the open state. In order to realise this function, a 5-bar linkage was designed, mainly composed of two connecting rods, a damper spring, a cover plate, and a frame. The kinematic diagram of the linkage mechanism is shown in Figure 6a.

Figure 6b shows the position of the flip mechanism in lifting and closing states. *DC* is the driving link, *AF* and *BE* are the connecting links, and *DF* is the cover plate. The solid lines in Figure 6b represent the cover plate's lifted position, and the dashed lines *AF*', *BE*', *CD*', *D*'*F*' indicate the closed position of the cover plate. The flip mechanism requires that the flip angle is and the overall backward shift is 45mm. Furthermore, considering the spatial layout, the conditions are as follows: *EF*=*E*'*F*'=300 mm, *OA*=45 mm, *AB*=91 mm∠, *FAF*'=60°, ∠*AE*'*E*=60°. The length of each link is determined by the geometric relationship in Figure 6b.

$$AF = \frac{OA}{\sin \angle FAF'} \tag{8}$$

$$EF^2 + AF^2 = AE^2 \tag{9}$$

$$PE = \cos \angle AE'E \cdot AE \tag{10}$$

$$PE^2 + AP^2 = AE^2 \tag{11}$$

$$PE^2 + (AP - AB)^2 = BE^2 \tag{12}$$

The results show that: *AF*=51.96 mm, *AE*=304.47 mm, *PE*=152.23 mm, *BE*=272.3 mm.

Design of steering mechanism

In order to ensure the unloading space of the seedling pots, no other parts can be designed at the bottom of the compartment of the transporting device. So, the steering system was designed as shown in Figure 7, which controls the steel wire rope to drive the two front wheels steering.

When steering, the angle of the inner and outer wheels should conform to the Ackermann steering principle (Wang *et al*., 2020). The isosceles trapezoid steering mechanism was designed to control the angle difference between the two steering wheels. The trapezoid structure is shown in Figure 8.

The overall design gave the centre distance between the two steering wheels of the transporting device. Therefore, the steering trapezoidal mechanism can be determined as long as the other two independent parameters are determined. A coordinate system was established, as shown in Figure 9. In this coordinate system, *AD=a,*

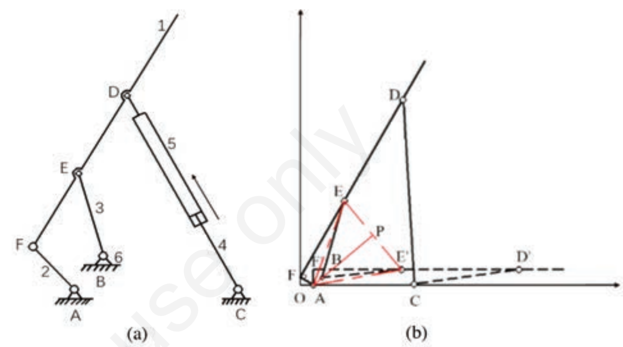

Figure 6. Structure of drive mechanism. 1) Electric motor; 2) gearboxbox; 3) stirring shaft; 4) drive chain; 5) conveyor chain wheel; 6) conveyor chain; 7) pull rod.

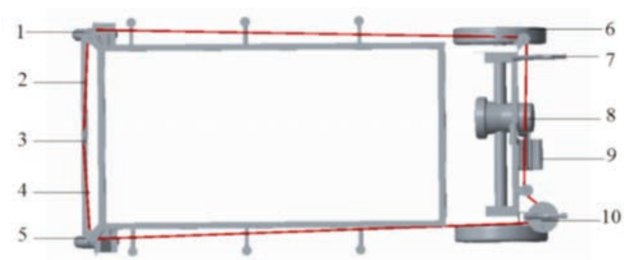

Figure 7. Diagram of the steering system. 1) Front wheel; 2) front-wheel synchronising link wheel; 3) wire rope connector; 4) wire rope; 5) pulley; 6) back wheel; 7) handle; 8) electric motor; 9) rechargeable battery; 10) rope drum.

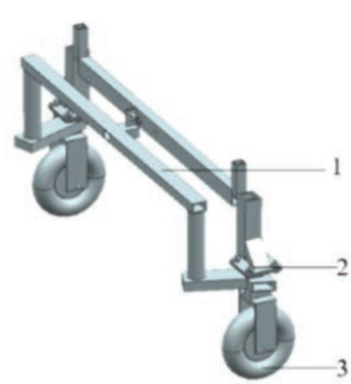

Figure 8. Steering mechanism. 1) Connecting rod; 2) bolt; 3) steering.

AB=*b*, the bottom angle of the trapezoidal mechanism is q. When turning, the rotation angle of *AD* is β and the rotation angle of *BC* is a. After a certain angle of deflection, the angle between *AD* and the x-axis is γ, and the angle between the *BC* and the x-axis is δ.

The angle relationship between the inner and outer wheels of the steering trapezoid and the angular displacement equation can be obtained by the method of analytical geometry.

$$\begin{cases} \alpha=180-\theta-\delta \\ \beta=\theta-\gamma \end{cases} \tag{13}$$

$$\frac{M}{a}\cos\gamma-\frac{M}{a}\cos\delta+\frac{b^2-2a^2-M^2}{2a^2}=-\cos(\gamma-\delta) \tag{14}$$

According to experience (Wu, 1998), the bottom corner q is preliminarily selected as follows:

$$\theta=\tan^{-1}\left(\frac{1.56H}{M}\right) \tag{15}$$

where *H* is the distance between the front and rear wheels. *M* is the distance between the two steering wheels.

Two groups of inner and outer angles (β_1, α_1), (β_2, α_2) which meet Ackerman steering theory (Eq. 16) are preliminary selected, and the inner angle β_1=0, β_2=(0.8~0.95) β_{max}·β_{max} is the max rotation angle of *AD*.

$$\cot\alpha-\cot\beta=\frac{M}{H} \tag{16}$$

θ, (β_1, α_1) and (β_2, α_2) were substituted into Eq. (13), and Eq. (14), then the steering trapezoid can be determined, and the designed steering trapezoidal mechanism generally can meet the requirements of the turning angle error.

Optimisation of operating parameters

The filling of the seedling pot requires that the substrate falling speed matches the moving speed of the transporting device. The substrate falling speed is related to the substrate's characteristics, the hopper opening's size, and the stirring shaft's rotating speed. The influence of the hopper opening size, the stirring shaft rotating speed, the seedling substrate moisture content and the transporting device's speed on the filling effect of the seedling pot were studied, and the best operating parameters were determined.

Materials and devices

The seedling substrate used in the experiment was mixed according to the volume ratio of loess, plant ash, perlite, and vermiculite 5:3:1:1. The seedling pot material used in the test is polyethylene hard plastic, which looks like an inverted cone and the top size is 100 mm × 100mm, 300 mm high. During the test, the transporting device is driven by the speed controller. The test materials and devices are shown in Figure 10.

Evaluation index

The evaluation index of the filling effect includes filling quality and uniformity. Filling quality was assessed by the average value of pot masses, and filling uniformity was assessed by the coefficient of variation of the mass. After filling, the seedling pots were weighed by an electronic balance (accuracy of 0.01 kg).

Test factors and methods

According to the single-factor test results, the main factors and scopes that affect the filling effect are determined as follows: the opening width of the hopper is 120 mm~160 mm, the rotation speed of the stirring shaft is 56r/min~70r/min, and the speed of the transporting device is 0.034 m/s~0.046 m/s, the moisture content of the substrate is 13.6%~19.6%. A four-factor five-level quadratic regression orthogonal rotation combination experiment was carried out (Yuan and Yun, 2007). The factor level coding table is shown in Table 3.

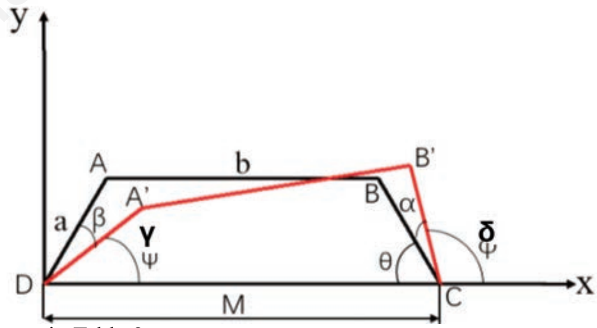

Figure 9. Steering trapezoid coordinate system.

Figure 10. Materials and device for loading test.

Results and Discussion

Operating parameters optimisation results

A total of 23 groups of tests were conducted according to quadratic regression orthogonal rotation combination design. Each test was repeated 3 times, and the average value was taken. The test results are shown in Table 4. It can be seen from Table 4 that in the orthogonal rotation combination design test, the average filling mass of the seedling pot is more than 1.7 kg, and the coefficient of variation of the mass is less than 4.5%.

Regression analysis was conducted on the test data, and quadratic regression models were established for filling mass, coefficient of variation of the mass, hopper opening width, steering shaft speed, speed of transporting device, and matrix moisture content. Variance analysis was conducted, as shown in Table 5. It can be seen from the variance analysis in Table 5 that the regression model tests of the loading quality and the coefficient of variation of the mass were significant ($P<0.01$), so the regression reached the significance level. Each factor significantly impacted the average filling quality and the coefficient of variation of the mass.

The regression equation is not significantly mismatched and fits well with the actual situation. The other items were removed due to insignificant differences, and the expression of the obtained regression equation was as follows:

$$y_1=1.7606-0.0095Z_1-0.0076Z_2+0.0077Z_3-0.0219Z_4+0.0148Z_1Z_4-0.0052Z_2^2-0.0062Z_4^2 \tag{17}$$

$$y_2=3.129-0.146Z_1-0.110Z_2-0.049Z_3-0.025Z_4-0.038Z_1Z_4+0.186Z_1^2+0.108Z_3^2 \tag{18}$$

Table 3. Coding table of test factor level.

Coding level	Factors			
	Width of adjusting plate opening Z_1, mm	Forward speed of transfer device Z_2, $m \cdot s^{-1}$	Rotating speed of the shaft Z_3, $r \cdot min^{-1}$	Moisture content of the substrate Z4, %
1.682	160	0.046	70	19.6
1	151.9	0.044	67.16	18.38
0	140	0.040	63	16.6
-1	128.1	0.036	58.84	14.82
-1.682	120	0.034	56	13.6

Table 4. The results of quadratic regression combination tests.

Test No.	Experimental factors				Test results	
	Z_1	Z_2	Z_3	Z_4	Average filling mass, kg	Coefficient of variation of the mass, %
1	1	1	1	1	1.724	2.95
2	1	1	-1	-1	1.733	3.14
3	1	-1	1	-1	1.757	3.47
4	1	-1	-1	1	1.742	3.35
5	-1	1	1	-1	1.807	2.86
6	-1	1	-1	1	1.704	3.60
7	-1	-1	1	1	1.756	2.90
8	-1	-1	-1	-1	1.795	3.85
9	1.682	0	0	0	1.750	3.35
10	-1.682	0	0	0	1.764	4.48
11	0	1.682	0	0	1.735	3.21
12	0	-1.682	0	0	1.748	3.38
13	0	0	1.682	0	1.774	4.08
14	0	0	-1.682	0	1.753	3.31
15	0	0	0	1.682	1.699	3.38
16	0	0	0	-1.682	1.778	3.39
17	0	0	0	0	1.753	3.27
18	0	0	0	0	1.749	3.25
19	0	0	0	0	1.760	2.94
20	0	0	0	0	1.761	3.65
21	0	0	0	0	1.756	2.96
22	0	0	0	0	1.766	3.15
23	0	0	0	0	1.773	3.74

where, y_1 is the regression value of average filling mass (kg); y_2 is the regression value of the coefficient of variation of the mass (%).

According to the requirements of the filling effect, the maximum value of average filling mass was taken, and the minimum value of mass variation coefficient was taken. The optimal parameter combination was obtained as shown in Table 6. It can be seen from Table 6 that for the two groups of optimal parameter combination, the forward speed level value of the transporting device is 1.682, the substrate moisture content level value is -1.682, the opening width of the hopper has little difference, taking the mean value, the rotating speed of the steering shaft has little difference take the mean value. After comprehensive consideration, the optimal parameter combination is as follows: the opening width of the hopper plate is 148 mm, the forward speed of the transporting device is 0.046 m/s, the rotational speed of the steering shaft is 69.2 r/min, and the substrate water content is 13.6%. By substituting the best combination of parameters into Equations (17) and (18), it can be obtained that the average filling mass is 1.887 kg, and the coefficient of variation of the mass is 2.85%.

Testing results

In order to verify the filling effect of the best parameter combination, a test prototype was produced for testing. The test prototype and the filling and unloading effect are shown in Figure 11.

Table 5. Variance analysis of orthogonal rotation combination tests.

Source	Average filling mass			Coefficient of variation of the mass		
	Sum of squares	Degree of freedom	F	Sum of squares	Degree of freedom	F
Regression model	0.0098	7	22.47**	1.960	7	31.77**
Z_1	0.0002	1	9.46**	0.026	1	19.15**
Z_2	0.0045	1	5.11*	0.340	1	11.90**
Z_3	0.0000	1	8.71**	0.001	1	23.15**
Z_4	0.0001	1	11.71**	0.007	1	9.51**
Z_{12}	0.0007	1	1.44	0.220	1	6.24*
Z_{22}	0.0000	1	6.73*	0.380	1	2.08
Z_{32}	0.0001	1	0.29	0.370	1	9.13**
Z_{42}	0.0005	1	5.42*	0.095	1	0.52
Z_1 Z_2	0.0019	1	3.91	0.110	1	0.62
Z_1 Z_3	0.0009	1	1.94	0.003	1	0.02
Z1 Z_4	0.0000	1	9.15**	0.220	1	10.23**
Z_2 Z_3	0.0005	1	1.14	0.026	1	0.15
Z_2 Z_4	0.0024	1	5.06	0.078	1	0.43
Z_3 Z_4	0.0001	1	0.18	0.034	1	0.19
Residual	0.0015	15		1.450	15	
Lack of fit		4	2.02	1.000	4	1.55
Total	0.0136	22		3.410	22	

$F_{0.05}(7,15)=2.71$; $F_{0.01}(7,15)=4.14$; $F_{0.05}(1,15)=4.54$; $F_{0.01}(1,15)=8.68$; $F_{0.05}(4,15)=3.06$; $F_{0.01}(4,15)=4.89$; **denotes the significance of variance analysis at the 0.01 probability levels; *denotes the significance of variance analysis at the 0.05 probability levels.

Table 6. Optimal parameter combination.

	Z_1	Z_2	Z_3	Z_4 mm	X_1 $m \cdot s^{-1}$	X_2 $r \cdot min^{-1}$	X_3 %	X_4
Average filling mass	0.731	1.682	1.682	-1.682	148.7	0.046	69.9	13.6
Coefficient of variation of the mass	0.564	1.682	1.237	-1.682	146.9	0.046	68.4	13.6

Figure 11. Prototype machine tests.

Table 7. Test results of reproducibility test in combination with optimal factors.

Test No.	Width of hopper opening, mm	Forward speed of transfer device, m·s^{-1}	Rotating speed of steering shaft, r·min^{-1}	Moisture content of substrate, %	Average filling mass, of the mass,kg	Coefficient of variation %
1	148	0.046	69.2	13.6	1.878	2.88
2	148	0.046	69.2	13.6	1.881	3.11
3	148	0.046	69.2	13.6	1.883	2.93
Average					1.881	2.97

In the filling test, the best combination of parameters was used to repeat the test three times. The prototype ran smoothly during the test, with 120 pots being filled simultaneously, and the average filling time was about 40 s. The filling and unloading conditions of seedling pots were good, and seedling pots were arranged neatly. The test results are shown in Table 7.

It can be seen from Table 7 that the average filling mass test value is 1.881 kg, with a difference of 0.006 kg from the predicted value and a relative error of 0.32%. The mass variation coefficient test value is 2.97%, 0.12% difference from the predicted value and a relative error of 4.0%. The test results verify the correctness of the predicted operating parameters.

The filling and transfer tests of the prototype showed that the structure design of the prototype was reasonable, and the filling uniformity and filling efficiency were high.

Conclusions

A new filling and transporting machine for filling 120 pots at a time is designed. The structure design is reasonable, and the filling uniformity and efficiency are high.

Under the optimal combination of operating parameters, the average filling mass of the prototype is 1.881 kg, the variation coefficient of the mass is 2.97%, and the single filling time is 40 s.

The research results can provide a reference for developing and optimising the equipment for filling and transporting citrus seedling pots.

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