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BIOMIMETIC DESIGN AND DRAG REDUCTION MECHANISM OF *PANAX NOTOGINSENG* (SANQI) DIGGING SHOVEL INSPIRED BY *ALLOMYRINA DICHOTOMA* BASED ON DEM

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To address the high excavation resistance and root damage in mechanised *Panax notoginseng* (Sanqi) harvesting, this study designed a specialised biomimetic digging shovel inspired by the drag-reducing morphology of the two-horned rhinoceros beetle (*Allomyrina dichotoma*). The shovel structure was designed based on 3D-scanned geometric features of the beetle and the agronomic requirements of raised-bed mulching cultivation. A root-soil-shovel interaction model was established using the Discrete Element Method (DEM) to simulate the effects of shovel shape and operational parameters on digging resistance and soil-root separation. Key structural parameters were optimised via Response Surface Methodology (RSM). Soil-bin tests confirmed the simulation results and drag-reduction performance. Compared to a conventional flat shovel, the biomimetic shovel achieved an average drag reduction of over 23%, with a maximum reduction of 31.4% at a 25° entry angle, 0.8 m·s⁻¹ working speed, and 30 mm blade spacing. The optimal parameters were a vertical spacing of 4.13 mm, horizontal spacing of 3.71 mm, and a top angle of 130°, yielding a theoretical digging resistance of 162.15 N and an experimental value of 165.39 N (deviation 1.96%). This study provides a reliable biomimetic design method and engineering solution for low-damage, high-efficiency mechanised harvesting of *Panax notoginseng*.

Keywords: *Panax notoginseng*; biomimetic digging shovel; simulation optimisation; *Allomyrina dichotoma*; discrete element method (DEM)

Panax notoginseng (Sanqi) is a valuable herb in traditional Chinese medicine. The notoginsenosides it contains exhibit excellent pharmacological activity in the prevention and treatment of cardiovascular and cerebrovascular diseases, as well as in wound repair, conferring it significant medicinal and economic value. However, the harvesting of this crop still relies heavily on manual labour, which suffers from low efficiency, high intensity, and considerable cost. Furthermore, the delicate rhizomes of *Panax notoginseng* are highly susceptible to mechanical damage during excavation (Zhang et al., 2023), severely compromising their medicinal grade and market value. Consequently, the development of an efficient and reliable digging device for *Panax notoginseng* is an urgent requirement for modernising and upgrading the Sanqi industry.

As a critical component of agricultural machinery, the design and optimisation of digging shovels have been extensively studied internationally. For instance, a research group designed a bionic digging shovel inspired by the streamlined morphology of a catfish head to reduce excavation resistance and improve operational efficiency (Yang et al., 2025). Other researchers have developed a novel rolling excavation shovel based on a high-precision root-soil composite model (Che et al., 2025). The influence of the blade face angle of a potato digger on operational

performance in hilly areas has been analysed using a finite element simulation system (Wang et al., 2023). Additionally, to address the issues of high digging resistance and difficult soil separation during ginger harvesting, an optimal parameter combination for the coordinated operation of digging and soil shaking has been proposed (Wang et al., 2025). Although harvesting technologies for root and tuber crops like potatoes and sweet potatoes are relatively mature, their solutions are not directly transferable to *Panax notoginseng* harvesting. This is primarily due to the irregular shape and fragile texture of Sanqi tubers, which are more sensitive to external damage than conventional crops. The clay loam soil in southern Chinese planting regions also presents challenges, with its complex physical properties that vary with humidity, leading to adhesion and compaction. Although institutions such as the Kunming University of Science and Technology have developed prototype harvesters, technical bottlenecks persist, including poor adaptability and high root damage rates during digging and low-damage conveying processes (Wang et al., 2018). Therefore, optimising the digging shovel design for *Panax notoginseng* harvesters to suit the specific conditions of hilly terrain holds significant practical importance.

The Discrete Element Method (DEM) is a powerful tool for revealing the microscopic interaction mechanisms between

soil, machinery, and roots (Nagy et al., 2024). By establishing an accurate DEM model of the *Panax notoginseng* root-soil complex, the dynamic processes under different shovel designs and operational parameters can be simulated. This allows for the prediction of excavation resistance, soil disturbance, and tuber stress distribution, providing a solid theoretical foundation for optimising shovel geometry towards low resistance and minimal damage.

To address these challenges, this study aims to systematically investigate the mechanisms and implementation pathways for achieving low-damage and efficient excavation of *Panax notoginseng*. The research will proceed sequentially as follows. First, based on the drag-reducing and anti-adhesive morphological characteristics of *Allomyrina dichotoma*, the structural design of the bionic digging shovel is carried out, combining the agronomic requirements of *Panax notoginseng* high-ridge cultivation. Second, an interaction model involving *Panax notoginseng*, soil, and the digging shovel will be constructed to simulate and analyse the influence of different structural and operational parameters on the digging dynamics. On this basis, the structural and operational parameters of the bionic shovel are further optimised to enhance its low-resistance and low-damage performance. Finally, simulation results will be validated through bench tests, and the comprehensive operational performance of the optimised shovel will be evaluated.

This study presents a novel biomimetic design for a low-damage *Panax notoginseng* digging shovel, inspired by the cephalic morphology of the double-forked rhinoceros beetle (*Allomyrina dichotoma*). Its primary innovation lies in the systematic integration of 3D scanning, DEM simulation, and RSM optimisation to tailor the shovel to high-ridge film mulching cultivation. Unlike previous biomimetic designs focused mainly on drag reduction, this study concurrently addresses root damage and soil adhesion by mimicking the beetle's non-smooth surface and forked structure. The optimised shovel achieves an average drag reduction exceeding 23% (maximum 31.4%), validated by both simulation and soil-bin experiments, with a deviation of only 1.96% between theoretical and experimental values. This research provides an effective engineering solution for mechanised Sanqi harvesting and offers a biomimetic reference for designing soil-engaging tools for delicate root crops in complex agronomic systems.

Material and Methods

Cultivation patterns of *Panax notoginseng*

Sanqi is cultivated under various patterns, all prioritising root integrity (Zi et al., 2025). The prevalent high-ridge film mulching mode (Fig. 1), while beneficial for moisture retention, presents specific challenges for mechanised harvesting. The ridge structure creates a soil resistance gradient with compacted sides and a looser centre. Critically, as Tarasenko et al. (2025) mentioned, the shallow root concentration (within 10–20 cm depth) necessitates a digging shovel capable of low-resistance penetration and precise depth control to minimise tuber damage. The standard ridge geometry (height: 150–200 mm; top

width: ~300 mm; bottom width: ~600 mm) also dictates that the shovel's working width must exceed the ridge bottom width for complete excavation.

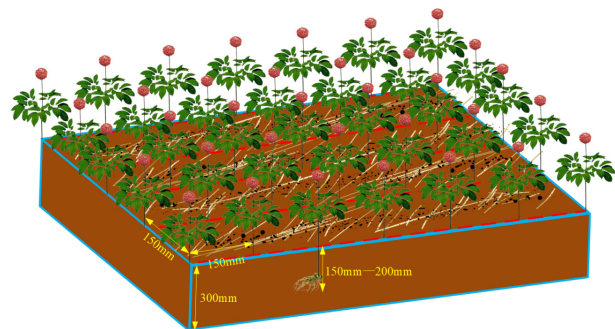


Fig. 1 Specifications for the cultivation of *Panax notoginseng*

These agronomic requirements – low-resistance soil penetration, precise root avoidance, and adaptation to the ridge shape – define the core design objectives for the bionic shovel. The non-uniform soil resistance further demands a design that balances breaking efficiency with root protection (Zhang et al., 2024). Therefore, developing a shovel tailored to these characteristics is essential to address the harvesting challenges.

Design background and bionic principle of the bionic digging shovel

Conventional digging shovels for root and tuber crops encounter prominent problems. As Fu et al. (2023) mentioned, these problems include high excavation resistance, severe soil adhesion, and rapid wear during Sanqi harvesting. These issues are exacerbated by Sanqi's unique agronomic characteristics – adhesive clay loam, shallow and fragile roots, and high-ridge cultivation – making existing general-purpose shovels unsuitable. Bionic design inspired by soil-dwelling organisms has been proven effective in optimising soil-engaging components, as natural selection has endowed these organisms with superior adaptability to soil environments (Zhu et al., 2024).

This study selected the soil-dwelling double-forked rhinoceros beetle (*Allomyrina dichotoma*) as the bionic prototype, which exhibits excellent drag-reducing and anti-adhesive capabilities in compact and moist soil (Shen et al., 2024). Its head morphology offers three key functional insights that are highly compatible with Sanqi harvesting requirements:

1. The forked V-shaped horn disperses soil reaction force, reducing local stress concentration and adapting to the uneven soil resistance of Sanqi ridges.
2. Non-smooth pits and dorsal grooves on the head surface disrupt soil adhesion, addressing the problem of soil clumping on shovels in high-moisture clay loam.
3. The streamlined, arched contour minimises soil shear resistance, facilitating low-resistance penetration in the shallow soil layer where Sanqi roots are distributed.

Unlike previous insect-inspired designs for potato or sweet potato harvesters (Li et al., 2020), this prototype is specifically tailored to Sanqi's unique cultivation and root

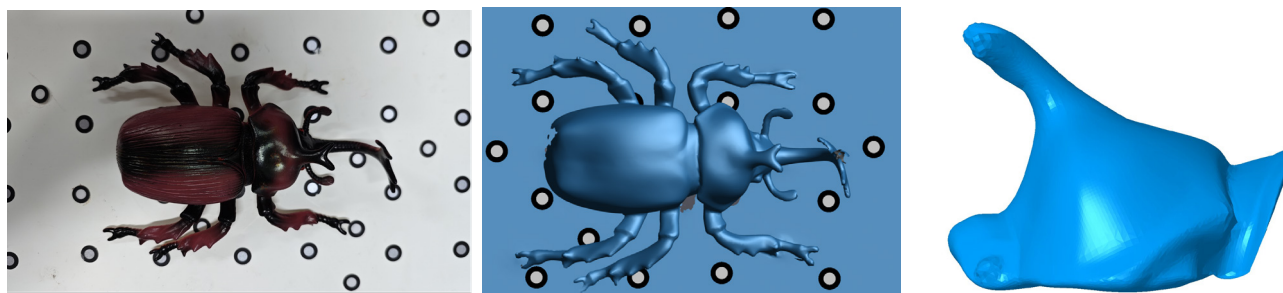


Fig. 2 Scanning the three-dimensional model of the head of the double-forked rhinoceros beetle
(a) the model to be scanned; (b) double-forked rhinoceros beetle point cloud; (c) three-dimensional structure of the head of the double-forked rhinoceros beetle

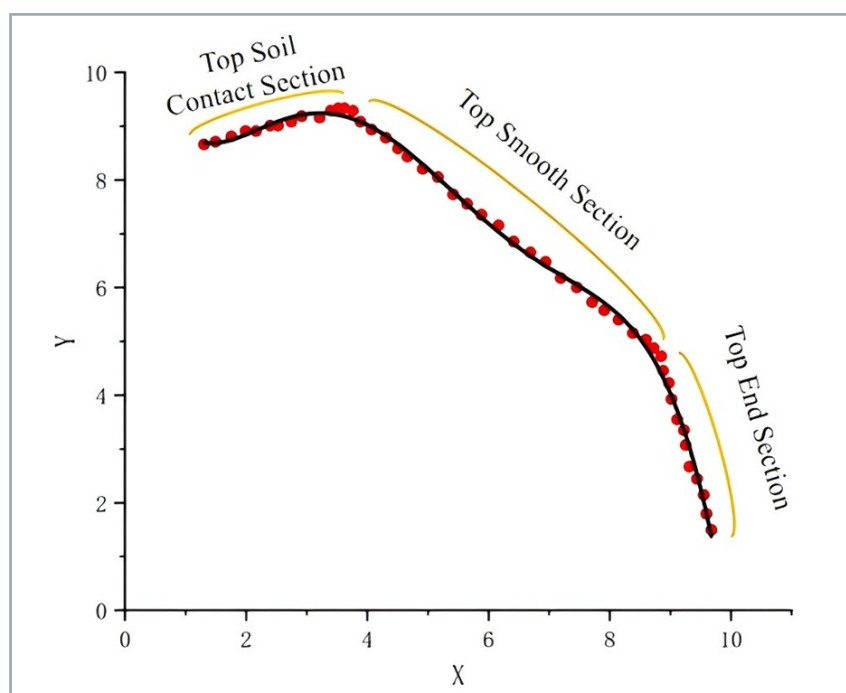


Fig. 3 Fitting curve of the top of the head of the double-forked rhinoceros beetle

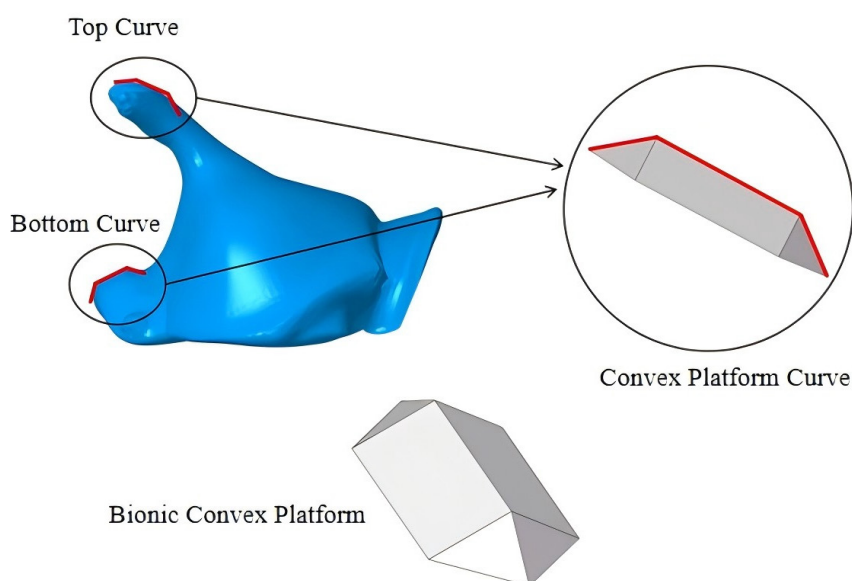


Fig. 4 Schematic diagram of the bionic structure

characteristics, providing a targeted solution for the technical bottlenecks of Sanqi harvesting.

Design and working principle of the single bionic shovel

The beetle's head was 3D scanned (HandySCAN 3D BLACK) and processed to create a precise model (Fig. 2). Its top contour was fitted to a curve (Fig. 3), which was then simplified into a polygonal framework of interconnected straight-line segments. This formed the basis for a stepped convex ridge structure, balancing geometric fidelity with manufacturing feasibility.

The core structure of the *Allomyrina dichotoma* head exhibits morphological similarity to the zigzag frame outlined in Fig. 4. This structure comprises multiple linear segments connected at nodes, forming an angular, zigzag contour. This topological configuration served as a direct inspiration for the bionic protrusions shown in the final design.

The finalised single-shovel model is shown in Fig. 5. Key structural parameters, informed by prior research to ensure conveying efficiency, are as follows: shovel length ($L1$) = 400 mm, shovel width ($L2$) = 80 mm, shovel edge tension angle (α) = 125°, shovel thickness (m) = 8 mm, and shovel tip slope angle = 45°.

Structure of the digging device

To realise the excavation of Sanqi high-ridge root-soil complexes, 13 optimised single bionic shovels were assembled into a complete digging device (Fig. 6), which serves as the core functional unit of the harvester.

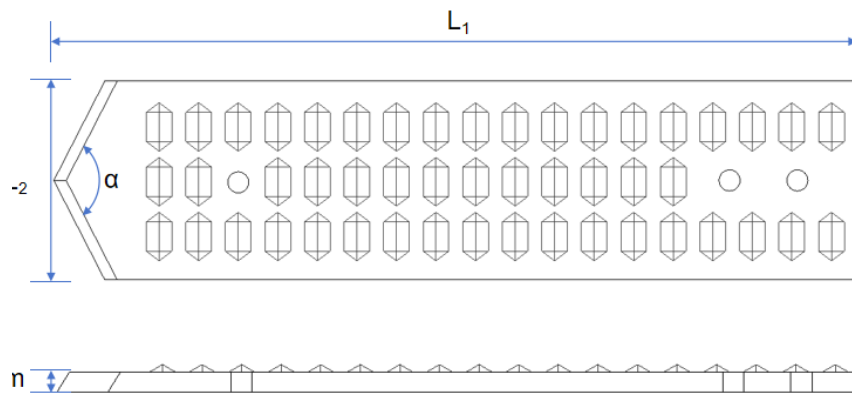


Fig. 5 Model of the single shovel

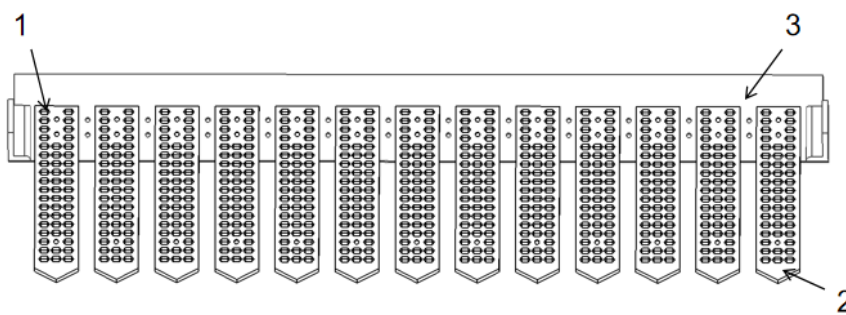


Fig. 6 Schematic diagram of the digging shovel structure
1 – bionic protrusion; 2 – digging single shovel; 3 – shovel frame

Table 1 Intrinsic setting parameters for discrete element simulation of the digging shovel

Soil intrinsic parameters	Numeric value
Planting soil Poisson's ratio (μ_1)	0.41
Steel Poisson's ratio (μ_2)	0.29
Planting soil shear modulus (Pa)	1.58×10^6
Steel shear modulus (Pa)	7.9×10^{10}
Planting soil density ($\text{g}\cdot\text{cm}^{-3}$)	0.90
Steel density ($\text{g}\cdot\text{cm}^{-3}$)	7.85
Surface JKR energy of soil ($\text{J}\cdot\text{m}^{-2}$)	14.52
Soil-steel cohesion ($\text{J}\cdot\text{m}^{-2}$)	6
Surface JKR adhesion radius (mm)	1.5
Collision recovery coefficient between soil	0.73
Collision recovery coefficient of soil and steel	0.60
Coefficient of static friction between soil	0.98
Static friction coefficient between soil and steel	0.56
Rolling friction coefficient between soil	0.16
Rolling friction coefficient between soil and steel	0.18

The single shovels are arranged in parallel with equal spacing, and the total working width of the device is 1600 mm. This width is determined to ensure complete excavation of the Sanqi ridge without missing or redundant digging.

The digging device is equipped with a unified depth-limiting and angle-adjusting mechanism, which can synchronously control the entry angle and digging depth of all single shovels. This ensures consistent operation performance across the entire ridge width to preclude localised over-excavation or under-excavation as identified by Saleh et al. (2025) due to inconsistent tool parameters.

Discrete element model establishment

The Hertz-Mindlin with JKR bonding contact model was employed to accurately simulate the mechanical behaviour of neutral clay during the Sanqi harvest period. Following the approach of Li et al. (2019), the cohesive and fragmentation characteristics of clay soil were effectively reproduced. This cohesive contact model was applied to simulate both the bionic and flat shovel operating in soil, capturing the adhesion and clumping behaviour typical of moist clay and root-soil complexes. The intrinsic parameters used in the EDEM simulations are summarised in Table 1. Based on this, a soil flume with dimensions of 2000 mm $\times$ 2000 mm $\times$ 300 mm (length $\times$ width $\times$ height) was constructed and approximately 2 million particles were generated, as shown in Fig. 7.

A discrete element model of the Sanqi rhizome was developed to simulate root-soil interaction and harvesting damage. The irregular main root and lateral roots were reconstructed in SolidWorks based on 3D scan data. The model employed the Hertz-Mindlin with JKR contact model, with bonding parameters referenced from typical root crops (Wang et al., 2024), as listed in Table 2.

To balance simulation accuracy and computational efficiency, the root geometry was filled with 7030 particles of 1 mm radius to establish the final

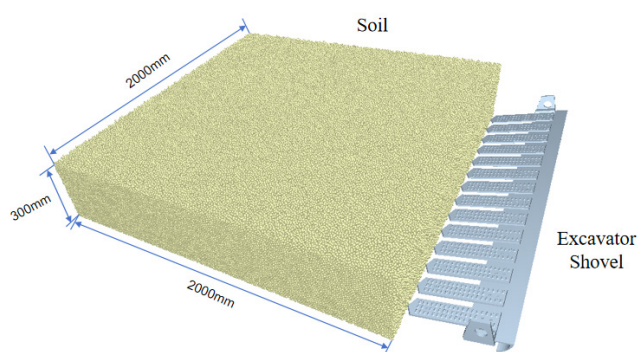


Fig. 7 Soil discrete element model

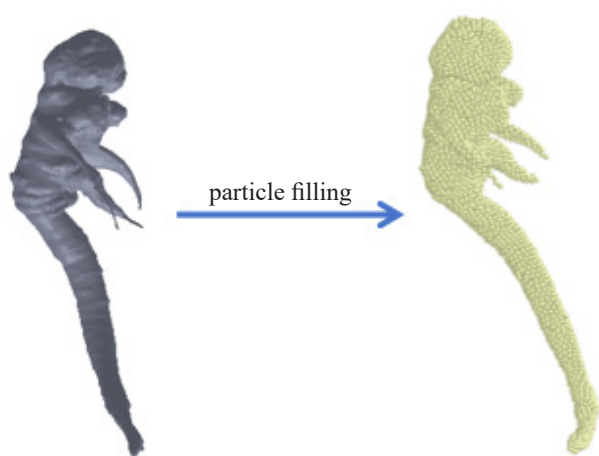


Fig. 8 *Panax notoginseng* rhizome model before and after filling

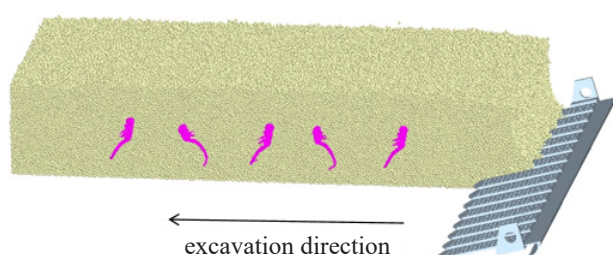


Fig. 9 Schematic diagram of simulation test

Table 2 Bonding parameters of *Panax notoginseng*

Parameter	Numeric value
Normal stiffness per unit area ($\text{N}\cdot\text{m}^{-3}$)	3.26×10^8
Tangential stiffness per unit area ($\text{N}\cdot\text{m}^{-3}$)	2.17×10^8
Critical normal stress (Pa)	2.27×10^6
Critical tangential stress (Pa)	9.65×10^6
Adhesion radius (mm)	0.1

discrete element model (Fig. 8). This model is similar to the one mentioned by Liu et al. (2024b) for analysing the movement and displacement of roots and stems as well as soil during the mining process.

Simulation and experimental test design

A soil box with dimensions of 2000 mm $\times$ 2000 mm $\times$ 300 mm (length $\times$ width $\times$ height) was established and filled with approximately 2 million soil particles. Simultaneously, the pre-imported *Panax notoginseng* rhizome model was filled with particles in EDEM. After the filling process was completed, the 3D model of the bionic shovel was converted to STP format, imported into EDEM, and assigned a Linear-Translation motion. To ensure simulation stability, the fixed time step was set to 20% of the Rayleigh time step, and the total simulation time was 5 seconds, as illustrated in Fig. 9.

To lay a solid foundation for subsequent tests with consistent comparability and reliability, this section specifies the unified precondition preparation and test framework targeting three key experiments. All the three tests share unified simulation models (soil, rhizome, and shovel models with consistent parameters), experimental conditions (soil properties, test bench specifications, and operation procedures), and data processing standards (drag reduction rate calculation, variance analysis, and reliability verification) to ensure the validity and cross-comparability of the results.

Results and discussion

Structural optimisation test: bionic boss arrangement and top angle parameters

To minimise digging resistance, the influence of bionic boss parameters – vertical spacing (S1), horizontal spacing (S2), and top angle (β) – was investigated based on soil adhesion mechanisms (Fig. 10). The selection of these influencing factors was inspired by some studies on bionic potato diggers (Li et al., 2020). A three-factor, three-level orthogonal test was designed (Table 3), and discrete element simulations were performed to obtain resistance values for each combination.

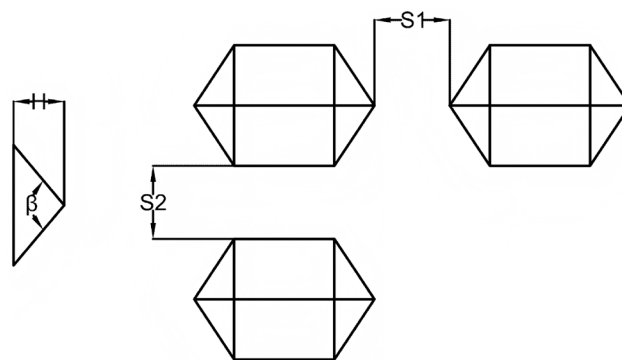


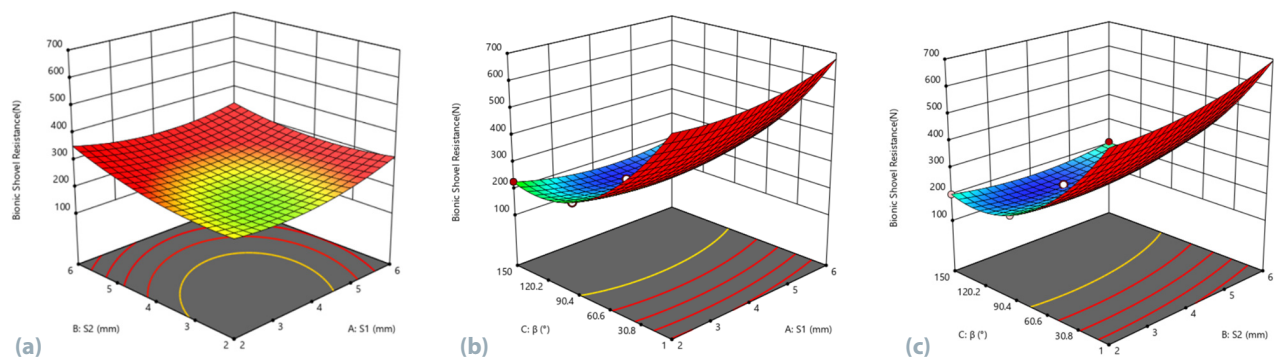
Fig. 10 Bionic convex platform arrangement mode

Subsequently, a response surface analysis was carried out, and the interaction effects were examined

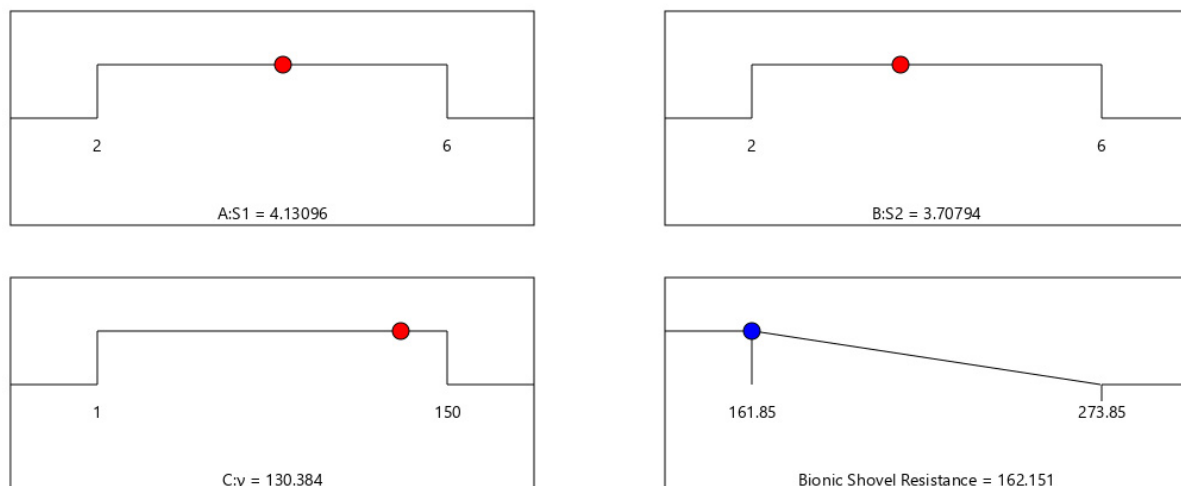
Table 3 Orthogonal test protocol and results

Number	S1 (mm)	S2 (mm)	β (°)	Drag overall (N)
1	2	6	120	273.85
2	4	4	120	165.27
3	6	2	120	239.67
4	4	4	120	163.30
5	2	4	150	227.39
6	2	2	120	204.79
7	2	4	90	239.67
8	4	2	150	200.52
9	4	4	120	161.85
10	4	4	120	173.67
11	6	6	120	226.57
12	6	4	150	194.72
13	4	6	90	264.70
14	4	4	120	167.45
15	4	2	90	211.28
16	6	4	90	251.26
17	4	6	150	207.25

S1 – vertical spacing; S2 – horizontal spacing; β – top angle

**Fig. 11** Effect of interaction factors on soil resistance of digging shovels

(a) Influence of S1 and S2 on the soil resistance of the excavating shovel; (b) Influence of S1 and β on the soil resistance of the excavating shovel; (c) Influence of S2 and β on the soil resistance of the excavating shovel

**Fig. 12** Slope profile of optimal design parameters for the bionic shovel

(Fig. 11). The analysis, summarised in the optimal slope graph (Fig. 12), yielded the following optimal parameter set: $S_1 = 4.13$ mm, $S_2 = 3.71$ mm, and $\beta = 130^\circ$. This configuration corresponds to a minimum predicted digging resistance of 162.15 N.

After determining the optimal parameters of the protrusion arrangement, it is necessary to further optimise the key parameters in actual operation (entry angle, shovel spacing, working speed) to ensure that the bionic shovel performs at its best under field conditions.

Application optimisation test: digging shovel operational parameters

To further optimise the performance of the bionic shovel, a three-factor four-level orthogonal experiment was conducted, selecting three factors: the angle of entry (γ), the spacing between shovel blades (d), and the working speed (v). The selection of these influencing factors was inspired by some studies on the difference in the face inclination angle of potato-digging buckets (Zhang et al., 2025; Kong et al., 2025). The excavation resistance encountered by the shovel during the EDEM simulation process was used

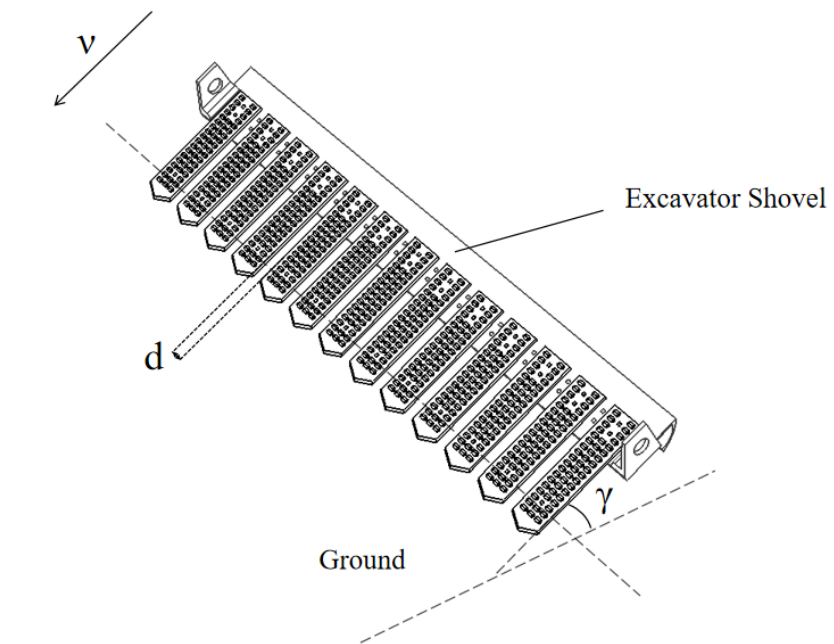


Fig. 13 Factors affecting the operation of the digging shovel

as the evaluation metric (Qin et al., 2024), as shown in Fig. 13.

The results of 16 sets of tests are recorded in Table 4. The data show that the resistance of the bionic shovel is significantly lower than that of the flat shovel under all parameter combinations.

During soil tillage, the horizontal force – which has a lesser compaction

effect than the vertical force – was analysed as the primary digging resistance (Hu et al., 2025; Yulan et al., 2025). Variance analysis of the bionic shovel tests showed that the entry angle (α) had a highly significant influence on digging resistance ($P < 0.01$), while working speed (v) and blade spacing (d) had secondary effects. A significant interaction was

Table 4 Results of the levels of various factors in the bionic digging shovel simulation test

Test number	Factor		Average mining resistance (N)		
	v ($\text{m}\cdot\text{s}^{-1}$)	d (mm)	γ ($^\circ$)	flat excavator	bionic excavator
1	0.4	20	15	1327.83	941.03
2	0.4	25	20	1184.48	862.66
3	0.4	30	25	1099.95	765.90
4	0.4	35	30	1034.74	697.30
5	0.6	20	20	1540.28	1092.58
6	0.6	25	15	1396.06	960.33
7	0.6	30	30	1357.02	832.50
8	0.6	35	25	1323.75	923.77
9	0.8	20	25	1659.85	1280.84
10	0.8	25	30	1567.36	1176.82
11	0.8	30	15	1448.85	1032.01
12	0.8	35	20	1214.23	960.29
13	1.0	20	30	1765.22	1387.21
14	1.0	25	25	1544.03	1221.80
15	1.0	30	20	1583.22	1168.87
16	1.0	35	15	1494.51	1376.19

v – working speed; d – spacing between shovel blades; γ – angle of entry

also observed between the entry angle and working speed ($P < 0.05$). The optimal drag reduction – 31.4% greater than that of the flat shovel – was achieved with $\alpha = 25^\circ$, $v = 0.8 \text{ m}\cdot\text{s}^{-1}$, and $d = 30 \text{ mm}$, providing clear guidance for subsequent shovel optimisation.

Comparative test: biomimetic shovel vs. conventional flat shovel

To objectively evaluate the comprehensive performance of the optimised bionic shovel, a controlled comparative test was conducted via DEM simulation and soil-bin experiment. The test strictly maintained unified conditions: both shovels shared identical basic dimensions (length 400 mm, width 80 mm, thickness 8 mm, blade angle 125° , tip slope 45°) to ensure the only variable was the bionic structure; the bionic shovel adopted the optimal parameters ($S1 = 4.13 \text{ mm}$, $S2 = 3.71 \text{ mm}$, $\beta = 130^\circ$, $\gamma = 25^\circ$, $v = 0.8 \text{ m}\cdot\text{s}^{-1}$, $d = 30 \text{ mm}$); the simulation and experimental conditions (soil properties, digging depth 200 mm, test bench specifications) were consistent with the previous optimisation tests (Fig. 14).

To eliminate randomness in the experiment, the simulation experiment was carried out in five groups. The test results of the planar shovel were designated as the control group to compute the drag reduction rate R of the bionic shovel. The formula is presented as follows:

$$R = \frac{D_1 - D_2}{D_2} \times 100\% \quad (1)$$

where: D_1 – resistance of the bionic shovel (N); D_2 – resistance to the flat shovel (N)

The test results are presented in Table 5. Through the analysis of the test results, it is evident that the drag-reduction performance of the bionic shovel is notably significant, with an average drag-reduction rate of 23.8%. It is even better than the optimal drag reduction efficiency of 14.469% proposed by Liu et al. (2024a) for the bionic digging shovel.

Comprehensive mechanism analysis of drag reduction

The drag-reduction mechanism of the bionic shovel was elucidated by analysing soil flow dynamics and root-soil separation. Compared to the flat shovel, the bionic shovel induced more ordered soil particle flow with higher velocity (most $> 0.9 \text{ m}\cdot\text{s}^{-1}$ vs. $0.84 \text{ m}\cdot\text{s}^{-1}$), which prevented soil accumulation and reduced operational resistance (Fig. 15).

Soil disturbance is defined as the disruption of the local topsoil by the digging shovel, resulting in internal loosening, movement, and mixing of the soil. However, more significant soil disturbance may lead to excessive traction resistance. The area enclosed by the outer contour curve of the soil above the horizontal plane and the horizontal line is denoted as the soil swelling area S_i , and the calculation formula for the soil disturbance rate is

$$Q = \ln \sum i = \ln S_i S_0 \times 100\% \quad (2)$$

where: Q – soil disturbance rate after excavation (%);
 i – number of simulation tests; S_0 – original cross-sectional area of the soil model (mm^2)

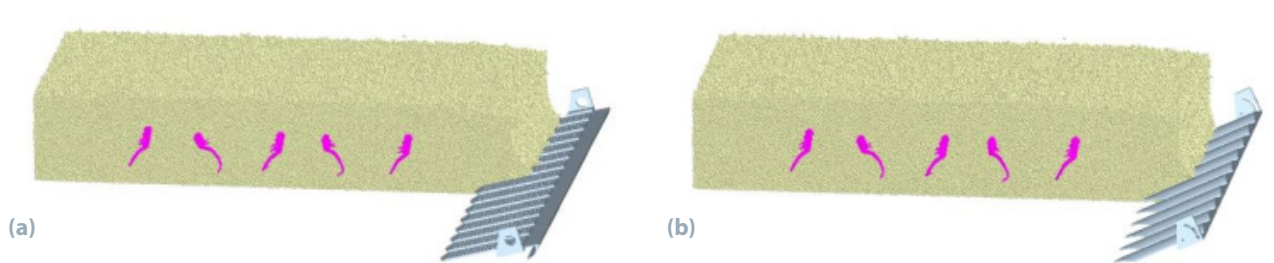


Fig. 14 Comparison of discrete element simulation for the excavator shovel
(a) simulation process of the bionic shovel; (b) simulation process of the flat shovel

Table 5 The results of discrete element simulation control test of digging shovel

Order number	D_2 (N)	D_1 (N)	Drag reduction efficiency
1	190.05	142.93	24.8%
2	203.46	159.92	21.4%
3	184.29	144.25	21.7%
4	219.54	158.27	27.9%
5	181.26	141.21	22.1%
6	194.20	148.35	23.6%
7	195.20	147.75	24.3%
8	202.00	255.72	22.9%
9	191.48	145.50	24.0%
Average value	195.72	149.32	23.8%

D_1 – resistance of the bionic shovel; D_2 – resistance to the flat shovel

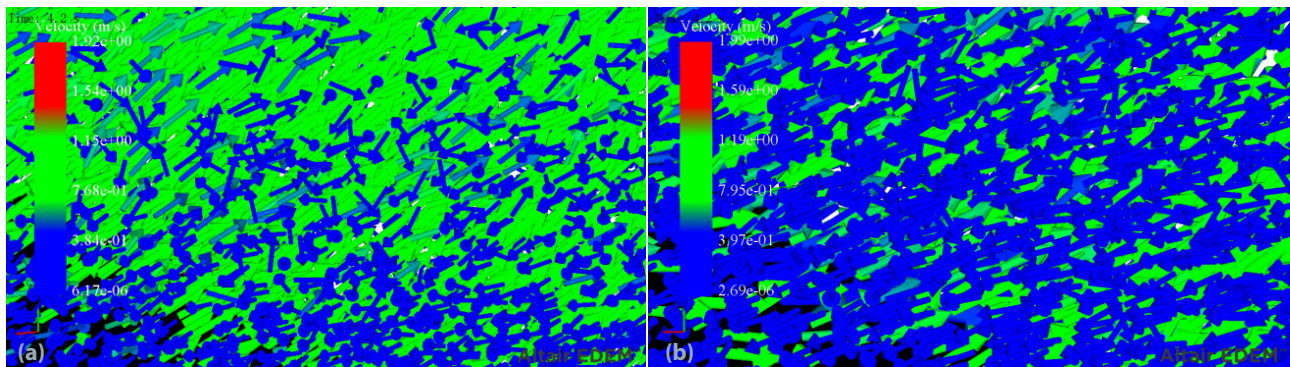


Fig. 15 Comparison of soil mobility on the surface of the digging shovel: (a) Soil fluidity on the surface of the bionic shovel; (b) Soil fluidity on the surface of the flat shovel



Fig. 16 Comparison of bond states after root and rhizome are excavated by the excavating shovel
(a) Initial state; (b) After planar excavation; (c) After biomimetic excavation

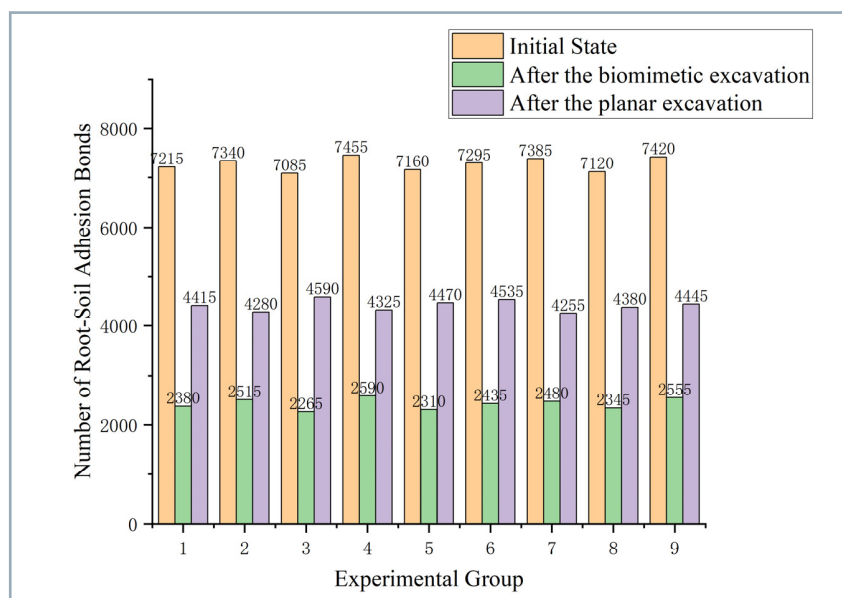


Fig. 17 Comparison of the number of bonding keys after the root and rhizome are excavated by the excavating shovel

The bionic shovel generated a higher soil disturbance rate (Q , calculated by Eq. 2) than the ordinary shovel. According to the research by Cao et al. (2023), this enhanced disturbance effectively loosened the soil structure, thereby reducing the traction resistance. More critically, the increased disturbance actively promoted root-soil separation. Discrete element simulations confirmed that the bionic shovel broke more soil-rhizome bonds, resulting in fewer residual bonds post-excavation. As shown in Fig. 16 and Fig. 17, this led to significantly less soil residue on roots, demonstrating superior anti-adhesion performance alongside drag reduction.

Drag reduction effect of soil tank verification test

To verify the drag reduction performance of the optimised bionic shovel, a soil flume validation test was carried out. The tests were performed on a bench (2.5 m × 0.9 m × 0.65 m) with soil prepared to simulate field conditions (Fig. 18). Both the bionic and flat shovels were tested at a travel speed of $0.84 \text{ m} \cdot \text{s}^{-1}$ and an entry angle of 25° , with resistance measured by calibrated sensors.

The results confirmed the bionic shovel's superiority. As shown in Fig. 19 and Fig. 20, the average digging resistance during stable operation was 168.97 N for the bionic shovel, compared to 219.64 N for the flat shovel, yielding a drag-reduction rate of 23.1%.

A separate test was conducted using the bionic shovel with optimised parameters (vertical spacing 4.13 mm, horizontal spacing 3.71 mm, top angle



Fig. 18 Soil trench test environment

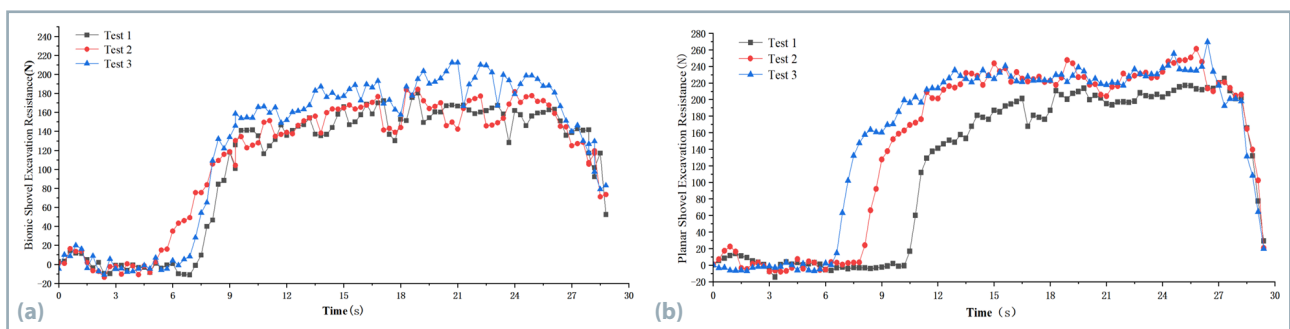


Fig. 19 Results of the drag-reduction effect verification test conducted in a soil tank
(a) resistance of the bionic shovel test; (b) resistance of the flat shovel test

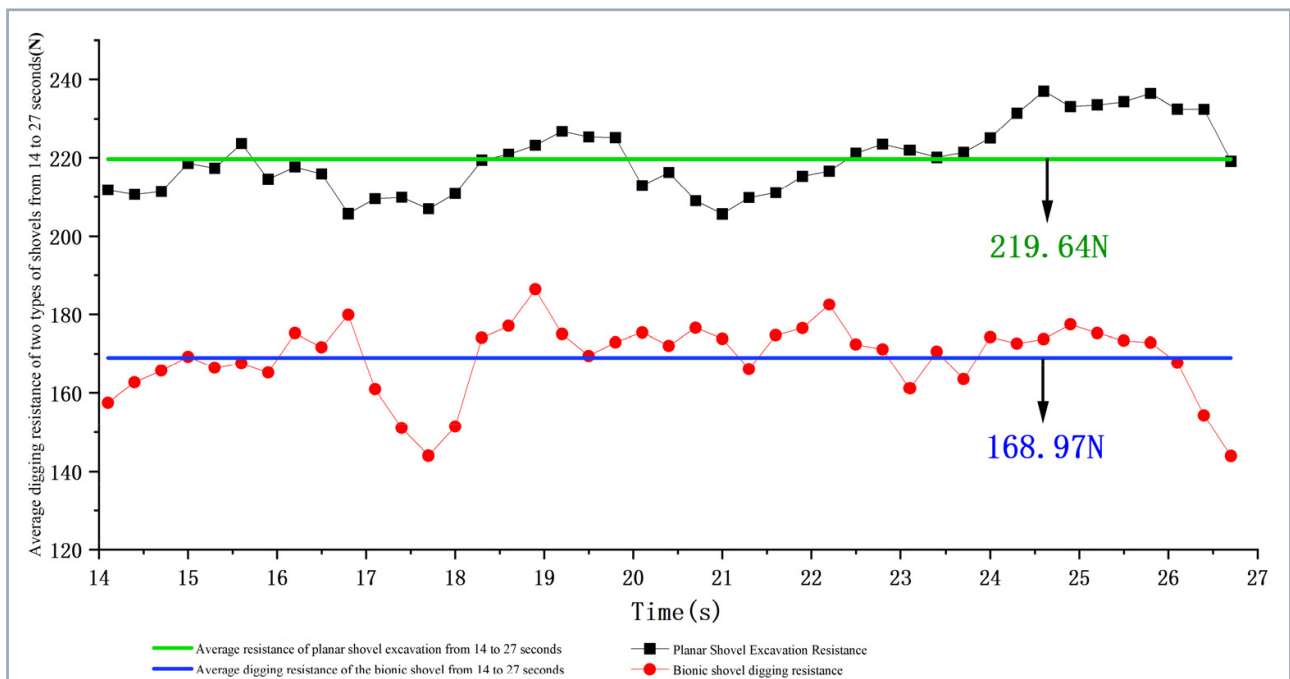


Fig. 20 Average drag from 14 to 27 seconds

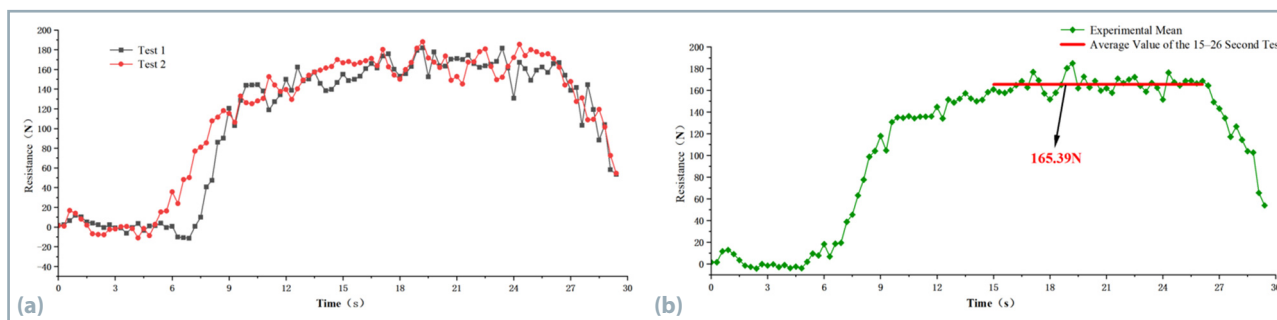


Fig. 21 Verification test of the optimised biomimetic shovel for soil trough
(a) the soil resistance encountered by the bionic shovel; (b) average soil resistance under stable working conditions

130°). The measured average resistance was 165.39 N (Fig. 21), which deviated by only 1.96% from the theoretically optimised value of 162.15 N, further validating the reliability of the response surface optimisation results.

The soil-bin test results further confirm that the bionic digging shovel optimised through this study exhibits superior comprehensive performance compared to the bionic digging tools designed by some previous researchers for root and tuber crops. For instance, Li et al. (2023) developed a potato bionic digging shovel based on DEM simulation, achieving a drag reduction rate of only 14.45% in clay and heavy soil, which is significantly lower than the average drag reduction rate (23.1–23.8%) and maximum drag reduction rate (31.4%) of the shovel in this study.

Conclusion

To tackle the issues of high excavation resistance and root damage during the harvesting of *Panax notoginseng*, this study designed and evaluated a biomimetic digging shovel inspired by *Allomyrina dichotoma*. The bionic shovel demonstrated significant drag-reduction effects, with an average drag reduction exceeding 23% when compared to a conventional flat shovel, as confirmed by Discrete Element Method (DEM) simulations and soil-bin tests. Key structural parameters were optimised through the application of the Response Surface Methodology. The optimal configuration (vertical spacing: 4.13 mm, horizontal spacing: 3.71 mm, apex angle: 130°) resulted in a theoretical digging resistance of 162.15 N, which was in close agreement with the experimental value of 165.39 N (deviation: 1.96%). Orthogonal testing was employed to identify the optimal operational parameters: an entry angle of 25°, a working speed of 0.8 m·s⁻¹, and a blade spacing of 30 mm, which achieved a maximum drag reduction of 31.4%.

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