

Drill-Suction Removal of Substandard Seedling Blocks in Greenhouse Tray Production

Xiaoqin Wang

Zhejiang Sci-Tech University

Shuyi Liu

Zhejiang Sci-Tech University

Jia Lu

Zhejiang Sci-Tech University

Junhua Tong

jhtong@zstu.edu.cn

Zhejiang Sci-Tech University

Feilong Wu

Zhejiang Sci-Tech University

Zhengjie Ye

Zhejiang Sci-Tech University

Article

Keywords: Tray seedlings, Negative pressure adsorption, Drill-suction removal, Response surface analysis

Posted Date: September 3rd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10666157/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Drill-Suction Removal of Substandard Seedling Blocks in Greenhouse Tray Production

Xiaoqin Wang^{a,b}, Shuyi Liu^a, Jia Lu^a, Junhua Tong^{a,b*}, Feilong Wu^a,

Zhengjie Ye^a

^a School of Mechanical Engineering, Zhejiang Sci-Tech University, Hangzhou 310018, China

^b Key Laboratory of Agricultural Equipment for Hilly and Mountainous Areas in Southeastern China (Co-construction by Ministry and Province), Ministry of Agriculture and Rural Affairs, Hangzhou 310018, China

Abstract: During the greenhouse tray seedling propagation process, some cells often experience missed seed sowing or stunted seedling growth, requiring the timely removal of such defective seedlings and replacement with healthy seedlings. Currently, the removal of substandard seedling substrate clumps is primarily carried out using the end of a standard transplanting machine. there are few machines specifically designed for this purpose. This often results in the substrate being crushed or left behind during removal, severely hindering the normal progress of the replanting process. This study attempted to replace traditional mechanical methods with a negative pressure approach, and preliminary results demonstrate its feasibility. However, it was also found that, due to factors such as the inherent clumping properties of the substrate or insufficient air pressure from the blower, negative pressure removal of the substrate often results in blockages at the pipe inlet. Therefore, a drill-suction anti-clogging structure was designed, and a three-factor, three-level response surface analysis experiment was conducted, with the tip inlet diameter, the draft angle of the “n”-shaped opening, and the tip descent height as key factors. The results showed that the optimal combination was a tip inlet diameter of 13 mm, a draft angle of 8.4° for the “n”-shaped opening, and a terminal descent of 21 mm. A dual-terminal synchronous operation mode was designed, which can effectively control pipeline blockages under a given negative pressure. when both ends are activated simultaneously, the cleaning efficiency decreases due to factors such as flow diversion, which is particularly noticeable under high moisture content conditions. however, this lays the foundation for further research on multi-end high-efficiency synchronous operation schemes for the substrate. when operating with a single end, regardless of whether the left or right side is activated, the substrate cleaning efficiency can be maintained at over 80%, which generally meets the requirements for seedling replanting.

Keywords: Tray seedlings; Negative pressure adsorption; Drill-suction removal; Response surface analysis

1. Introduction

During greenhouse tray seedling cultivation, it is common to find that some seedlings exhibit stunted growth. Influenced by factors such as individual seed variations and changes in the growing environment, the overall germination rate per tray ranges from 80% to 95%, with 5%-20% of the cells exhibiting missed sowing, failure to germinate, or poor seedling development^[1], as shown in **Fig.1**. This severely impacts the mechanized transplanting operations or sales of the entire tray of seedlings after they leave the nursery. Therefore, it is necessary to thoroughly remove the substrate clumps from these cells in advance and promptly replant them with healthy seedlings^[2]. Currently, the removal and replanting of defective seedlings in Chinese greenhouses is still partially carried out manually, resulting in low efficiency, high labor intensity, and high labor costs, as shown in **Fig.2**. Developing intelligent greenhouse equipment for the removal, replanting, and transplanting of seedlings can effectively address the equipment shortage in the seedling cultivation process.



Fig.1. Distribution ratio of inferior seedlings



Fig.2. Manually removing inferior seedlings

Currently, the main methods for removing defective seedlings from growing media in China include mechanical end-insertion, ejection-and-gripping, negative-pressure suction, and positive-pressure air-blowing. The mechanical end-insertion and ejection-and-gripping methods are primarily used for transplanting healthy seedlings. Based on structural design, the mechanical end-insertion method can be further classified into finger-spade and steel-needle types. The finger-spade type^[3] uses a shovel blade to grasp the substrate in a single block. its structure is relatively complex, making it difficult to implement a multi-end array layout. Jin^[4] and others utilized seedling growth status detection and visual servo control to assess seedling health and perform targeted transplanting actions. Liang Xifeng^[5] and others focused primarily on the issue of empty cells in seedling trays during greenhouse tray propagation-caused by uncontrollable factors such as seed quality and growing conditions-and developed a dedicated end-effector for removing and replacing seedlings. The optimal combination for substrate removal efficiency was found to be 26 days, a substrate ratio of 2:2:1, and a substrate moisture content of 74.1%, providing a relatively high-performance shovel-type end-effector for the removal, replacement, and transplanting of greenhouse tray seedlings. Miao Hong^[6] et al. designed a shovel-type seedling removal and replanting mechanism for the cultivation of chili pepper seedlings and developed a corresponding control system. Using 45-day-old chili pepper tray seedlings as the research subjects, they set the

horizontal travel speed, end-effector seedling retrieval depth, and substrate moisture content as experimental variables to analyze trends in the success rates of removing defective seedlings from the substrate and replanting. The results showed that changes in the tip seedling extraction depth and substrate moisture content had a significant impact on the overall seedling removal success rate and the associated transplanting success rate. Under the relevant combinations, the average seedling removal success rate reached as high as 94%, and the transplanting success rate reached as high as 91.1%. The steel-needle type^[7] is a simplified version of the finger-shovel type. It uses a rigid needle to penetrate the substrate to gather and grip the seedlings, but the substrate tends to become loose and spill during operation. Sun^[8] et al. designed a four-finger substrate removal end-effector and proposed a path planning algorithm based on improved particle swarm optimization, which reduced the time required to remove defective seedlings from an entire tray. Xu^[9] et al. proposed a binary classification-based health assessment method. Based on the classification results, substandard potted seedlings are removed. Du^[10] et al. conducted research on issues such as the difficulty in controlling end-effector needle spacing and needle convergence angle. Using a 200-cell tray as the test subject, they designed a system with a grasping acceleration of 0.28m/s^2 , a penetration angle of 11° , a substrate insertion depth of 32 mm, and an insertion margin ratio of 10%, achieving a substrate grasping rate of over 90%. Han^[11] and colleagues designed a simplified four-finger end-effector driven by a pneumatic cylinder, capable of effectively grasping, holding, and releasing seedling substrate blocks. Experiments found that the best seedling removal results were achieved when the end-effector's transplanting frequency was set to 15 plants/min, the spring tension was set to 1.2 N, and the end-effector's insertion depth into the substrate was 35 mm.

The ejector clamping type^[12] uses a pusher rod or airflow to pre-push the substrate from below before the end effector grips it. However, the small size of the bottom hole makes it difficult to align the ejection device with the planting hole. Li Bo^[13] and colleagues addressed the issue of damage to healthy leaves surrounding the planting hole during mechanical transplanting operations by designing a system that uses a jet air tube to blow aside obstructing leaves. High-pressure airflow is utilized to expand the working space at the tip of the transplanting tool. Experiments showed that when the leaf-blowing device operated in conjunction with the seedling removal tool-with 8 jet holes in the air tube, each 1.2 mm in diameter, and a pressure of 0.28 MPa-the success rate for removing seedlings from pots reached 92%. Hu Jianping^[14] et al. innovatively proposed a seedling retrieval device based on a combination of pushing and clamping mechanisms. Through testing, they determined the adhesion force and corresponding displacement of seedlings at different pushing speeds. The results indicated that the optimal diameter of the pushing rod is 6 mm, the pushing displacement is 15 mm, and the depth of the clamping jaws into the seedling pot should be 35 mm. At a retrieval speed of 225 mm/s, the seedling retrieval success rate reached 94.12%.

The negative-pressure suction method uses a vacuum generator to create negative pressure and

extract defective seedlings. While this method improves the thoroughness of substrate removal, it is prone to pipe blockages-particularly at inlets or bends-and the limited spatial structure makes it difficult to resolve the issue by simply increasing pipe diameter. Cui Yongjie^[15] et al. developed an innovative pneumatic suction-type substrate removal end-effector that utilizes negative pressure to adsorb and remove substrate from holes with missing seedlings. Using a coupled DEM-CFD simulation, the study evaluated the effects of nine pneumatic suction port configurations on removal performance. At an air pressure of 0.5 MPa, a substrate moisture content of 50%–55%, an adsorption time of 3 s, and when used in conjunction with a silicone pad, a substrate removal rate of over 90% can be achieved, with an overall operational efficiency of approximately 57 s per tray. The positive-pressure air-blowing method^[16] uses airflow impact to blow the substrate out. Typical examples include the Dutch companies Flier Systems and TTA. This method has two major issues, it is difficult to control the positive pressure level. if the air pressure is too low, the substrate cannot be blown away, and if it is too high, the substrate scatters and splatters. the dislodged substrate scatters randomly, making it difficult to collect centrally, and it may land on the leaves of healthy seedlings, affecting their further growth.

Based on the above research findings, to achieve automated and efficient seedling culling in industrialized greenhouse seedling cultivation, the method of conveying substandard seedling growing media via negative pressure is feasible. However, under the negative-pressure culling scheme, sedimentation and blockages are prone to form inside the pipes. Therefore, the pipe structure was optimized while maintaining a constant negative-pressure input, this study attempted to combine mechanical and vacuum methods by using a drill-suction approach to break up and remove substrate clumps, while optimizing the design of the suction nozzle tip to prevent clogging during the removal process.

2. Materials and methods

2.1 System structure and analysis

To achieve high efficiency in greenhouse seedling cultivation, the design of a seedling culling and replacement production line is of great significance, as shown in **Fig.3**.

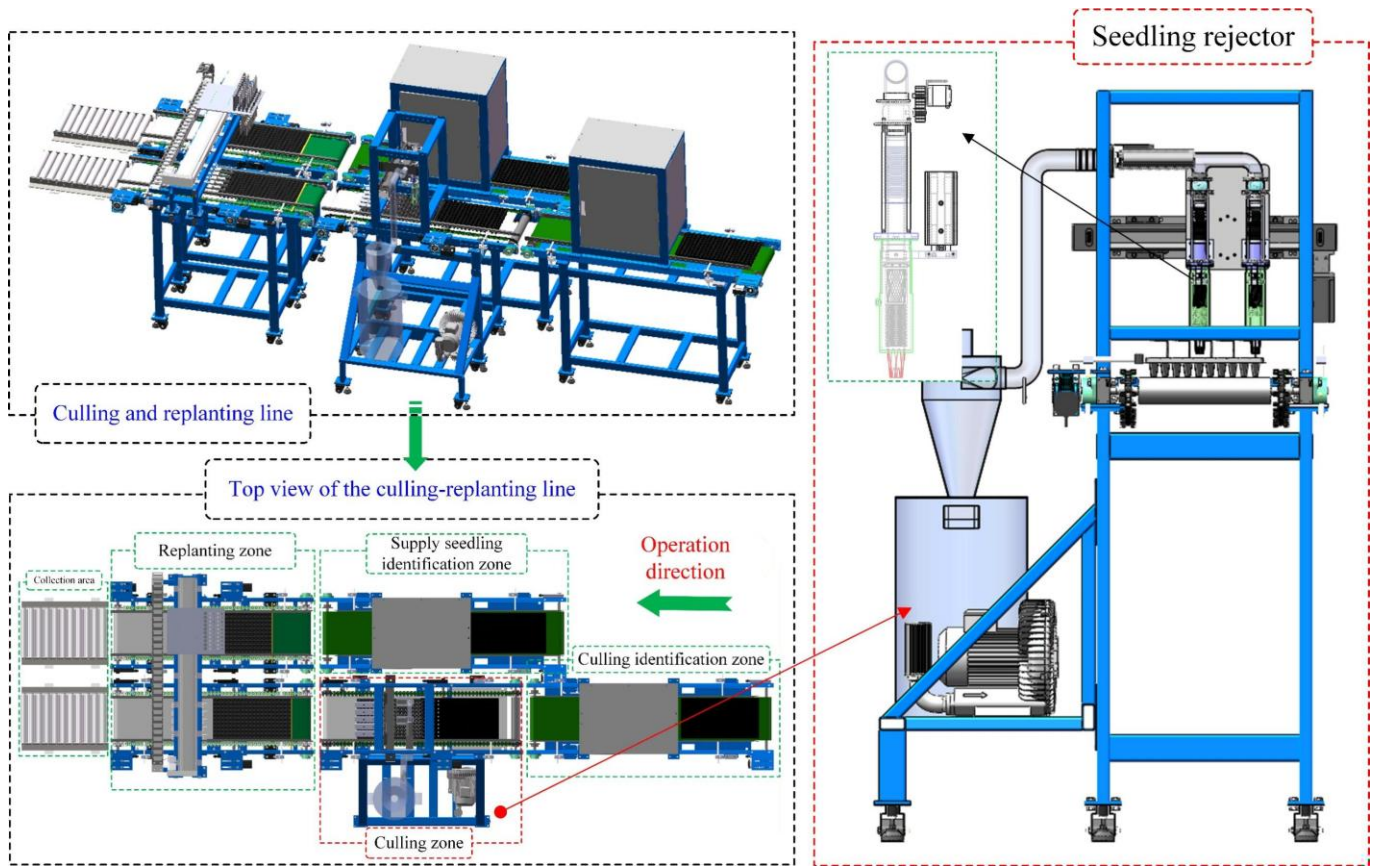


Fig.3. Three-dimensional structure of the seedling removal zone

The seedling culling and replacement system consists of several sections, the seedling culling identification zone, the seedling culling zone, the seedling supply identification zone, the seedling replacement operation zone, and the collection zone. This study focuses its analysis on the seedling culling zone, with the primary objective of ensuring the clean and smooth removal of substandard seedlings from their growing media.

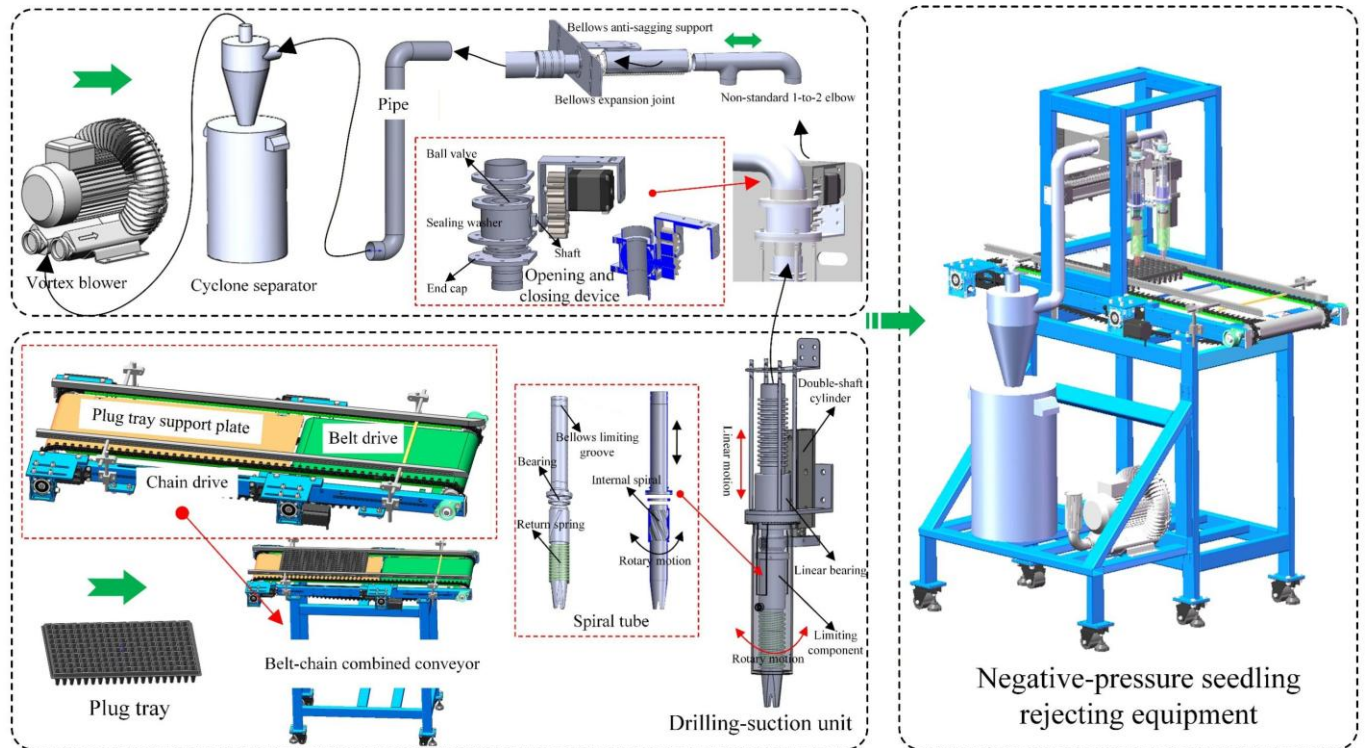


Fig.4. Component diagram of the seedling removal equipment

Tab.1. Summary of test part parameters

Part Name	Model
Vortex fan	HG-750W/220V
Cyclone separator	50×50×880×417 mm
Twin-shaft cylinder	TR10×45S
Transverse movement module	RXP60-L300
DC motor	120 W, 280 r/min
57 Closed-loop stepper motor	57ZDT56C
Ball valve actuator	28HS2401-22B-600
Laser through-beam sensor	E3F-20C1/20L
Magnetic switch	DMSM-020
Servo motor controller	SV630-400W
RV30 gearbox	Reduction Ratio 7.5

The structure of the seedling removal machine designed in this study primarily includes, a vortex blower, a cyclone separator, an end-effector, a lateral movement module, and a conveyor belt. The vortex blower provides the negative pressure required for the machine's operation. the cyclone separator is primarily responsible for collecting the substrate from defective seedlings via spiral settling without damaging the blower. The end effector crushes and conveys the substrate. and the lateral movement module and dual-axis cylinders drive the end effector to move horizontally and vertically. The conveyor belt employs a combined chain-and-belt drive design to ensure that seedling trays can be smoothly transferred between sections after completing corresponding operations in different zones (The belt drive

moves trays forward while keeping them flat, chain drives transfer trays between sections). A model of the entire machine is shown in **Fig. 4**. The parameters of relevant parts and supporting components are summarized in **Tab.1**.

2.2 Design and analysis of key components

2.2.1 Structural design and simulation optimization of the bend

The pipe cross-section is designed as a circle, and the pipe geometry is defined by the combination of the bend diameter D and the bending radius R_b , as shown in **Fig.5**. For any combination, the pipe geometry must satisfy the constraint $R_b > D/2$ (i.e., the bending radius must be greater than the pipe radius). For a 90° pipe bend, extensive prior experiments have established that the pipe diameter D is 26 mm. The curvature ratio $\zeta = D/R_b$. assuming a bending radius R_b of 30 mm, then $\zeta = 0.87$. The length of the inlet section is set to 130 mm, and the length of the outlet section of the elbow is set to 260 mm. In the experiment, the inlet and outlet sections were initially designed to be sufficiently long to avoid an abrupt termination of flow, while the outlet section was extended to ensure the accuracy of the downstream computational domain. The analysis is performed at a cross-section located $0.67D$ from the elbow outlet (Dean's vortex-stable surface). The distance from the elbow outlet is denoted as Y . For the analysis, the vertical centerline of the cross-section along the z -direction is defined as line A, and the horizontal centerline along the x -direction is defined as line B. Gravitational acceleration is set in the negative y -direction, and the fluid is air, which is assumed to be a continuous, incompressible fluid.

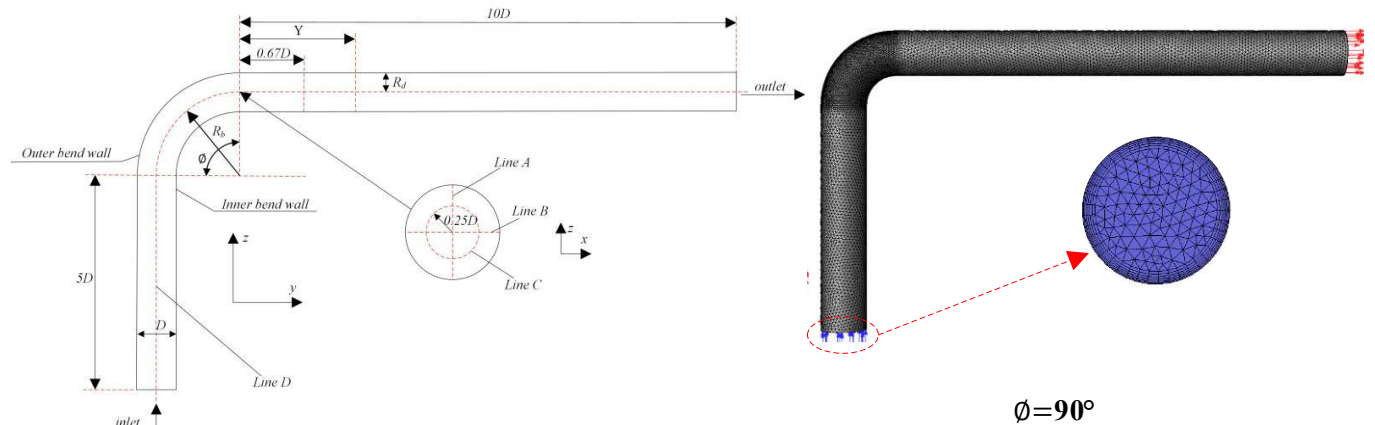


Fig.5. Schematic diagram of the circular elbow cross-section

(1) Mesh independence verification

Before starting the simulation, operations such as mesh generation were performed to discretize the spatial topology. A structured hexahedral mesh was used for the calculation, with boundary layer refinement applied near the pipe wall to simulate particle flow near the boundary layer as accurately as possible. the number of boundary layers was set to 7. Additionally, since flow conditions in the elbow are more complex than in straight pipe sections, local mesh refinement was required at the elbow. Changes in the number of mesh elements directly affect simulation results, influencing not only the computational accuracy of the flow field but also the convergence of the iterative calculations. An excessive number of

167 mesh elements leads to prolonged computation times, while too few compromise computational accuracy.
 168 Therefore, mesh independence tests^[17] must be conducted prior to the simulation .Using a 90° elbow as
 169 an example for mesh generation, mesh independence tests were conducted using changes in inlet and
 170 outlet pressures as indicators (see **Tab.2**). The tests showed that when the number of mesh elements
 171 exceeded 135,042, the pressure in the elbow remained essentially constant regardless of changes in the
 172 number of mesh elements. Consequently, the number of mesh elements was set around this value for this
 173 experiment. Subsequent mesh generation was also based on this finding.

174 **Tab.2. Results of mesh independence verification**

No	Number of mesh elements	Pressure/kPa
1	33,506	0.3136
2	59,232	0.3470
3	135,042	0.3585
4	207,053	0.3610
5	565,333	0.3650

175 (2) Analysis of the flow field at the pipe bend

176 In this experiment, the Eulerian method was used to simulate the flow field for the fluid phase,
 177 while the Lagrangian method was used to simulate the forces acting on and the motion of particles in the
 178 flow field. To improve computational efficiency, a unidirectional coupling method was employed to track
 179 the particle trajectories, with particles assumed to be smooth spheres. The particle trajectories were
 180 obtained by integrating the force balance equations according to Newton's Second Law, and the k-ε
 181 turbulence model was selected for the calculation process. The inlet boundary condition was set as a
 182 pressure inlet with an inlet pressure of 0 kPa, and the outlet boundary condition was set as a pressure
 183 outlet with an outlet pressure of -3.2 kPa. No-slip boundary conditions were applied to the pipe walls at
 184 both the inlet and outlet straight sections as well as at the elbow. The SIMPLEC algorithm was used to
 185 solve the coupled pressure and velocity fields, with the turbulent kinetic energy residual set to 10^{-5} .

186 To ensure the reliability of the results, this paper drew upon previous research for validation^[18] ,
 187 maintaining settings essentially identical to those of previous studies and comparing results at the same
 188 cross-sections (**Fig.6**). The main comparisons were made with the PIV experimental results by Kalpakli^[19]
 189 and the simulation results by zhang^[20] .

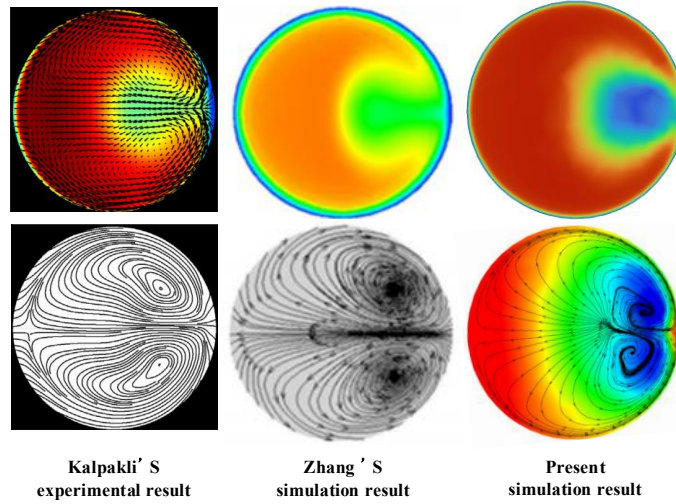


Fig.6. Reliability test of the simulation model

Due to differences in the bend angle, the forces acting on the particles and their motion states change as they flow through the bent pipe, and erosion of the outer pipe wall may even occur. To thoroughly analyze the characteristics of changes in the downstream fluid domain, equidistant slices of the downstream pipe ranging from 0 to 10D were extracted. the results are shown in **Fig.7**.

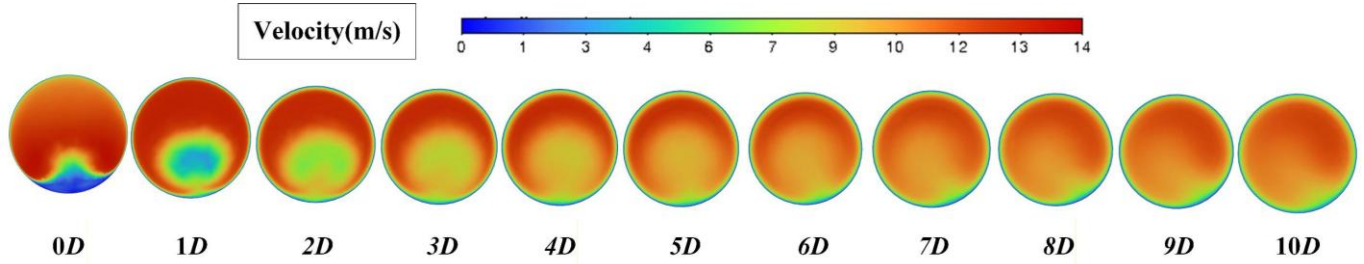


Fig.7. Secondary flow phenomena at different cross-section distances

It can be observed that secondary flow occurs near the outlet of the elbow. as the distance increases, the secondary flow gradually weakens. The phenomenon is most pronounced within the 0-2D range. velocity changes gradually stabilize between 3 and 7D. and after 8D, the downstream velocity remains essentially constant. Particles collide with the wall under the influence of fluid adsorption. at the elbow, kinetic energy is converted into pressure energy. Velocity decreases near the wall, and the overall velocity exhibits an axisymmetric distribution, gradually increasing from the center toward both sides.

As shown in the pressure distribution contour plot in **Fig.8(a)**, when particles transition from vertical to horizontal motion within the pipe, centrifugal force causes them to strike the outer wall of the elbow at high speed, thereby creating a local high-pressure zone, while a local low-pressure zone forms on the inner side of the elbow. As shown in the velocity distribution contour plot in **Fig.8(b)**, the change in particle trajectory causes a decrease in velocity at the outer wall of the elbow, while a local high-velocity region forms on the inner side. This is consistent with Bernoulli's principle, which states that velocity decreases as static pressure increases.

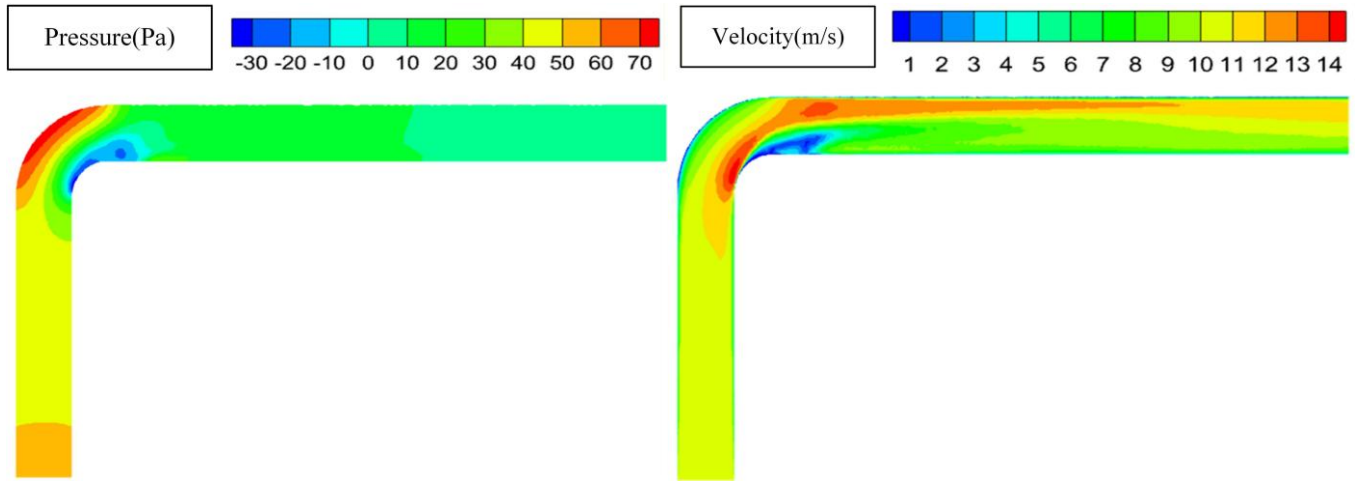


Fig.8. Velocity distribution contour plot of the elbow cross-section

2.2.2 Terminal design and optimization

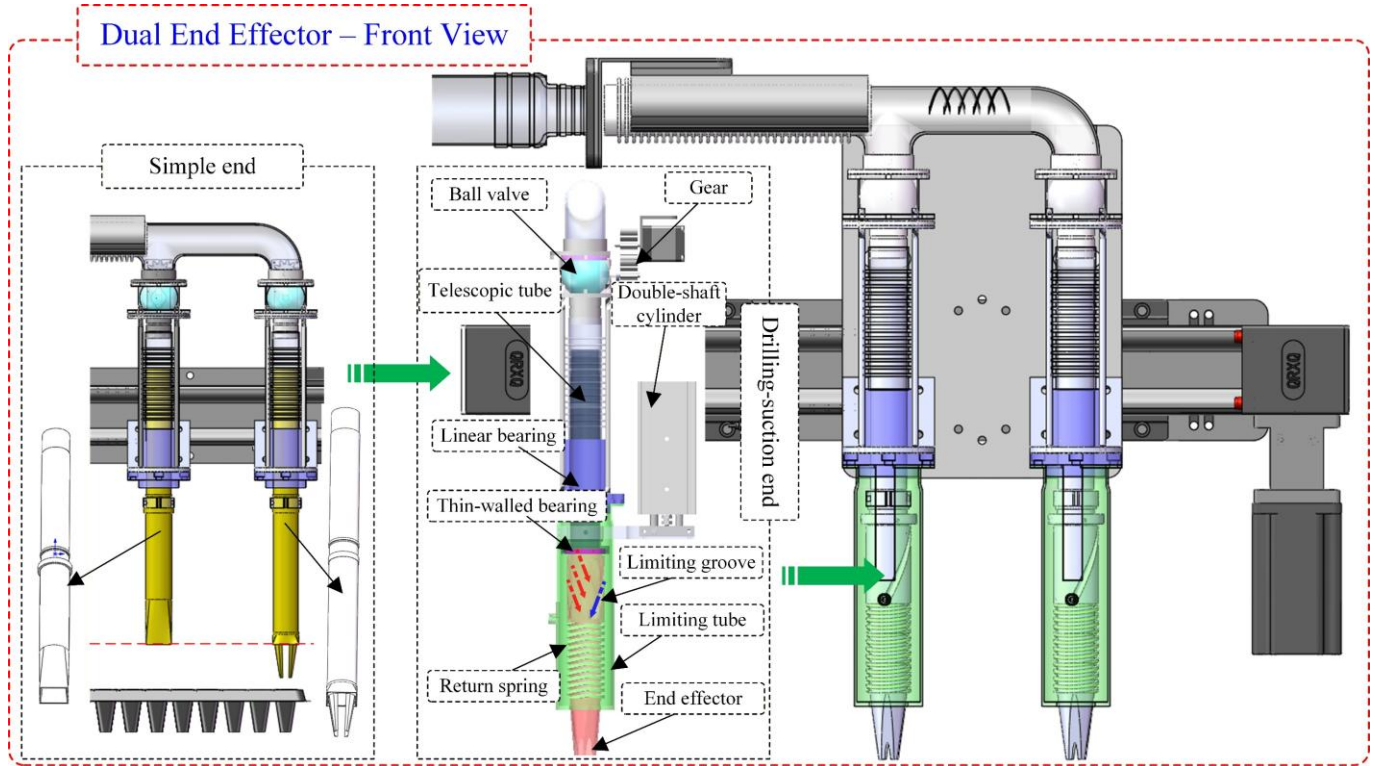


Fig.9. Schematic diagrams of different three-dimensional terminal structures for the

To effectively address blockages in the negative-pressure substrate pipeline removal process while minimizing design complexity and reducing design costs, this study focuses on issues such as excessive substrate agglomeration that cause pipeline blockages. An integrated drill-suction tip structure was designed to provide a solution for effective negative-pressure substrate removal.

The operating principle of the integrated drill-suction mechanism is shown in **Fig.9**. While ensuring a continuous supply of negative pressure, a guide groove is installed on the outer side of the end effector and a guide tube is nested within it. A dual-axis pneumatic cylinder drives the end effector to descend in a helical motion to mechanically break up the substrate clumps. Once the substrate suction is complete, the cylinder retracts, and a return spring works in conjunction with it to snap the end effector back up,

225 completing the suction cycle. To enhance the degree of substrate fragmentation, a swirl channel is
 226 installed on the inner side of the end effector. the spiral angle and height can be adjusted as needed to
 227 further increase the degree of fragmentation of the substrate block. The overall design employs a dual-end
 228 convergent mechanism, which effectively improves operational efficiency within a limited working space.

229 (1) End-effector simulation analysis and optimization

230 To quantify the entire process of substrate removal under the sealed adsorption scheme and to
 231 observe the substrate's motion trajectory and fragmentation status, the CFD-DEM two-way coupling
 232 method was employed-building upon the aforementioned unidirectional coupling framework-to simulate
 233 the complete particle adsorption process under various input conditions. The study employed an
 234 Euler-Lagrange framework model, in which the EDEM software established an agglomerate particle
 235 bonding model and was coupled with FLUENT using the Hertz-Mindlin with JKR contact model. the
 236 relevant parameters are listed in **Tab.3**.

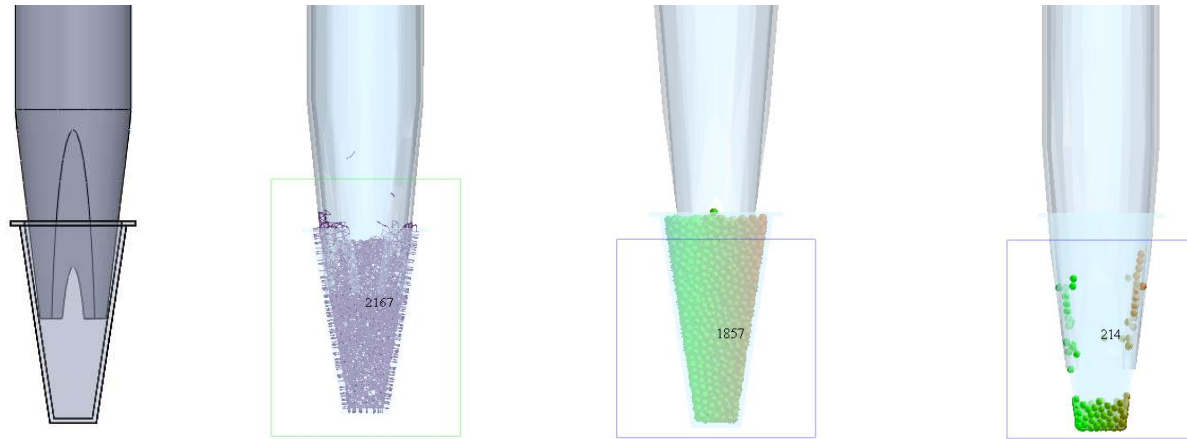
237 **Tab.3. Summary of substrate simulation parameters**

Parameter	Value
Poisson's ratio	0.35
Shear modulus/Pa	1.3×10^7
Density/($\text{kg} \cdot \text{m}^{-3}$)	1721.95
Substrate particle-particle collision recovery coefficient	0.142
Substrate particle-particle static friction coefficient	0.5385
Substrate particle-particle rolling friction coefficient	0.097
Substrate particle-wall collision recovery coefficient	0.16
Static coefficient of friction between substrate particles and the wall	0.223
Rolling friction coefficient between substrate particles and the wall	0.0275
Surface energy of the JKR substrate, $\text{G}/(\text{J} \cdot \text{m}^{-2})$	2.325

238 To achieve thorough crushing, the test setup featured an “n”-shaped tapered tip. The tip was slowly
 239 driven into the substrate block in a helical pattern to disrupt its original cohesive structure. the
 240 three-dimensional structure of the tip is shown in **Fig.10(a)**. As shown in **Fig.10(b)**, the drilling and
 241 suction action caused the cohesive bonds within the substrate mass to break, forcing the large substrate
 242 block to fragment into multiple smaller pieces, thereby essentially achieving the crushing objective. The
 243 experiments revealed that during the crushing process, the substrate exhibited particle adhesion to the
 244 wall and tip jamming. Furthermore, because the “n”-shaped tip cannot maintain an absolute seal with the
 245 borehole, airflow leaks occur at the substrate inlet under equal suction conditions, significantly reducing
 246 the pressure differential and severely diminishing adsorption efficiency. Consequently, it is necessary to
 247 extend the adsorption time or increase the adsorption frequency to ensure that the small substrate
 248 fragments produced by crushing can still be removed. Furthermore, comparisons reveals that when the
 249 contraction angle at the tip is too small and the substrate's cohesive strength is too high, the tip penetrates

250 directly into the substrate clump, causing the entire clump to rotate and subsequently blocking the inlet.
 251 conversely, if the contraction angle is too large, the tip cannot fully reach the bottom of the pore, resulting
 252 in some substrate remaining unremoved. In summary, based on the “n”-shaped open-end structure design
 253 of the negative-pressure tube, the final dimensions were optimized with the goal of achieving a high
 254 substrate removal rate while ensuring an adequate crushing rate.

255



(a) 3D model of the tip (b) Interparticle bonding (c) Particle statistics before removal (d) Particle statistics after removal

256

Fig.10. Substrate removal rate under different parameter combinations

257

(2) Response surface design of experiments

258

259 To increase the degree of substrate fragmentation during the terminal descent, the terminal descent
 260 was set to a specific height while simultaneously rotating 90° clockwise. Under this scheme, the substrate
 261 removal rate is primarily related to the terminal inlet diameter, the draft angle of the “n”-shaped opening,
 262 and the terminal descent height. The terminal inlet was uniformly machined with an inward draft to form
 263 an “n”-shaped opening, with the draft rectangle set to 0.95 times the inner diameter of the terminal inlet.
 Based on empirical data, a three-factor, three-level design was established, as shown in **Tab.4**.

264

Tab.4. Table of key end parameter levels

Level	End Inlet Diameter A/mm	“n”-shaped opening draft angle B/°	End Drop Height C/mm
-1	12	7	26
0	14.5	8	21
1	17	9	16

265

2.2.3 Experimental apparatus and measurement

266

267 All processes, including machining, assembly, and testing of the complete unit, were conducted at
 Hangzhou Chuangsheng Intelligent Agricultural Equipment Co., Ltd. To improve testing efficiency, the
 268 study employed a dual-end convergent comparative test, designating the left side as “L” and the right side
 269 as “R”. When L or R is activated individually, considering that airflow leakage is inevitable in a dual-end
 270 structural design, the tubing material was replaced from transparent plastic tubing to 3D-printed metal,
 271 thereby increasing the internal friction coefficient. The negative pressure was initially set to 5 kPa for
 272 single-end operation. when L and R are activated simultaneously, the input negative pressure was further

increased to 5-9 kPa. Additionally, to demonstrate the reliability of this approach, the experiment involved sorting out defective seedlings of various types at different moisture content levels (during the experiment, there was an unavoidable interaction between changes in negative pressure within the tubes and the substrate moisture content regarding the sorting efficiency. however, due to limited experimental conditions, a detailed analysis of this interaction is not conducted here). The physical assembly of the entire system is shown in **Fig.11**.

Before the test, the total initial mass of the seedling tray was weighed, and this value was recorded as a baseline. With the seedling tray maintained at a specified moisture content, 200 cell units each of rootless and rooted substrate samples were selected and weighed using a precision electronic balance. It was assumed that, at the same moisture content, the masses of substrate blocks containing similar substandard seedlings within the same cell were equal.

The experimental procedure employed a group-controlled design, with removal operations conducted separately on substrate blocks containing roots and those without roots. First, the right (*R*) side was opened while the left (*L*) side remained closed, maintaining a continuous supply of negative pressure within the tube. A single set consisted of three repeated descents of the end, with adsorption maintained for at least 1 second after each descent. This process was repeated for 200 wells, and the total mass reduction of the substrate blocks was recorded (total mass of the seedling tray before removal minus the total mass after removal). then, the right-side end was opened while the left-side end was closed, and the removal test was repeated under the same parameters. next, a dual-group collaborative operation mode was adopted, simultaneously activating the left and right suction devices for synchronized operation at both ends. In this mode, the distance between the two suction ends is set to 5 well-center distances (currently, the distance between the two ends is 5 well-center distances. in the future, provided space permits, a greater number of ends may be to operate synchronously). Each cycle simultaneously removes two substandard seedlings. this process is repeated 100 times, completing the removal of seedlings from 200 wells. During the test, the positioning accuracy of the dual-end coordination must be controlled to match the well spacing. Finally, the substrate removal rate under each input condition is calculated as T_2 . Removal is considered successful if more than 80% of the substrate within a cell is removed. During the experiment, operations first remove substrate blocks without roots, followed by those containing roots, using the same procedure. At the same time, pipeline blockages are monitored, and the substrate removal rate is recorded.

$$T_2 = \frac{N_{2i-k}}{N_{2i}} \quad (1)$$

Where: T_2 is the substrate removal rate during the test, %

N_{21} is the total weight of 200 holes of rootless substrate blocks, kg

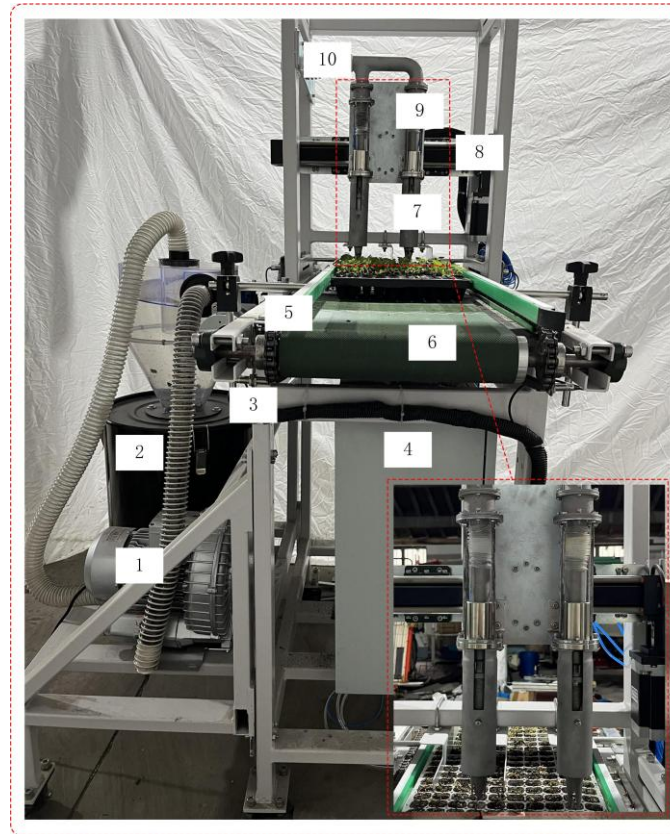
N_{22} is the total weight of the 200 rootless substrate blocks, kg

307 N_{2i-L} is the total mass reduction of the two types of substandard seedling substrate blocks when L
308 is open and R is closed, kg

309 N_{2i-R} is the total mass reduction of the two types of substandard seedling substrate blocks when R
310 is on and L is off, kg

311 N_{2i-LR} is the total mass reduction of substrate blocks containing substandard seedlings of both
312 types when LR are simultaneously activated, kg

313 During the test, a horizontal traverse module moves the end effector to the specified coordinate
314 position of each well. The center-to-center distance between the two end effectors is fixed. During the test,
315 the supply of negative pressure to the left and right end effectors is controlled by opening and closing ball
316 valves (the ball valves feature a custom-designed structure. double-layer gaskets are incorporated inside
317 to prevent airflow leakage, and a rack-and-pinion mechanism controls their opening and closing. further
318 optimization is possible).



319 1. Vortex blower, 2. Cyclone separator, 3. Laser through-beam sensor, 4. Control system, 5. Limit switch, 6. Trays conveyor,
320 7. End-effectors, 8. Transverse linear module, 9. Ball valve 10. Manifold.

321 **Fig.11. Actual photograph of the complete substrate removal system**

322 3. Results and discussion

323 (1) Results and analysis of terminal simulation optimization

324 Based on multiple experiments, it was found that to ensure all types of substrate blocks remain
325 suspended and move forward within the negative-pressure tube, the negative pressure at the outlet must
326 be set to at least 3.176 kPa, with the simulation duration set to 3.1 s. The substrate removal rates were
327

calculated for different combinations of variables, and the corresponding response surface experiment results are shown in **Tab.5**.

$$T=\frac{N_1-N_2}{N_1} \tag{2}$$

Where: T_1 is the substrate removal rate during simulation, %.

N_1 is the number of agglomerated substrate particles in the holes before the removal operation, in pieces.

N_2 is the number of bound substrate particles in the pore after the removal operation, in units.

Tab.5. Results of the response surface experiment

Experiment	End inlet diameter A	“n”-Type nozzle draft angle B	End-of-hole descent height C	Substrate removal rate T1/%
1	0	1	1	96.53
2	-1	-1	0	95.56
3	0	0	0	92.11
4	0	-1	1	96.93
5	0	0	0	89.13
6	-1	1	0	78.76
7	-1	0	1	82.93
8	1	0	1	97.78
9	1	1	0	97.02
10	0	-1	-1	98.22
11	0	0	0	94.17
12	0	1	-1	90.17
13	1	0	-1	90.49
14	0	0	0	90.21
15	0	0	0	96.14
16	1	-1	0	97.64
17	-1	0	-1	93.16

Combining the experimental data in Table 5 with Design-Expert analysis yields the results of the analysis of variance (ANOVA) for the substrate removal rate, as shown in Table 6. The P-values for the lack-of-fit terms in the table are all greater than 0.05, indicating that the model lack-of-fit is not significant and that this regression model has a high degree of fit. Furthermore, based on the P-values in Table 6, the factors influencing the substrate removal rate, ranked by significance from highest to lowest, end inlet diameter, “n”-type inlet draft angle, and end descent height. Among these, the end inlet diameter and the “n”-shaped mouth draft angle had significant effects ($P < 0.05$), while the end descent height had

no significant effect ($P > 0.1$). That is, the end inlet diameter had the most pronounced effect on the test results, followed by the “n”-shaped mouth draft angle, with the end descent height having the least effect. The order of significance for the three factors is $A > B > C$, and among the interaction terms, AB and AC had significant effects.

The optimized test results are as follows, terminal inlet diameter of 13.115 mm, “n”-type draft angle of 8.358° , and terminal drop height of 20.962 mm. To meet practical design requirements and improve computational efficiency, the optimized parameters were rounded to the nearest whole number. The final optimized parameter combination is as follows, end inlet diameter of 13 mm, “n”-type draft angle of 8.4° , and end drop height of 21 mm. The corresponding ends were machined, and substrate removal tests were conducted.

Tab.6. Results of analysis of variance

Source of variation	Sum of squares	Mean square	F-value	P-value
Model	415.50	46.17	5.47	0.0178
A	132.19	132.19	15.66	0.0055
B	83.66	83.66	9.91	0.0162
C	0.5671	0.5671	0.0672	0.8029
AB	65.45	65.45	7.75	0.0271
AC	76.74	76.74	9.09	0.0195
BC	14.63	14.63	1.73	0.2294
A2	21.12	21.12	2.50	0.1577
B2	19.15	19.15	2.27	0.1757
C2	4.03	4.03	0.4769	0.5121
Residual	59.08	8.44		
Residual term	26.40	8.80	1.08	0.4535
Pure error	32.68	8.17		
Total	474.58			

(2) Substrate subtraction results and analysis

Based on the optimized data, the corresponding end pieces were designed and manufactured, the complete unit was assembled, and testing was conducted. **Tab.7** presents the statistical results from the complete unit testing. It can be seen that when either L or R is activated individually, since there is no diversion of suction, the negative pressure is concentrated at a single point. The overall substrate removal rate remains above 80%, and there is little difference in the substrate removal rates between the left and right end pieces when activated, which generally meets the practical needs for replanting. It can also be observed that as moisture content increases, the removal rate for both rootless and rooted substrate clumps tends to decrease. This is because, while substrate clumping is relatively stable at moderate moisture levels, forced disruption actions such as drilling and suction generally succeed in breaking large agglomerates into smaller pieces. However, for substrate clumps at high moisture levels, the abundant

moisture results in relatively greater weight, at this point, the substrate's internal cohesion decreases, while the adhesion between the particles and the inner wall of the seed tray increases, requiring a corresponding increase in negative pressure to remove them. When both *LR* functions are activated simultaneously, even with increased negative pressure, the overall removal rate of substrate from substandard seedlings decreases due to factors such as end-point synchronization issues, airflow leakage, and pipeline convergence.

Experiments found that when the tip descends too rapidly during the drilling and suction process, the substrate is forced into the gap between the outer side of the drill bit and the inner wall of the tray before it has been fully adsorbed, thereby reducing the substrate removal rate. However, after the study tested a sequence of three movements-continuous ascent and descent of the tip-the removal rate was effectively controlled. During the first downward stroke of the drill-suction process, the central portion of the substrate is adsorbed first, while the remaining loose substrate particles are squeezed outward. during the second and third downward strokes, the remaining substrate gradually collapses toward the center and is ultimately adsorbed and removed.

Tab.7. Statistical results of substrate removal tests

Substrate category	Moisture content/%	Removal efficiency /%		
		<i>L</i>	<i>R</i>	<i>LR</i>
Root-free	20-40	94.4	92.7	87.7
	40-60	88.1	87.5	80.1
	60-80	84.8	86.2	73.8
Including roots	20-40	90.4	89.1	77.4
	40-60	86.1	86.4	74.8
	60-80	83.9	81.7	72.5

An analysis of pipeline blockage rates revealed that, regardless of whether single-end or double-end simultaneous operations were conducted, the drill-suction design effectively achieved thorough fragmentation of the substrate, preventing mechanically fragmented substrate chunks from becoming lodged at the inlet of the vacuum pipe. Tests showed that when the substrate moisture content was high, particles were highly prone to adhering to the pipe walls during the adsorption process, which increased the likelihood of blockages in the manifold and led to a rising trend in pipeline blockage rates. However, as adsorption continues and the end moves between holes, even if a small amount of fragmented substrate accumulates, the pressure differential caused by the opening and closing of the ball valve creates a surge in the airflow within the pipe, forcing some of the substrate adhering to the walls to become resuspended. Through this repeated process, the pipeline blockage rate is kept under control to a certain extent, and the system as a whole can meet practical requirements.

When the tip adsorbs substrate clumps with high moisture content and continues operation for 200 cycles, statistical analysis shows that the substrate deposition rate in the horizontal pipe is less than 10%,

with only a few particles adhering to the pipe wall. these can be cleaned periodically. For substrate clumps with other moisture contents, no accumulation was observed inside the pipe when they were broken up and removed. increasing the negative pressure appropriately is sufficient to carry away the loose particles.

Fig.12 shows the particle size distribution of the substrate collected after the drilling-suction process and an image of the seedling tray. It can be seen that the end-of-line drilling-suction action effectively achieved the goal of thoroughly mixing and breaking up the substrate. most of the substrate was broken into loose particles, and clumping is no longer a major factor contributing to pipeline blockage. At this point, only a slight increase in negative pressure is needed to suck up the broken loose particles. At the same time, it can be seen that, with the exception of a few holes, the substrate removal effect generally meets the requirements for seedling replenishment.



(a) Substrate particle sizes after drill-suction removal

(b) Image of the seedling tray after drill-suction removal

Fig.12. Effectiveness of drill-suction removal of substrate clumps

Overall, the design of the drill-suction tip structure has significantly reduced pipeline blockages. During single-end operation, although the removal rates of agglomerates from different types of substandard seedlings vary across moisture content levels, all meet the requirements for replanting operations. For dual-end operation, appropriate optimizations-such as improvements to pipeline sealing-can be made to ensure the system meets practical needs.

4. Conclusions

This paper focuses on the phenomenon of pipeline blockages occurring in the negative-pressure removal system for substandard seedling substrate blocks. The main research areas include three aspects.

(1) Establishing an experimental platform, and proposing a drill-suction-type nozzle to reduce the probability of pipeline blockages. designing the structure of the drill-suction-type removal nozzle. and optimizing basic parameters such as the nozzle structure and descent height. The model's lack-of-fit term $P > 0.05$, indicating no significant lack-of-fit and a high degree of fit. The order of significance of the three factors affecting the substrate removal rate was end inlet diameter greater than "n"-type orifice draft angle and then end descent height. The optimal combination of end parameters was determined through simulation analysis to be an end inlet diameter of 13 mm, an "n"-type orifice draft angle of 8.4° , and an end descent height of 21 mm.

(2) A dual-end synchronous operation mode was designed, and a comparison of substrate removal effectiveness was conducted. The results showed that when both ends were activated simultaneously, the removal rate decreased due to factors such as flow diversion, which was particularly noticeable under high moisture content conditions. when operating with a single end-regardless of whether the left or right side was activated-the substrate removal rate remained above 80%, which generally met the seedling replanting requirements. During the drilling and suction process, if the end descends too rapidly, the substrate removal rate decreases. However, after performing three cycles of continuous ascending and descending movements at the end, the removal rate was effectively controlled. Regardless of whether single-end or dual-end synchronous operation was used, the drill-suction structural design essentially achieved the goal of thoroughly breaking up the substrate.

CRedit authorship contribution statement

Xiaoqin Wang and Feilong Wu: Conceptualization, Investigation, Supervision, Writing - original draft. Shuyi Liu and Jia Lu: Methodology, Investigation, Writing - review & editing. Junhua Tong and Zhengjie Ye: Methodology, Project administration, Resources, Funding acquisition.

Acknowledgements

Funding: This work was supported by the China Postdoctoral Science Foundation (2025M782477).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References:

- [1] Wang L, Li Y T, Lin H, et al. Rtr-CNN: Rotated Tray Region Selection and Young Seedling Health Status Detection by CNN in Greenhouse Seedbeds[J]. Computers and Electronics in Agriculture, 2025, 229: 109723.
- [2] Song Wenbin, Ren Ling, Zhao Bindong, et al. Design of the Missing Seedling Detection and Seedling Replenishment System of the Plug Seedling Transplanting Test Bench[J]. Journal of Agricultural Mechanization Research, 2023, 45(07): 58-64.
- [3] Tong Junhua, Shi Hufeng, Wu Chuanyu, et al. Simulation and Test of Seedling Pot Grabbing by Spade End-effector[J]. Transactions of the Chinese Society for Agricultural, 2019, 50(08): 107-116.
- [4] Jin X, Tang L, Ji J, et al. Potential Analysis of an Automatic Transplanting Method for Healthy Potted Seedlings Using Computer Vision[J]. International Journal of Agricultural and Biological Engineering, 2021, 14(6): 162-168.

-
- [5] Liang Xifeng, Xiao Xize, Zhu Yuhao, et al. Design and experiment on pot-seedling supplementing end-effector for vegetables in cotyledon phase[J]. Transactions of the Chinese Society of Agricultural Engineering, 2018, 34(09): 49-57.
- [6] Miao Hong, Li Mengli, Xu Hao, et al. Design and Experiment of the Control System of Automatic Replanting Seedling Machine for Pepper in Greenhouse[J]. Journal of Agricultural Mechanization Research, 2024, 46(01): 67-74.
- [7] Tian Z, Ma W, Yang Q, et al. Design and Experiment of a Gripper for Greenhouse Plug Seedling Transplanting Based on EDM [J]. Agronomy, 2022, 12(7): 14-87.
- [8] Sun E, Xiao Z, Tan Y. A Fast Path Planning Method for Seedling Tray Replanting Based on Improved Particle Swarm Optimization [J]. Agronomy, 2023, 13(3): 853-874.
- [9] Xu S, Zhang Y, Dong W, et al. Early Identification and Localization Algorithm for Weak Seedlings Based on Phenotype Detection and Machine Learning[J]. Agriculture, 2023, 13(1): 212-231.
- [10] Du X, Yun Z, Jin X, et al. Design and Experiment of an Automatic Adjustable Transplanting End-Effector Based on a Double-Cam Mechanism[J]. Agriculture, 2023, 13(5): 987-1002.
- [11] Han L, Xiang D, Xu Q, et al. Development of a Simplified Seedling Transplanting Device to Support Efficient Production of Vegetable Raw Materials[J]. Applied Sciences, 2023, 13(18): 3390-3410.
- [12] Hu Jianping, Liu Yutong, Liu Wei, et al. Top Clamping and Pulling Experiment on Combined Seedling Picking Device with[J]. Transactions of the Chinese Society for Agricultural, 2022, 53(S1): 110-117.
- [13] Li Bo, Gu Song, Xie Zhongjian, et al. Design and experiments of the mechanism of blowing leaves and replanting of plug seedlings[J]. Transactions of the Chinese Society of Agricultural Engineering, 2021, 37(03): 1-8.
- [14] Ma Guoxin. Study on Enhancement Mechanism of Low Loss Seedling Picking in Biochar and Air Ejection-Package ClampingPick-up Device[D]. Zhenjiang: 2021.
- [15] Cui Yongjie, Zhu Yutao, Ma Li, et al. Design and Experiment of Air-suction Substrates Removal Device for Plug Lack of Seedlings Trays[J]. Transactions of the Chinese Society for Agricultural, 2022, 53(11): 140-151.
- [16] Gu Song. Mechanized Replanting Technology for Greenhouse Seedling Production [J]. Agricultural Engineering Technology, 2021, 41(07): 12-15.
- [17] Vahaji S, Nguyen N-H, Shang Y, et al. Sedimentation Effects on Particle Position and Inertial Deposition in 90° Circular Bends[J]. Powder Technology, 2021, 393: 722-733.

-
- [18] Gu X, Yang D, Guo A, et al. Ecvr Imaging and Cfd Simulation of Particle Flow in a 90° Bend[J]. Powder Technology, 2025, 451: 120476.
- [19] Kalpakli A, Örlü R. Turbulent Pipe Flow Downstream of a 90° Pipe Bend with and without Superimposed Swirl[J]. International Journal of Heat and Fluid Flow, 2013, 41(06): 103-111.
- [20] Zhang J, Wang D, Wang W, et al. Numerical Investigation and Optimization of the Flow Characteristics of Bend Pipe with Different Bending Angles[J]. Processes, 2022, 10(8): 1510-1527.