OPTIMISATION AND EXPERIMENTAL RESEARCH OF FURROWING TOOL BASED ON EDEM
/
基于 EDEM 的开沟刀具优化与试验研究

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ABSTRACT
Mechanised furrowing and fertiliser application is an effective engineering solution for improving operational efficiency and reducing labour intensity in hilly and mountainous orchards. In this study, a systematic optimisation methodology for a disc-type furrowing tool is proposed by integrating discrete element method (DEM) simulations using EDEM with quadratic orthogonal regression experiments and response surface analysis. Key structural parameters, including bending radius, bending angle, and alpha angle, were selected as design variables, and their individual and interactive effects on furrowing power consumption were investigated. The results of the response surface analysis indicate that appropriate structural optimisation can significantly reduce trenching power consumption. The optimal structural parameters were determined as follows: bending radius of 36.79 mm, bending angle of 126.94°, and alpha angle of 43.65°. Under these conditions, the predicted power consumption was 0.85 kW, representing a reduction of 8.88% compared with the original tool design. Soil bin experiments were conducted to validate the DEM simulation results, and the experimental trends showed good agreement with the simulation predictions, demonstrating the reliability of the proposed optimisation approach. This study provides a practical reference for the engineering design and performance improvement of soil-engaging tools.

摘要
果园机械化开沟施肥技术是提高丘陵山区果园作业效率、降低劳动强度的关键手段之一。本文基于EDEM仿真技术，结合二次正交回归试验与响应曲面分析，优化了圆盘式开沟刀具的结构参数。研究重点分析了弯折半径、弯折角度和阿尔法角等关键参数，并通过响应曲面分析揭示了这些参数之间对开沟功耗的交互影响。优化结果表明，合理调整刀具结构能够显著降低开沟功耗，优化后的刀具参数为：弯折半径 X_1 = 36.79 mm、弯折角度 X_2 = 126.94°、阿尔法角 X_3 = 43.65°，优化后的功耗为 0.85 kW，相较未优化刀具，功耗降低了约 8.88%。土槽实验验证了仿真结果的准确性，为进一步优化开沟刀具提供了理论依据。

INTRODUCTION
Fertilisation is a fundamental management practice in orchard production because it directly influences tree growth, fruit yield, and fruit quality. In modern orchard management, strip fertilisation along the tree drip line is widely adopted to improve nutrient availability and root uptake. This practice requires efficient furrowing and subsequent backfilling to ensure uniform fertiliser placement and favourable soil conditions for root development *(Chen M. et al., 2024; Chen P. et al., 2024).* However, conventional furrowing methods generally exhibit high energy consumption and low operational efficiency, particularly when traditional soil-engaging tools are employed. These limitations become more pronounced in hilly and mountainous orchards, where steep terrain, irregular planting layouts, and limited accessibility restrict the use of conventional agricultural machinery *(Fang et al., 2024; Jian et al., 2024)*. Consequently, fertilisation in these regions still relies heavily on manual labour, resulting in low productivity and high labour intensity. With the continuing shortage of agricultural labour, the development of efficient and energy-saving furrowing equipment has become an important prerequisite for improving the mechanisation of orchard fertilisation in hilly and mountainous areas.

As the key soil-engaging component of a furrowing machine, the structural design of the furrowing tool directly determines soil cutting performance, soil disturbance characteristics, and power consumption during operation *(Aikins et al., 2019; Madhusudan et al., 2024).* An appropriately designed tool not only improves trenching efficiency but also reduces energy consumption and enhances fertiliser placement quality, thereby improving both the economic and environmental sustainability of orchard production *(Wang et al., 2015; Yi et al., 2024).* These studies indicate that optimising the structural parameters of furrowing tools is an effective engineering approach for reducing power consumption and improving operational performance.

As a core component, tool structure significantly affects efficiency and energy demand. Extensive research has been conducted in this field. For instance, *Kang et al., (2016),* reduced power consumption by optimizing blade geometry, while *Yang et al., (2018)* developed a cut-and-throw furrowing tool tailored for tea plantations, thereby improving soil displacement performance. *Kim et al., (2021)* employed discrete element method simulations to optimise soil–tool interaction, achieving considerable reductions in power consumption and offering valuable guidance for tool design. Despite these advances, traditional furrowing tools still suffer from low efficiency and excessive power consumption when used in orchards located in hilly and mountainous regions—where high soil viscosity and sloughing are prevalent—indicating a clear need for further optimisation. Improving tool configuration is essential to enhance efficiency, reduce power consumption, and improve adaptability to diverse soils and fertilisation needs.

In this study, DEM simulations (EDEM) and soil trench tests were conducted to investigate the effects of bending radius, bending angle, and alpha angle on power consumption. A quadratic orthogonal regression model was established to optimise tool parameters.

MATERIALS AND METHODS

MAIN STRUCTURE AND PARAMETERS OF FURROWING TOOL

In this study, a disc-type furrowing cutter was adopted as the research object, and its structural design was developed based on the working principles of a wetland furrowing curved cutter, as illustrated in Figure 1. The tool mainly consists of a lateral cutting edge, a frontal cutting edge, a central shaft, and mounting apertures. The lateral cutting edge is formed along an Archimedean helix to facilitate soil cutting and conveyance, while the frontal cutting edge is designed with a circular arc profile to enhance soil penetration and stabilise the furrowing process *(Aikins et al., 2020; Amantayev et al., 2018; Barr et al., 2020; Mi et al., 2025).*

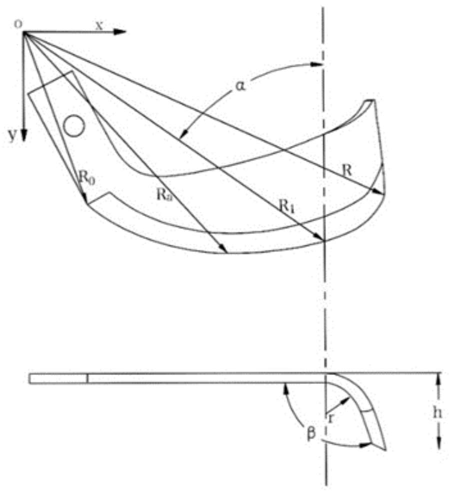


Fig. 1 - Tool structure diagram. O-centre of rotation

O-centre of rotation, R-radius of rotation, R_0-radius of the starting point of the side cutting edge, R_1-radius of the end point of the side cutting edge, R_α-radius of any point on the side cutting edge, α-angle between the end point of the side cutting edge and the bending line, r-bending radius, β-bending angle, h-working width.

The key structural parameters of the furrowing tool are listed in Table 1. These geometric parameters were obtained by measuring the manufactured prototype and were used to establish the three-dimensional model for DEM simulation.

Table 1

Main structural parameters of furrowing tool.

Parameter	Value
Radius of rotation [R]	245 mm
Bending radius [r]	45 mm
Bending angle [β]	145°
Alpha angle [α]	40°
Working width [h]	35 mm
Blade edge thickness	1.5 mm
Blade back thickness	5 mm
Working depth [H]	20 mm

Tool-soil coupling model based on EDEM

To ensure accuracy and reliability, a representative orchard soil from a hilly region was selected as the simulation medium. Measured soil properties were combined with literature values to define DEM input parameters *(Fang et al., 2016; HAO et al., 2023; Li et al., 2018; Liu et al., 2024; Liu et al., 2019; Zhu et al., 2020).* The soil is shaly and clayey, composed of fine particles that are difficult to measure directly at the particle scale. Thus, assumptions were made to balance computational efficiency and realistic soil behaviour. The Hertz–Mindlin with JKR model was used to simulate soil–soil and soil–tool interactions, with particle diameter set to 5 mm. Simulation parameters for the soil and tool are listed in Table 2.

Table 2

Tool-soil coupling model parameters

Parameter	Value	Parameter	Value
Machine forward speed [m/s]	0.3	Soil-soil recovery factor	0.28
Tool speed [rpm]	300	Soil- steel recovery factor	0.6
Soil density [kg/m³]	2500	Soil-soil static factor	0.5
Poisson's ratio for soil	0.32	Soil-steel static factor	0.5
Soil shear modulus [Pa]	1×10^{6}	Soil-soil rolling factor	0.37
Steel density [kg/m³]	7850	Soil-steel rolling factor	0.05
Shear modulus of steel [Pa]	7.962×10^{10}	Steel Poisson's ratio	0.3

Test equipment

The experimental system consisted of soil bin testing and processing equipment. The soil bin system included a P71 magnetic tachometer for speed measurement, an APN1211E-U power tester, a TAILI three-phase AC motor, and a TAILI S18 frequency converter. Processing equipment included a CNC machining centre (Huazhong CNC Co., Ltd.) for tool fabrication.

EDEM simulation test

A three-dimensional furrowing tool model was built in UG NX12 using the geometry and soil parameters from the previous section. The model was exported in STL format and imported into EDEM for simulation. The tool–soil coupling model was established by assigning material and contact properties to the tool and soil particles. Figure 2 shows the model generated using these methods and parameters.

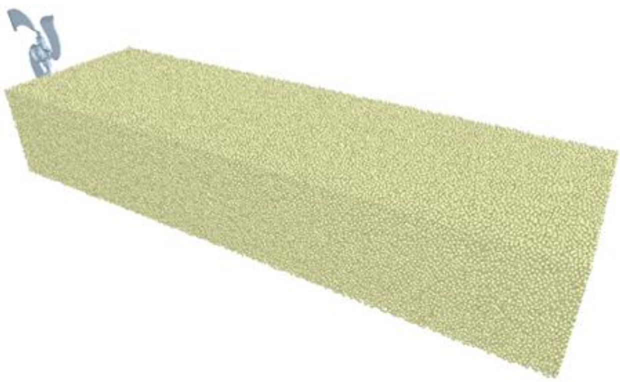


Fig. 1 - Tool-soil simulation model diagram

As EDEM does not directly provide tool power consumption as an output, the torque acting on the furrowing tool was first obtained from the simulation results and then converted into power consumption using the following Eq. 1:

$$P = \frac{T \cdot n}{9549} \tag{1}$$

where:

P-power consumption, [kW];

T-torque, [Nm];

n-tool speed, [rpm].

Soil bin experiment

To validate the EDEM simulation, a soil bin test bench was constructed. The soil bin measured 2500 × 600 × 500 mm, and the same disc-type tool as in the simulations was used. During testing, the tool was driven by an electric motor, and power consumption was recorded in real time. Each condition was repeated three times, and no-load power was subtracted to obtain net cutting power. Motor speed was controlled by a variable-frequency drive, while forward speed was manually adjusted. To reduce uncertainty, data were collected in the central region of the soil bin. Figure 3 shows the setup.

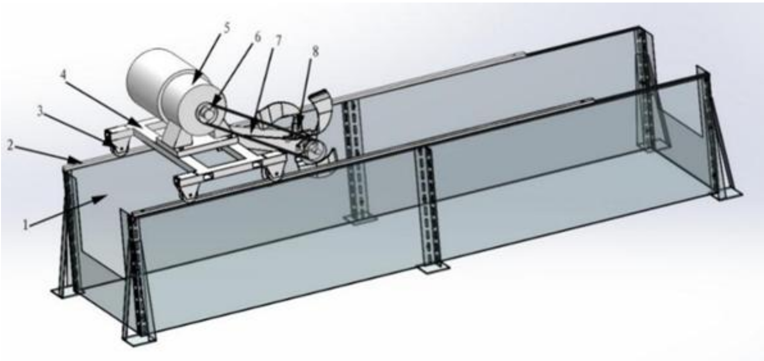


Fig. 2 - The schematic diagram of soil trough experimental scheme

1. soil tank; 2. guide rail; 3. pulley; 4. motor mounting; 5. motor; 6. chain drive; 7. tool arm; 8. cutter plate.

The constructed soil-tank experimental stand is illustrated inFig. **3** 3.

Fig. 3 - Soil trough test bench

Optimisation of furrowing tool parameters

This section optimises the parameters of the disc-type furrowing tool. Based on DEM simulations and soil bin tests, three parameters—bending radius (X_1), bending angle (X_2), and alpha angle (X_3)—were selected. The objective was to reduce power consumption and improve efficiency, thereby enhancing tool performance under typical orchard conditions.

Quadratic regression orthogonal experimental design

The orthogonal combination design includes a two-level test m_c, an asterisk test $2m_\gamma$ and zero-level experiment m_0. The total number of tests, n is calculated using the following Eq.(1):

$$n = m_c + 2m_\gamma + m_0 \tag{1}$$

In accordance with the orthogonality requirement, the arm length parameter, denoted as γ, must satisfy the following Eq. (2):

$$\gamma = \sqrt{\frac{\sqrt{(m_c + 2m_\gamma + m_0)m_c} - m_c}{2}} \tag{2}$$

The present experiment was a three-factor, two-level full-scale trial, which resulted in $\gamma = 1.353$.

In the context of the given factors, the arithmetic mean is defined as the zero level of factor x_j, denoted x_{j0}, where x_{j2} and x_{j1} represent the upper and lower levels of factor x_j, respectively. Let $x_{j\gamma}$ and $x_{-j\gamma}$ denote the upper and lower asterisk arm levels of factor x_j, respectively. These values correspond to the upper and lower levels of factor x_j(3).

$$x_{j0} = \frac{x_{j1} + x_{j2}}{2} = \frac{x_{j\gamma} + x_{-j\gamma}}{2} \tag{3}$$

Therefore, the variation in this factor is as Eq. (4):

$$\Delta_j = \frac{x_{j\gamma} - x_{j0}}{\gamma} \tag{4}$$

The factor levels and their corresponding coding results for this trial are shown in Table 3.

Table 3

Test factors and levels

coding	X_1 (bend radius)	X_2 (bending angle)	X_3 (Alpha angle)
γ (1.353)	58.53	145.15	46.77
1	55.00	142.50	45.00
0	45	135	40
-1	35.00	127.50	35.00
$-\gamma$ (-1.353)	31.47	124.85	33.23
Δ_j	3.6954	11.0864	3.6954

The quadratic regression orthogonal test design and the corresponding operating power consumption of the furrowing tool are presented in Table 4.

Table 4

Experimental arrangement and results

	X_1(Bending radius)	X_2(bending angle)	X_3(Alpha Angle)	Y（kW）
1	-1.000	-1.000	-1.000	0.901936
2	1.000	-1.000	-1.000	0.887035
3	-1.000	1.000	-1.000	0.943716
4	1.000	1.000	-1.000	0.954311
5	-1.000	-1.000	1.000	0.856537
6	1.000	-1.000	1.000	0.908795
7	-1.000	1.000	1.000	0.909632
8	1.000	1.000	1.000	0.987465
9	-1.353	0.000	0.000	0.882938
10	1.353	0.000	0.000	0.905925
11	0.000	-1.353	0.000	0.855001
12	0.000	1.353	0.000	0.93794
13	0.000	0.000	-1.353	0.920778
14	0.000	0.000	1.353	0.884145
15	0.000	0.000	0.000	0.879881
16	0.000	0.000	0.000	0.879881
17	0.000	0.000	0.000	0.879881

The objective was to minimize power consumption by optimising the structural parameters of the disc-type furrowing tool. A quadratic regression model was established to quantify the relationship between structural parameters and power consumption. The optimal parameters were obtained by solving the objective function in MATLAB.

RESULTS AND DISCUSSION

EDEM simulation results analysis

The torque acting on the disc-type furrowing tool during the furrowing process was obtained using the EDEM post-processing module, as shown inFig. 4. The mean torque was determined to be 29.79 Nm, and the corresponding furrowing power consumption was calculated to be 0.94 kW.

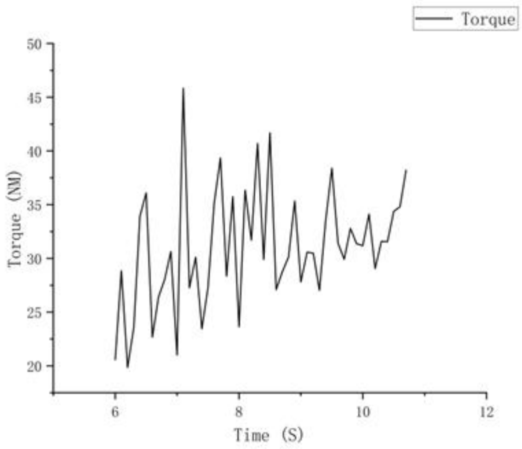


Fig. 4 - Tool furrowing torque diagram

The operation of the disc-type furrowing tool in the soil trench demonstrated its effectiveness in soil cutting and trench formation. During the furrowing process, the soil was lifted and displaced, with the majority returning to the trench, while a small portion of soil was ejected outside the simulation domain. This behaviour confirms the appropriateness of the tool's selected structural parameters for efficient trenching. The furrowing process is illustrated inFig. 5.

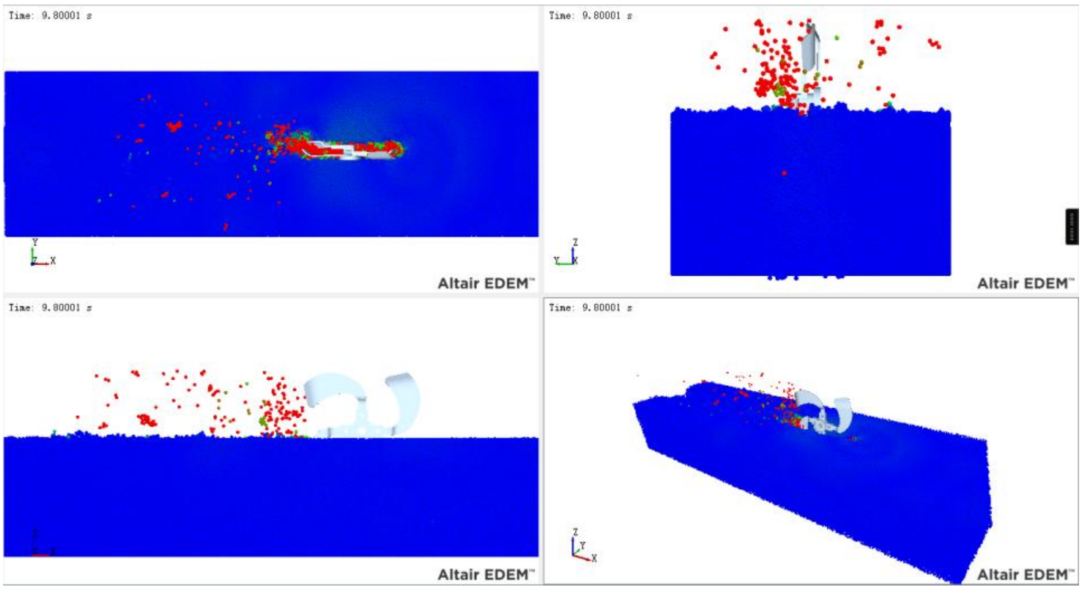


Fig. 5 - Schematic diagram of tool furrowing process

Comparative analysis of simulation test and soil tank test results

This section presents a comparative analysis of the simulation results and soil bin test data. Analysis of the soil bin experiments indicates that, during the furrowing process, the tool's lateral cutting edge initially engages and cuts the soil, followed by plastic deformation of the soil. As the disc-type furrowing tool rotates, the operating depth gradually increases, and the main cutting edge comes into contact with the soil, enlarging the contact area. This interaction results in shearing and extrusion of the soil, culminating in soil fragmentation, overturning, and partial ejection, thereby completing the furrowing and backfilling operations (Fig. **6**).

Fig. 6 - Effect diagram after furrowing

A detailed analysis of the soil bin test data indicated that the average power consumption of the disc-type furrowing tool was 1.07 kW. In comparison, the EDEM simulation predicted a furrowing power of 0.94 kW, yielding a relative error of 13.83%. The discrepancy can be attributed to fluctuations in the tool's forward speed, machining and assembly tolerances, and variations in soil properties. Nevertheless, this relative error is within an acceptable range for agricultural machinery, particularly for furrowing and tillage implements. These results demonstrate that the EDEM simulation can accurately predict the power consumption of the furrowing tool and can be effectively used to guide its structural optimisation.

Analysis of optimisation results of furrowing tool parameters
Quadratic regression orthogonal test results analysis

The results of the quadratic orthogonal regression experiments were imported into the statistical analysis software Design-Expert 13 for further evaluation. The outcomes of the analysis are summarised in Table **5**.

Table 5

Variance analysis

Source	Sum of Squares	df	Mean Square	F-value	p-value	VIF
Model	0.0196	9	0.0022	28.52	0.0001	1
A	0.0021	1	0.0021	27.70	0.0012	1
B	0.0107	1	0.0107	140.26	< 0.0001	1
C	0.0005	1	0.0005	6.19	0.0418	1
AB	0.0003	1	0.0003	4.28	0.0774	1
AC	0.0023	1	0.0023	29.63	0.0010	1
BC	0.0001	1	0.0001	0.8459	0.3883	1
A^2	0.0009	1	0.0009	11.62	0.0113	1
B^2	0.0011	1	0.0011	13.98	0.0073	1
C^2	0.0017	1	0.0017	22.18	0.0022	1

Note: $p \le 0.01$ (highly significant), $p \le 0.05$ (significant).

As shown in Table 5, the model has an F-value of 28.52, indicating statistical significance. The P-value indicates significance, with values < 0.05 denoting significant effects. Factors A, B, C, AC, and A^2, B^2, C^2 significantly affect power consumption. SS, DF, MS, and VIF denote sum of squares, degrees of freedom, mean square, and variance inflation factor, respectively; VIF = 1 indicates factor orthogonality.

ANOVA confirms that the model is statistically significant. Factor B (X_2) has the greatest effect, followed by C (X_3) and A (X_1). The interaction A × C also significantly affects power consumption. The analysis also yielded regression coefficients and model fit metrics.

The regression model is:

$$Y = +0.8770 + 0.0135 * X_1 + 0.0303 * X_2 - 0.0064 * X_3 + 0.0064 * X_1X_2 + 0.0168 * X_1X_3 + 0.0028 * X_2X_3 + 0.0115 * X_1^2 + 0.0126 * X_2^2 + 0.0159 * X_3^2 \quad (5)$$

Table 6

Fit degree analysis results

Std. Dev.	0.0087	R^2	0.9735
Mean	0.9045	Adjusted R^2	0.9393
C.V. %	0.9651	Predicted R^2	0.8023
		Adeq Precision	18.9286

The regression model exhibited an R^2 of 0.9735, an adjusted R^2 of 0.9393, and a P-value of 0.0001, indicating that the model fits the experimental data well, is highly reliable, and statistically significant. The predicted R^2 of 0.8023 is reasonably close to the adjusted R^2, with a difference of less than 0.2, further confirming the stability and predictive capability of the model.

Model adequacy was also evaluated using the Adeq Precision, which should ideally exceed 4. In this study, the Adeq Precision was 18.929, demonstrating that the model has sufficient signal strength and applicability. Additionally, the normality of the standardized residuals was assessed, showing that they approximately follow a normal distribution and converge along a standard normal probability plot, as illustrated in Fig. 7.

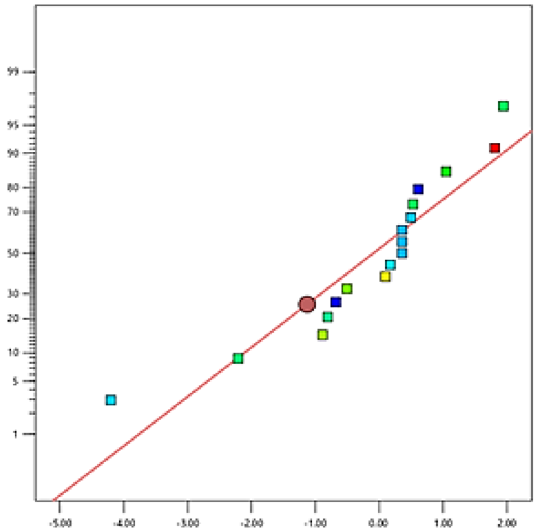


Fig. 7 - The distribution map of residual research

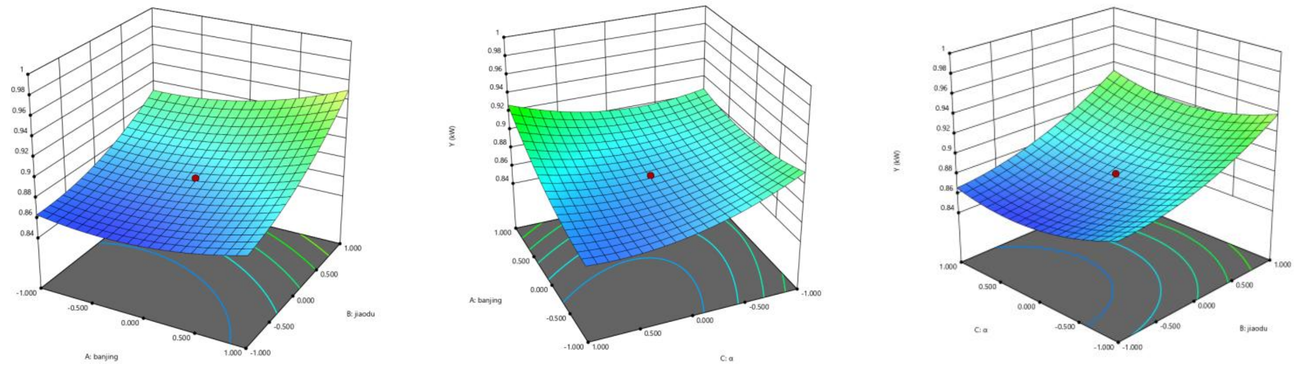
As shown in Fig. 7, the data points exhibit a linear trend and closely follow a normal distribution. This indicates a high degree of confidence in the predictive regression model and demonstrates strong agreement with the assumptions underlying the analysis of variance (ANOVA).

Optimisation analysis of tool structure parameters

The effect of tool structural parameters on furrowing power consumption.

Fig. **8** illustrates the interaction effects of the disc-type furrowing tool's structural parameters on power consumption, as generated using Design-Expert 13. The figure indicates that an increase in the bending radius (X_1, factor A) leads to a gradual increase in furrowing power consumption, while an increase in the bending angle (X_2, factor B) also results in higher power consumption. In contrast, increasing the alpha angle (X_3, factor C) reduces furrowing power consumption.

Simulation analysis further revealed the underlying mechanisms of these effects. The bending radius strongly affects the tool–soil contact area and cutting characteristics. A smaller bending radius concentrates the cutting force and reduces the thickness of the soil layer being removed, but may increase soil reaction forces. Conversely, a larger bending radius allows deeper soil penetration but results in higher power consumption. The bending angle primarily influences the direction and efficiency of the shear force: smaller angles are more suitable for shallow cutting but may cause soil accumulation, whereas larger angles facilitate deeper cutting and improve the fragmentation of compacted soil layers. The alpha angle affects both the cutting depth and soil dispersion direction, with smaller angles promoting deeper penetration but increasing power requirements.



(a) (b) (c)

Fig. 8 - The interaction effect of tool structure parameters on power consumption

(a) The interaction between A (X1) and B (X2) on power consumption. (b) The interaction between C (X3) and B (X2) on power consumption. (c) The interaction between C (X3) and A (X1) on power consumption.

Optimisation of tool structure parameters

The objective of the optimisation was to minimise the furrowing power consumption by appropriately selecting the structural parameters of the disc-type furrowing tool. To achieve this, a regression model was established to quantify the relationship between the tool's structural parameters and power consumption, providing a quantitative foundation for optimisation.

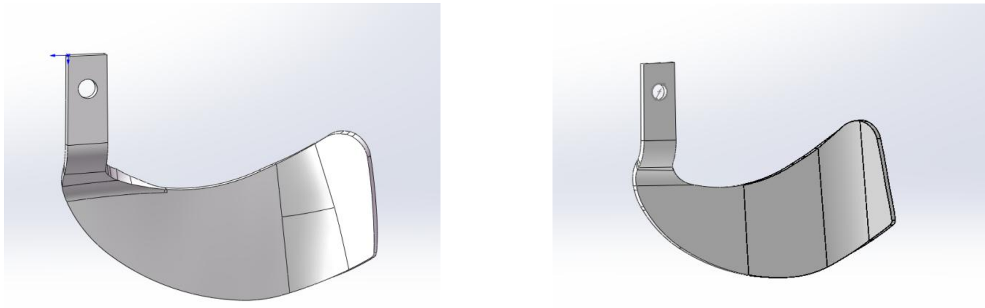
The following constraints were applied during the optimisation process:

$$\begin{cases} X_1 = [-1.353, 1.353] \\ X_2 = [-1.353, 1.353] \\ X_3 = [-1.353, 1.353] \end{cases} \tag{6}$$

The objective function was solved using MATLAB, yielding the optimal solution as follows:

$$\begin{cases} X_1 = 36.7939 \\ X_2 = 126.938 \\ X_3 = 43.6471 \end{cases} \tag{7}$$

The optimised parameters were applied to the regression equation, resulting in a furrowing power of 0.853 kW.



(a) (b)

Fig. 10 - Comparison of cutting tools before and after optimisation.

(a) Optimizing the front tool. (b) Optimised tool.

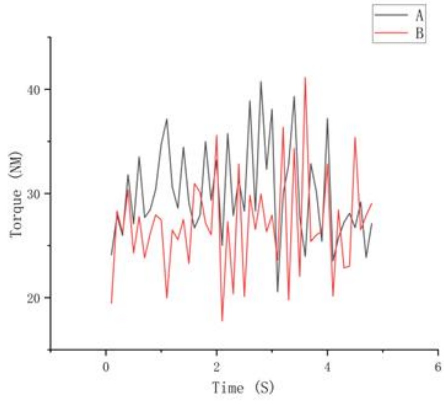


Fig. 11 - Comparison of furrowing torque before and after optimisation.

A Pre-optimisation torque. B Optimised furrowing torque

Simulation verification was performed to evaluate the furrowing power, which was determined to be 0.85 kW under the optimised tool parameters. The regression model predicted a furrowing power with a relative error of 0.6% compared to the simulation results. When compared with the pre-optimisation power of 0.94 kW, the optimised tool exhibited an 8.88% reduction in furrowing power consumption.

CONCLUSIONS

This study systematically optimised a disc-type furrowing tool using EDEM simulations combined with quadratic orthogonal regression. Results show that bending radius, bending angle, and alpha angle are key factors influencing furrowing power consumption. Response surface analysis revealed interactions: increasing bending radius or angle raises power, while increasing alpha angle reduces it. Tool optimisation reduced furrowing power by 8.88%.

Soil bin tests verified the simulation, showing a 13.8% relative error between experimental and simulated power. Discrepancies arose from soil property variations and experimental uncertainties. The error is acceptable for agricultural machinery, confirming the reliability of the EDEM simulation and structural optimisation approach.

Overall, this study offers a practical approach to improve open-furrow fertilisation in hilly orchards and a foundation for tool design and optimisation. Future work could refine soil parameters, improve model accuracy, and explore better tool configurations for more energy-efficient furrowing.

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