DESIGN AND EXPERIMENT OF A VIBRATION-BASED LOOSENING DEVICE FOR ROOT PLUGS OF VEGETABLE TRAY SEEDLINGS
/
蔬菜穴盘苗振动式钵体松脱装置设计及试验

Xiaohu BAI, Xinyu WANG, Kai WANG, Lianrui TAN, Yingze LIU, Subo TIAN*
College of Engineering, Shenyang Agricultural University, Shenyang/China
E-mail: tiansubo@syau.edu.cn
DOI: https://doi.org/10.35633/inmateh-78-75

Keywords: *Transplanting; Vibration frequency; Adhesive force; Response surface method; Seedling picking*

ABSTRACT
To address the issues of low seedling extraction success rates and high susceptibility to damage caused by excessive adhesion between the root plug and the tray cell during mechanical transplanting of vegetable tray seedlings, this study designed a vibration-based loosening device according to the principle of inertial force. Using tomato seedlings as the research subject, the range of vibration frequency was determined through single-factor experiments. A three-factor, three-level factorial experiment was conducted, with plug moisture content, vibration frequency, and vibration duration as the experimental factors, and the reduction in adhesive force of the plug as the response indicator. The results of variance analysis showed that the established regression model fitted the actual data well. The order of influence of the factors on the response was: vibration frequency, plug moisture content, and vibration duration. Both the individual factors and their interactions had significant effects on the response indicator. Optimal operating parameters were determined through optimization: plug moisture content of 50%, vibration frequency of 35 Hz, and vibration duration of 60 s. Under these conditions, the reduction in adhesive force reached 1.01 N. The experimental results indicate that vibration-based loosening can significantly reduce the adhesive force between the plug and the tray cell, providing a reference for improving seedling extraction success rates and for designing the seedling-picking mechanisms of transplanters.

摘要
针对蔬菜穴盘苗机械化移栽过程中，苗钵与穴孔间粘附力过大导致取苗成功率低、幼苗易损伤等问题，本文设计了一种基于惯性力原理的振动松脱试验台。以番茄穴盘苗为对象，通过单因素试验确定了振动频率范围。以苗钵含水率、振动频率和振动时间为试验因素，苗钵粘附力减少值为试验指标，进行了三因素三水平组合试验。方差分析结果表明，建立的回归模型与实际情况高度拟合，因素影响主次顺序为：振动频率、苗钵含水率、振动时间，各因素及其交互作用对试验指标影响显著。通过优化确定了最优工作参数，当苗钵含水率为 50%、振动频率为 35Hz、振动时间为 60s 时，粘附力减少值为 1.01N。试验结果表明，振动松脱能显著降低苗钵与穴孔间的粘附力，为提高取苗成功率和移栽机取苗机构设计提供了参考。

INTRODUCTION
As the world's largest producer and consumer of vegetables, China faces a steadily increasing demand for vegetables, driven by rapid urbanization (*Xiao et al., 2015*). Transplanting, a critical step in vegetable production, directly affects crop survival rates, growth cycles, and final yields. The use of tray seedlings for transplanting is a common practice in greenhouse vegetable production, significantly improving both crop yield and economic efficiency (*Li et al., 2026*). Currently, approximately 60% of vegetables in China are cultivated using transplanting methods (*Han et al., 2025*). However, during the transplanting process, the adhesive force between the root plug and the tray cell often prevents the smooth removal of the seedling, significantly reducing the success rate of the operation.

During the transplanting process, whether performed manually or by a mechanical gripper that holds the root plug or stem, the fundamental action is the extraction of the root plug from its tray cell. At a certain stage of growth, the seedling's roots, confined by the cell wall, entwine the growing medium to form a cohesive root plug (*Ramachandran et al., 2025*).

Xiaohu Bai, Associate Prof., Ph.D.; Subo Tian, Prof., Ph.D.,Corresponding Author.

This establishes an adhesive force between the plug and the cell wall. Therefore, separating the plug from the cell requires a pulling force sufficient to overcome this adhesion. Research has demonstrated that pre-loosening the plug significantly improves seedling extraction. The transplanting success rate for pre-loosened seedlings can reach up to 96.3%, compared to only 50.9% for those that were not pre-loosened (*Yang et al., 1991*).

Several methods are currently employed to loosen the root plug, including pushing, air-blowing, compressing, and vibrating. The FUTURA automatic transplanter, developed by the Italian company Ferrari, features a whole-row push system for seedling extraction, based on the principle that push action facilitates gripping (*Zhou et al., 2024*). This system offers high production efficiency and extraction rates while causing minimal damage to the root plug. However, its structure is complex and its size is relatively large. Hu et al. investigated a combined extraction technique involving pushing, gripping, and pulling. In their system, after a push rod loosens the plug, a control system activates a cylinder to extend its piston rod. This action causes the extraction claws to insert into and grip the plug. The piston rod then retracts, allowing the claws to pull the plug from the tray (*Hu et al., 2022*). Zhang et al. designed and studied a pushing-gripping combined extraction mechanism. In their design, the tray is transported by a conveyor belt to a position beneath the gripper, where it is secured by a tray presser. A push rod then pushes the seedling up from the tray cell, after which the mechanical gripper takes hold of it (*Zhang et al., 2016*). Han et al. developed an air-blowing device for loosening root plugs to aid in transplanting. Utilizing the principle of air injection, high-pressure air jets are directed through the drainage holes at the bottom of the tray cell to blow the plug. This non-contact method loosens the plug within its cell, facilitating easier manual extraction or more reliable mechanical gripping during transplanting (*Han et al., 2019*). Chen et al. designed a rotary tray-feeding device. As the tray is fed, it is guided around guard rods, causing it to bend. This bending action expands the top of the cell and compresses the bottom, altering the contact area between the plug and the cell wall. This reduces the adhesive force, making it easier to remove the plug seedling from the tray (*Chen et al., 2025*). Yuan et al. designed a combined air-blowing and vibration extraction mechanism along with a compatible seedling tray. By integrating vibration with air-blowing for automatic seedling picking and dispensing, they developed a dynamic model of the tray and plug system. They also analysed the effects of vibration frequency, amplitude, and substrate moisture content on the success rate of extraction (*Yuan et al., 2019*). Yao et al. designed a combined vibration-gripping extraction mechanism. This system uses vibration to loosen the plug and reduce adhesion, followed by a gripper for precise extraction. By integrating dynamic analysis with structural optimization, their work ensures effective seedling removal. This approach offers a new pathway for the development of fully automatic seedling picking and dispensing mechanisms for vegetable transplanters, holding significant theoretical value and practical implications (*Yao et al., 2022*).

Taking tomato seedlings as the research object, this paper designed a vibration-based loosening device by combining theoretical analysis with experimental methods. Response surface method was employed to optimize the vibration parameters. The objective was to minimize the adhesive force while ensuring a smooth and safe extraction process. The findings are intended to provide technical support for the advancement of modern agricultural transplanting equipment.

MATERIALS AND METHODS

Experimental materials

The experiment utilized tomato tray seedlings, cultivated in 72-cell trays, which were obtained from Liaoning Yunfeng Company. The growing substrate was a mixture of peat, vermiculite, and perlite in a 2:1:1 ratio (*Erdal et al.,2025*). From each tray, only healthy seedlings exhibiting vigorous growth, well-developed root systems, sturdy stems, and dark green leaves were chosen to use. Any seedlings showing signs of pests, diseases, malformation, or yellowing were discarded. The tray seedlings used in the experiment are shown in Fig. 1.

Fig. 1 - Tomato tray seedlings used in experiments

The growth characteristics of the selected tomato seedlings were evaluated. A random sampling method was employed. Plant height and leaf spread were measured using a graduated ruler, stem diameter was measured with a digital calliper, and individual plant mass was determined using an electronic balance (*Cui et al., 2023*). The seedlings exhibited robust growth, with plant heights ranging from 95 to 125 mm. Their leaf spread measured between 100 and 135 mm, and stem diameter ranged from 2.9 to 4.2 mm, further indicating vigorous development. The individual plant mass for these 72-cell tray seedlings was between 18 and 23 g. While some variation in external morphology was observed among individual plants, the overall health and vigour of the seedling population were excellent. Therefore, they were suitable for the subsequent transplanting and experimental procedures.

Overall structural design of the vibration-based loosening device

The overall structure of the vibration-based loosening device is shown in Fig. 2. Its main components include a PT-MV5DCB12-1 variable-speed rotary vibration motor, a set of springs, a vibration plate, a frame, fixing clamps, and a digital speed controller. The seedling tray is secured to the vibration plate by four fixing clamps, which ensures that no relative movement occurs between the tray and the plate during the vibration process. Driven by the vibration motor and supported by the four springs, the vibration plate performs continuous simple harmonic motion. This motion causes the seedling tray to vibrate vertically. The vibration frequency is adjusted by regulating the motor's rotational speed using the digital speed controller. The inertial force generated on the root plug during this vibration effectively reduces the adhesive force between the tray and the plug (*Liu et al., 2025*).

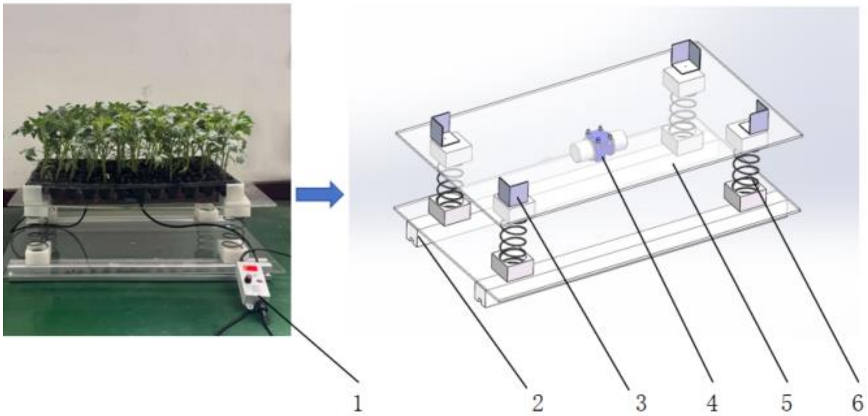


Fig. 2- Overall structure of the vibration device

1-digital speed controller; 2-frame; 3-fixing clamp; 4-variable-speed vibration motor; 5-vibration plate; 6-spring

Force analysis of tray seedlings under vibration action

Fig. 3 illustrates the vibration system, which consists of a full tray of plug seedlings and the device. A coordinate system was established with the equilibrium position of the plug seedlings as the origin *o*, and the positive *y*-axis oriented vertically downward.

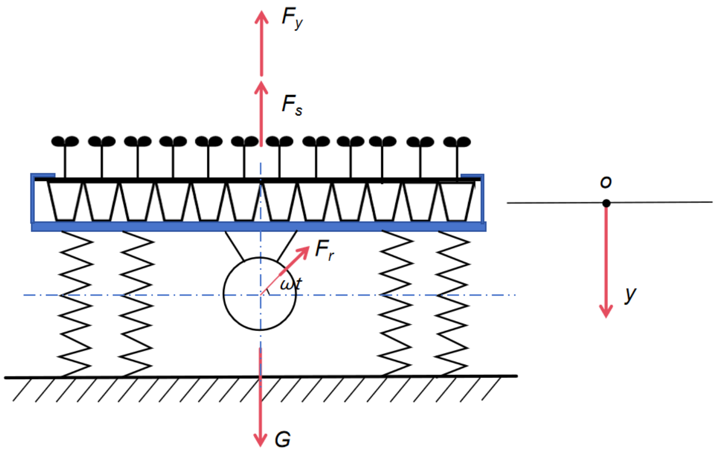


Fig. 3- Force analysis diagram of the vibration system

The forces acting on the vibrating system can be calculated using Eqs. (1), (2), (3) and (4).

$$G=(m_1+m_2+m_3)g \tag{1}$$

where G is the gravitational force of the vibrating system (N); m_1 is the mass of a full tray of plug seedlings (kg); m_2 is the mass of the vibration plate (kg); m_3 is the mass of the vibration motor (kg); g is the gravitational acceleration (m/s^2).

$$F_s=4k\left[y+\frac{(m_1+m_2+m_3)g}{4k}\right] \tag{2}$$

where F_s is the elastic force (N); k is the stiffness of each individual spring (N/m); y is the displacement of the plug seedlings in the y-axis (m).

$$F_r=m\ e\ \omega^2 \tag{3}$$

where F_r is the added inertial forces along the radial direction of the motor (N); m is the eccentric mass of the motor rotor (kg); e is the eccentricity distance (m); ω is the angular velocity of the motor (rad/s).

$$F_y=(m_1+m_2+m_3)\ddot{y} \tag{4}$$

where F_y is the added inertial forces along the vertical direction (N); $\ddot{y}$ is the acceleration of the system along the vertical direction (m/s^2).

According to d'Alembert's principle (*Sadeghi et al., 2020*), we can obtain:

$$G\text{-}F_s\text{-}F_y\text{-}F_r\sin(\omega t)=0 \tag{5}$$

where t is the rotation time of the motor (s).

After rearrangement, Eq. (5) can be expressed as:

$$(m_1+m_2+m_3)\ddot{y}+4ky=\text{-}me\omega^2\sin(\omega t) \tag{6}$$

From Eq. (6), we can obtain Eqs. (7) and (8).

$$y=\text{-}A\sin(\omega t) \tag{7}$$

$$A=\frac{me\omega^2}{4k\text{-}(m_1+m_2+m_3)\omega^2} \tag{8}$$

By differentiating Eq. (7), we can conclude Eq. (9).

$$a=A\omega^2\sin(\omega t) \tag{9}$$

where a is the acceleration of a full tray of plug seedlings (m/s^2).

The inertial force acting on an individual plug seedling during vibration can be given by Eq. (10).

$$F_n=m_n a=m_n A\omega^2\sin(\omega t) \tag{10}$$

where F_n is the inertial force (N); m_n is the mass of an individual plug seedling (kg).

From Eq. (10), it can be seen that when $\sin(\omega t) < 0$, the direction of the inertial force acting on an individual plug seedling is vertically upward, and its magnitude varies with ωt. Under this upward inertial force, the adhesive interfaces between the root plug and the side and bottom surfaces of the tray cell are gradually disrupted, thereby reducing the adhesive force.

Parameter determination and component selection of the vibration system

The total mass of the vibration system is fundamental for conducting dynamic analysis, determining the excitation force and the spring stiffness coefficients (*Banerjee, 2012*). Measurements indicated that the mass of a full tray of tomato seedlings m_1 was approximately 1.65 kg, the mass of the vibration plate m_2 was 1.29k g, and the mass of the vibration motor m_3 was 0.65 kg. Consequently, the total mass M of the vibration system can be calculated as follows:

$$M=m_1+m_2+m_3=3.59\text{ kg} \tag{11}$$

The primary function of the springs in the vibration device is to support the total mass of the vibration system and to prevent the occurrence of resonance (*Sun et al., 2020*). Eq. (12) can be used to calculate the frequency.

$$f=\frac{n}{60} \tag{12}$$

where f is the motor frequency (Hz); n is the motor speed (r/min).

The motor speed for the vibration tests was set within a range of 0 to 3000 r/min, so the corresponding motor frequency range was 0 to 50 Hz. To ensure that the system does not resonate at any operating frequency, its natural frequency f_n must be significantly lower than the minimum operating frequency (*Kong et al., 2026*). The total spring stiffness coefficient k_t can be derived using Eq. (13).

$$k_t = \left(2\pi f_n\right)^2 M \approx 5370 \text{ N/m} \tag{13}$$

where k_t is the total spring stiffness coefficient of the system (N/m); f_n is the natural frequency of the system (Hz), taken as; M is the total mass of the system (kg).

The device uses four springs. Therefore, the stiffness coefficient of a single spring is approximately 1342.5 N/m. Consequently, four springs with stiffness coefficient of 1350 N/m were selected for this device. This selection ensures that the system's natural frequency remains stable at around 5 Hz, effectively avoiding the operating frequency range and preventing resonance.

To ensure that the vibration effectively reduces the adhesive force between the root plug and the tray cell and produces a discernible effect, the selection of the vibration source must meet two requirements. First, it must provide sufficient excitation force. Second, its vibration frequency must be precisely adjustable within the experimental range. Accordingly, a PT-MV5DCB12-1 variable-speed rotary vibration motor was selected for this study. This motor provides an excitation force of 60 N, with a rotational speed adjustable from 0 to 3000 r/min, corresponding to a maximum vibration frequency of 50 Hz. This performance meets the variable-frequency excitation requirements of the device. As the power core of the vibration device, the motor generates the excitation force through the rotation of its eccentric blocks.

Single-Factor experiment

To scientifically and rigorously determine the appropriate range for the vibration frequency factor, a single-factor experiment investigating the effect of vibration frequency on the adhesive force of the root plug was conducted prior to the main tests. As the optimal substrate moisture content during transplanting is approximately 50% (*Gao et al., 2020*), it was fixed at 50 ± 3% for this experiment. Furthermore, given that a single transplanting operation typically takes about 60 seconds, the vibration duration was set to 60 s. The vibration frequency was tested across a range of 0 to 50 Hz, with 10 levels selected at 5 Hz intervals. The extraction force was measured at each frequency level, with the experiment repeated five times for each condition. The results are presented in Fig. 4.

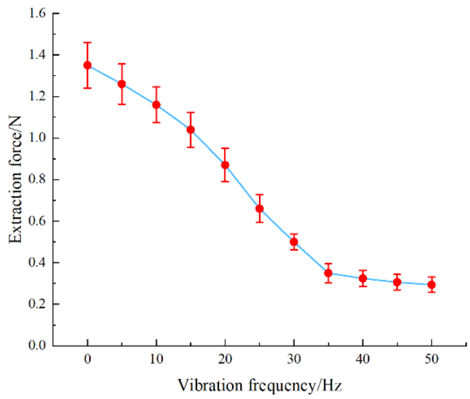


Fig. 4 - Relationship between vibration frequency and extraction force

As can be seen from the Fig. 4, the force required to extract the root plug showed a clear downward trend with increasing vibration frequency. Within the range of 0 to 35 Hz, the extraction force decreased markedly. However, when the frequency exceeded 35 Hz, the rate of this decrease gradually levelled off. The vibration frequency has a positive correlation with the reduction of adhesive force. Nevertheless, once the energy input reaches a certain threshold, the marginal benefit for the loosening effect diminishes. Excessive vibration frequencies also pose a risk of damaging the integrity of the root plug. Therefore, to maximize the reduction of adhesive force while ensuring the plug seedlings' integrity during extraction, vibration frequencies of 20 Hz, 35 Hz, and 50 Hz were selected as the three levels for the subsequent multi-factor response surface experiment.

Determination of experimental factors

To investigate the influence of various parameters on the reduction of adhesive force achieved by vibration and to determine their optimal combination. Three key parameters were selected for this study: vibration duration, vibration frequency, and plug moisture content. Based on the operational requirements of the transplanter, the experimental ranges were set as follows: plug moisture content between 40% and 60%, vibration frequency between 20 and 50 Hz, and vibration duration between 30 and 90 s. The factor levels are shown in Table 1.

Table 1

Factors and levels

Levels \ Factors	Moisture content	Vibration frequency	Vibration duration
	[%]	[Hz]	[s]
-1	40	20	30
0	50	35	60
1	60	50	90

Experimental indicators and measurement methods

To evaluate the effectiveness of the loosening process, the reduction in adhesive force before and after vibration was used as the key indicator. This reduction directly reflects the change in adhesion between the root plug and the tray cell. The extraction force between the root plug and the inner wall of the tray cell was measured using a digital spring force gauge, both before and after the vibration impact test.

Fig. 5 - Extraction force measurement after and before vibration

As shown in Fig. 5, the instrument was zeroed and calibrated before measurement. For the measurement, tomato seedlings with nearly identical growth characteristics were selected. The fixture attached to the force gauge was clamped onto the base of the seedling stem, at a point 1 cm above the surface of the growing medium. The seedling was then pulled vertically upward at a constant rate of 5 mm/s. The maximum force value F_0 recorded at the moment the root plug detached from the tray cell was documented. Subsequently, the vibration was applied. After the vibration ceased and the device had stabilized, the same experimental procedure was repeated to measure the residual adhesive force, designated as F_1. Each experimental condition was replicated three times. The adhesive force reduction for a single test was determined by calculating the arithmetic mean of the three replicate measurements, which was then taken as the final result. The reduction in adhesive force F_2 was calculated by subtracting F_1 from F_0.

Experimental procedure

The first step involved controlling the moisture content of the root plugs. To achieve the three target levels of 40%, 50%, and 60%, a natural evaporation method was employed in this study. Some trays of tomato seedlings with uniform growth were thoroughly watered until water seeped from the bottom of the cells, ensuring that the substrate in each tray was fully saturated. Subsequently, the tray seedlings were placed in a constant-temperature chamber set to 26±2°C and 50±10% humidity for static evaporation. After 72 hours, the moisture content was measured using a halogen moisture analyser. For each tray, substrate samples were taken from five different seedling positions. The average moisture content was determined to be approximately 60±3%. All experiments for the 60±3% moisture level were then conducted immediately. The remaining trays were left to stand for another 24 hours. Following the same measurement procedure, the average moisture content was found to be approximately 50±3%. All experiments for this moisture level were subsequently carried out. This process was repeated for a final 24-hour period to achieve and conduct the experiments for the 40±3% moisture content level.

Before the vibration loosening test, three seedlings were randomly selected from each tray. The pre-vibration extraction force was measured by pulling each seedling vertically upward at a constant speed.

The peak extraction force for each seedling was recorded, and the average of these three values was calculated as the initial extraction force for that tray. The entire tray of seedlings was then carefully placed onto the vibration device and securely fixed to prevent any displacement or tipping during the vibration process. According to the corresponding experimental plan, the rotational speed of the vibration motor was precisely adjusted using the digital speed controller, and the vibration duration was set with a timer. After the vibration was completed, another three seedlings from the same tray were selected for post-vibration extraction force measurement, and the data were recorded.

RESULTS

Box-Behnken experimental design

This experiment employed a Box-Behnken design based on response surface methodology. A three-factor, three-level experimental design was established, with five replicates at the center point, resulting in a total of 17 experimental runs. The experimental design and corresponding results are shown in Table 2.

Table 2

Experimental scheme and results

No.	Factors and levels			Experimental indicators
	Moisture content	Vibration frequency	Vibration duration	Reduction in adhesive force
	A	*B*	*C*	*Y*/s
1	-1	-1	0	0.17
2	1	-1	0	0.31
3	-1	1	0	0.53
4	1	1	0	0.98
5	-1	0	-1	0.27
6	1	0	-1	0.39
7	-1	0	1	0.32
8	1	0	1	0.82
9	0	-1	-1	0.25
10	0	1	-1	0.60
11	0	-1	1	0.35
12	0	1	1	0.98
13	0	0	0	1.00
14	0	0	0	1.01
15	0	0	0	0.98
16	0	0	0	1.01
17	0	0	0	0.99

Regression model establishment and significance test

The experimental data presented in Table 2 were analysed using the statistical software package Design-Expert 8.0.5, with the results shown in Table 3. The model term for the reduction in adhesive force yielded a *p*-value of less than 0.0001, indicating that the regression model is highly significant. The corresponding p-value for the lack of fit was 0.5413, which is greater than 0.05. This suggests that the regression model fits the actual data well, confirming that the response surface methodology is appropriate for analysing this experiment. The significance of the quadratic terms A^2, B^2, C^2 and interaction terms *AB, AC, BC* shown in Table 3 indicates that there is a quadratic nonlinear relationship and interaction effects between the three experimental factors and the response variable. A quadratic polynomial regression model was therefore established, with the reduction in adhesive force *Y* as the response variable and moisture content *A*, vibration frequency *B*, and vibration duration *C* as the independent variables. The model is presented in Equation (16).

$$Y=1.00+0.15A+0.25B+0.12C+0.08AB+0.10AC+0.07BC-0.30A^2-0.20B^2-0.25C^2 \quad (16)$$

Table 3

Results of variance analysis

Variance source	**Reduction in adhesive force *Y***			
	Square sum	**Degree of freedom**	***F* value**	***P* value**
Model	1.79	9	1256.49	< 0.0001
A	0.1830	1	1159.36	< 0.0001
B	0.5050	1	3199.17	< 0.0001
C	0.1152	1	729.77	< 0.0001
AB	0.0240	1	152.19	< 0.0001
AC	0.0361	1	228.69	< 0.0001
BC	0.0196	1	124.16	< 0.0001
A^2	0.3733	1	2364.70	< 0.0001
B^2	0.1731	1	1096.46	< 0.0001
C^2	0.2637	1	1670.40	< 0.0001
Residual	0.0011	7		
Lack of fit	0.0004	3	0.8333	0.5143
Error	0.0007	4		
Sum	1.79	16		

Note: $P<0.01$ means highly significant (**), and $P<0.05$ means significant (*).

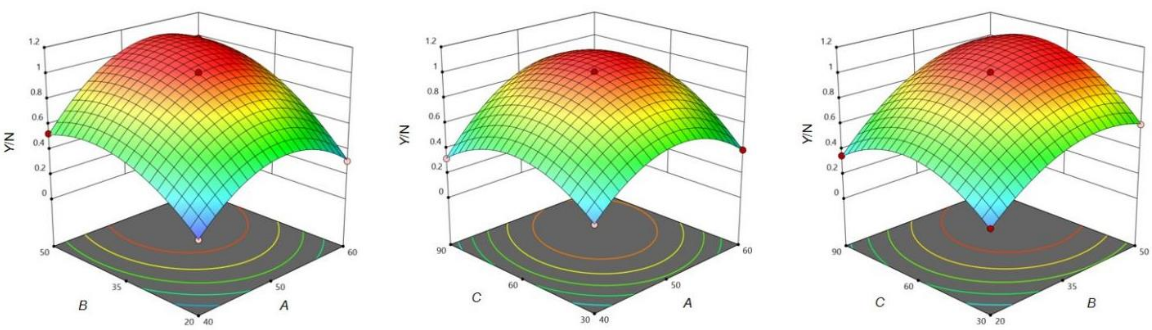
Analysis of the effects of factors on the response

The significance of the effects of each experimental factor on the reduction in adhesive force can be analysed through their corresponding *F*-values and *p*-values presented in Table 3. As shown in Table 3, the *p*-values for the linear terms *A*, *B*, and *C* were all less than 0.0001, indicating that each of these three individual factors has a highly significant effect on the reduction of adhesive force.

In the analysis of variance, the magnitude of the *F*-value directly reflects the relative contribution of each factor to the response. The order of influence of the factors on the reduction in adhesive force was: vibration frequency, moisture content, and vibration duration. Vibration frequency had the most significant impact. This is primarily because the frequency directly determines the magnitude of the excitation force; higher frequency vibrations can rapidly generate sufficient inertial force at the interface between the root plug and the substrate, thereby disrupting the adhesive structure.

Analysis of Interaction effects of factors on the response

Response surface plots were generated using the statistical software Design-Expert 8.0.5 to analyse the effects of the interactions between moisture content, vibration frequency, and vibration duration on the reduction in adhesive force. These plots are shown in Fig. 6.



(a) *Y=f*(*A*, *B*, 0) **(b) *Y=f*(*A*, *0*, C)** **(c) *Y=f*(*0*, *B*, C)**

Fig. 6 – Interaction effects of factor on the reduction in adhesive force

As shown in Fig. 6(a), the response surface exhibits a clear convex downward curvature. When the vibration duration was fixed at 60 s, the reduction in adhesive force initially increased and then decreased with increasing levels of both moisture content and vibration frequency. At higher vibration frequencies, the effect of moisture content on the reduction of adhesive force was more pronounced. From Fig. 6(b), the response surface also demonstrates significant curvature. As both the vibration duration and moisture content increased, the reduction in adhesive force showed a trend of initially rising and then declining. With the vibration frequency fixed at 35 Hz, the response surface displayed a distinct curvature. The reduction in adhesive force increased with prolonged vibration time up to a point, after which it began to decrease. As depicted in Fig. 6(c), under the condition of 50±3% moisture content, the contribution of vibration frequency to the response was significantly greater than that of vibration duration. The peak reduction in adhesive force was achieved with a combination of high frequency and a moderate vibration duration.

Parameter optimization

To achieve the optimal loosening effect, the regression model was optimized using Design-Expert software. With the goal of maximizing the reduction in adhesive force, the optimization yielded the following optimal parameter combination: plug moisture content of 50%, vibration frequency of 35 Hz, and vibration duration of 60 s. Under these optimal conditions, the model predicted a reduction in adhesive force of 1.01 N.

CONCLUSIONS

In this study, a vibration-based loosening device for tray seedlings was developed based on the principle of inertial force to address the issue of seedling damage caused by excessive adhesion during mechanical transplanting. The results of dynamic analysis and experiments indicated that vibration frequency is the most critical factor affecting the reduction of adhesive force. A Box-Behnken experimental design based on response surface methodology was employed to investigate the effects of moisture content, vibration frequency, and vibration duration on the reduction in adhesive force. A quadratic regression model was established and analysed using variance analysis. Analysis of the factor effects revealed that the order of influence on the reduction of adhesive force was: vibration frequency, followed by moisture content, and then vibration duration. Analysis of the response surfaces elucidated the patterns of interaction among moisture content, vibration frequency, and vibration duration. Through optimization, the optimal operating parameters were obtained.

This study not only identified the key factors influencing the reduction in adhesive force through vibration but also provides a theoretical foundation and data to support the future design and improvement of vibration-based loosening mechanisms for high-speed automatic plug seedling transplanters. Future research should focus on integrating the vibration-based loosening mechanism with the transplanter to significantly enhance its operational efficiency and quality.

ACKNOWLEDGEMENT

This research was funded by the Basic Scientific Research Project of the Educational Department of Liaoning Province (grant number JYTMS20231284).

REFERENCES

[1] Banerjee, J.R. (2012). Free vibration of beams carrying spring-mass systems - a dynamic stiffness approach. *Computers and Structures*, 104-105, 21-26. UK.

[2] Cui, J., Li, X., Zeng, F., Bai, H., Zhang, Y. (2023). Parameter calibration and optimization of a discrete element model of plug seeding pots based on a collision impact force. *Applied Sciences*, 13(10), 6278. Switzerland.

[3] Chen, H., Quan, W., Shi, F., Jiang, X., Xiang, Y., Wu, M. (2025). Design and test of the rotary seedling tray conveying device for oilseed rape seedling transplanting machine (油菜钵苗移栽机回转式送盘装置设计与试验). *Transactions of the Chinese Society of Agricultural Engineering*, 41(14), 61-70. China.

[4] Erdal, I., Aktas, H. (2025). Comparison of the perlite, leonardite, vermicompost and peat moss and their combinations with cocopeat as tomato growing media. *Journal of Soil Science and Plant Nutrition*, 25, 2726-2741. Turkey.

[5] Gao, W., Xu, G., Sun, Y., Han, B., Fan, X. (2020). Influence of tomato plug seedling characteristics and substrate drop loss on mechanical transplanting of seedlings (番茄穴盘苗特性和基质掉落损失对幼苗机械移栽的影响研究). *Anhui Agricultural Science Bulletin*, 26(11), 62-63. China.

[6] Han, L., Wang, Y., Du, X., Xu, Q., Ma, G., Liu, Y., Mao, H. (2025). Design and test analysis of clamping mechanics test bench for plug seedlings (穴盘苗夹取力学试验台设计与测试分析). *Transactions of the Chinese Society of Agricultural Engineering*, 41(7), 47-55. China.
[7] Han, L., Mao, H., Zhao, H., Liu, Y., Hu, J., Ma, G. (2019). Design of root lump loosening mechanism using air jets to eject vegetable plug seedlings (蔬菜穴盘育苗底部气吹式钵体松脱装置设计). *Transactions of the Chinese Society of Agricultural Engineering*, 35(4), 37-45. China.
[8] Hu, J., Liu, Y., Liu, W., Zhang, S., Han, L., Zeng, T. (2022). Experiment on combined seedling picking device with top clamping and pulling (蔬菜自动移栽机顶夹拔组合式取苗装置试验研究). *Transactions of the Chinese Society for Agricultural Machinery*, 53(S1), 110-117.China.
[9] Kong, W. (2026). Influence mechanism of mechanical vibration and equipment coupling on underground canal surge (机械振动与设备耦合对暗渠涌动的影响机制). *Mechanical & Pneumatic Tools*, 52(1), 79-81. China.
[10] Li, G., Yu, J., Qin, X., Wang, W., Wang, J., Wu, X., Qu, J. (2026). Phenotypic detection of tomato seedlings based on YOLO-SDCG and elliptic Fourier descriptors (基于 YOLO-SDCG 和椭圆傅里叶描述子的番茄苗表型检测). *Transactions of the Chinese Society of Agricultural Engineering*, 42(3), 179-191.China.
[11] Liu, Z., Huang, Y., Zhou, B., Xu, D. (2025). Peony multi-mode vibration seedling separation mechanism and experimental study. *Plant and Soil*, 514, 937-954. Germany.
[12] Ramachandran, P., Ramirez, A., Dinneny, J. R. (2025). Rooting for survival: how plants tackle a challenging environment through a diversity of root forms and functions. *Plant Physiology*, 197(1), 1-18. USA.
[13] Sun, W., Thompson, D., Zhou, J. (2019). A mechanism for overcoming the effects of the internal resonances of coil springs on vibration transmissibility. *Journal of Sound and Vibration*, 468, 115145. Netherlands.
[14] Sadeghi, K., Incecik, A. (2020). Damping potential, generalized potential, and D'Alembert' s principle. *Iranian Journal of Science and Technology*, 44, 311-319. Iran.
[15] Xiao, T., He, C., Cao, G., Chen, Y., Cui, S., Zhao, R. (2015). Research on development status of vegetable industry in China and foreign models from the perspective of mechanization (机械化生产视角下我国蔬菜产业发展现状及国外模式研究). *Research of Agricultural Modernization*, 36(5), 857-861.China.
[16] Yang, Y., Ting, K. C., Giacomelli, G. A. (1991). Factors affecting performance of sliding-needles gripper during robotic transplanting of seedlings. *Applied Engineering in Agriculture*, 7(4), 493-498. USA.
[17] Yuan, T., Wang, D., Wen, Y., Zhu, S., Chen, Y., Tan, Y. (2019). Design and experiment of seedlings unloading mechanism based on methods of air-blowing and vibration for vegetable Transplanter (基于气吹与振动组合式的蔬菜移栽机落苗装置设计与试验). *Transactions of the Chinese Society for Agricultural Machinery*, 50(10), 80-87. China.
[18] Yao, S., Liu, J., Zeng, J., Shi, Q., Zhao, C., He, X. (2022). Design of taking-combined-with-vibration-type seedlings unloading mechanism of vegetable transplanter (夹取振动复合式取苗机构的结构设计). *Agricultural Equipment & Vehicle Engineering*, 60(1), 70-73. China.
[19] Zhou, B., Miao, H., Guan, C., Ji, X., Wang, X. (2024). Design and test of seedling-picking mechanism of fully automatic transplanting machine. *Applied Sciences*, 14(20), 9235. Switzerland.
[20] Zhang, Z., Zhang, N., Lv, Q., Han, C., Xu, H., Li, H., Bai, Z. (2016). Design and research on the automatic transplanting machine of the top pinch combined type plug seedling (顶夹组合式全自动移栽机的设计研究). *Xinjiang Agricultural Mechanization*, (6), 16-18. China.