DESIGN AND EVALUATION OF A NEW DEEP VERTICAL ROTARY TILLER FOR ENHANCED FIELD PERFORMANCE
/
新型深松立式旋耕机的设计与试验

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ABSTRACT
Deep tillage is capable of penetrating the tough subsoil layers, while vertical rotary tillage improves soil aggregate structure and moisture retention. In this study, an innovative deep vertical rotary tiller was engineered. Utilizing ANSYS Workbench, stress simulation on the blade was conducted. The EDEM software was employed to explore how the machine's forward speed and the blade's rotational speed impact operational quality. Field trials of the developed prototype revealed that the tillage depth, tillage depth stability coefficient, and soil fragmentation rate all complied with the national standard GB/T 5668-2017 for rotary tiller testing. Comparative analysis with the current vertical rotary tiller confirmed that the tiller developed in this study exhibited superior performance, thereby facilitating the adoption and technological evolution of vertical rotary tillers.

摘要
深耕能打破坚硬的犁底层，而垂直旋耕能改善土壤团粒体结构和提高蓄水能力。本研究设计了一种新型深松立式旋耕机。利用 ANSYS Workbench 对旋耕刀进行了力学仿真。利用 EDEM 软件探究机具前进速度和旋耕刀转速对耕地质量的影响。所研制样机的田间试验表明：耕深、耕深稳定系数、土壤破碎率均符合旋耕机试验国家标准 GB/T 5668-2017。通过与现有立式旋耕机进行对比分析，证实了本研究中立式旋耕机性能的优越性，从而促进了立式旋耕机的技术发展。

INTRODUCTION
Due to the rolling by agricultural machinery and the long-term use of shallow tillage, hard subsoil compaction forms in most areas of the fields (*Hu et al., 2024*). Thick subsoil compaction is not conducive to energy transfer and downward extension of crop roots, meanwhile soil permeability and water storage capacity are significantly reduced, which further leads to increased chances of disease and reduced crop yields (*Bogunovic and Kisic, 2017; Yang et al., 2022; Huang et al., 2023*). To eliminate hard subsoil compaction, deep loosening and vertical rotary tillage techniques are required. These methods break subsoil compaction by increasing tillage depth and loosening the soil without turning it over (*Tarverdyan et al., 2017*), thereby improving soil granular structure while preserving the original soil layers and enhancing the soil's capacity for water storage, as well as its moisture and air permeability (*Chandrashekar et al., 2021; Gjoka et al., 2024*). *Bai et al., (2024),* further demonstrated that deep vertical rotary tillage is effective in mitigating soil salinity and significantly increasing seed cotton yield.

Tian have designed and tested a vertical strip rotary cultivator for conservation tillage and wide-narrow-row operation of straw (*Tian, 2023*).

Zhang (*2016*) developed a Y-shape vertical rotary cultivator and then proposed three design schemes for rotary blades. In order to reduce the resistance of the blade when cutting soil, *Liu et al. (2017)* put forward a vertical rotary blade with internal bending angle.

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Zhai et al. (2022) designed various vertical rotary tillers with different structural forms, then they conducted a series of discrete element simulation experiments on the interaction between rotary tillers and soil. In results, the optimal structure and operating parameters of the rotary tiller were obtained to improve the tillage quality. A simulation model of a spiral cutter–soil system was established using Smoothed Particle Hydrodynamics (SPH) by *Yang et al. (2023*). Based on this model, the forces acting on the rotary cutter were thoroughly analyzed, providing an important basis for optimizing its design.

However, through literature search and market research, it can be found that scholars still have less research on vertical rotary tillers, and there are fewer types of vertical rotary tillers, with low popularity. On the other hand, the tillage depth of existing vertical rotary tillers is generally shallow (less than 200 mm). Therefore, in this work, a deep vertical rotary tiller has been developed, featuring a subsoiling depth of 350 mm, a rotary tillage depth of 250 mm, and a tillage width of approximately 2000 mm, which enhances the tillage efficiency and the soil quality, achieving the purpose of deep tillage and vertical rotary tillage.

This research introduces two innovative contributions: (1) Leveraging finite element and discrete element simulation techniques, an innovative vertical rotary blade was designed, achieving improvements in rotary tillage depth, stability coefficient, and soil fragmentation rate. (2) Deep tillage was combined with vertical rotary tillage to develop a novel deep vertical rotary tiller. Compared with existing vertical rotary tillers, this design enhances work performance in multiple aspects, thereby not only advancing the application of vertical rotary tillers but also providing crucial theoretical groundwork for future research in this field.

MATERIALS AND METHODS

Overall Design of the Deep Vertical Rotary Tiller

To achieve the objectives of deep plowing and vertical rotary tillage, the rotary tiller designed in this study primarily consists of a body frame, a reducer, a gearbox, 8 vertical rotary units, and 4 chisel-shaped subsoiling shovels. Its structural layout is schematically illustrated in Fig. 1.

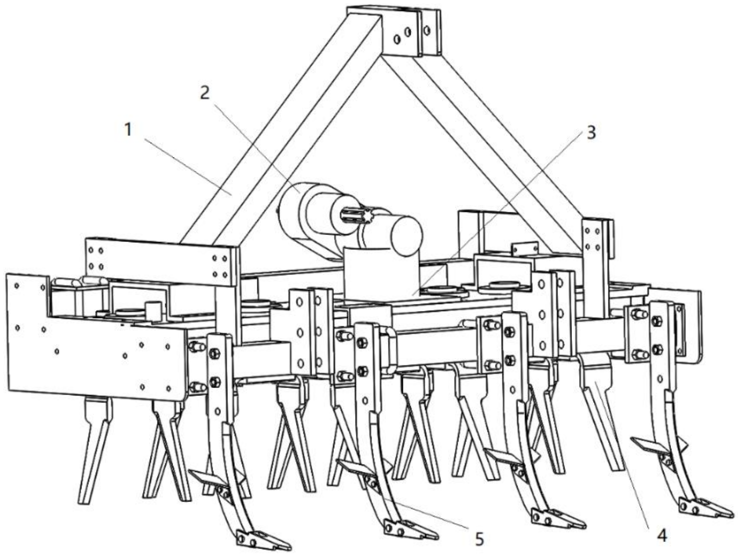

Fig. 1 - Structure diagram of vertical rotary tiller

1 - Body frame; 2 - Reducer; 3 - Gearboxes; 4 - Vertical rotary units; 5 - Chisel-shaped subsoiling shovels

The working principle of the machine is as follows: the power output from the tractor is transmitted to the reducer by the universal joint drive shaft, and then the reducer transmits the power downward to the gearbox through the bevel gear transmission. There are 8 cylindrical gears in the gear box, and each cylindrical gear drives a set of vertical rotary units to rotate. Each vertical rotary unit contains two vertical rotary blades, which are used to cut and break the soil, with tillage depth of 250 mm. Four chisel-shaped subsoiling shovels are installed in front of vertical rotary units, and the distance between two adjacent shovels is 580 mm and the subsoiling depth is 350 mm.

Design of the Chisel-shaped Subsoiling Shovel

The primary function of these shovels is to break the hard bottom layer of the soil and to reduce the cutting resistance of the vertical rotary blade. Each chisel-shaped subsoiling shovel consists of mounting holes, a shovel handle, a shovel handle blade and a shovel head, as illustrated in Fig. 2.

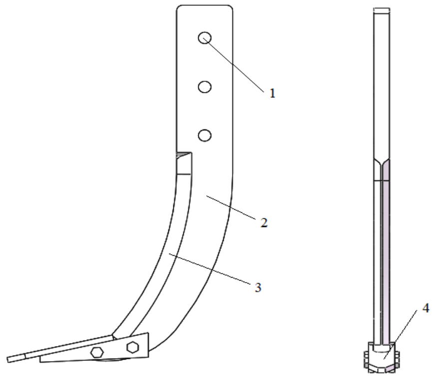

Fig. 2 - Schematic diagram of chisel-shaped subsoiling shovel
1 - Mounting holes; 2 - Shovel handle; 3 - Shovel handle blade; 4 - Shovel head

Design of Vertical Rotary Units

Vertical rotary units are divided into forward (clockwise rotation) vertical rotary units and reverse (counterclockwise rotation) vertical rotary units, each unit consists of blade box base, blade box, two same forward vertical rotary blades or two same reverse vertical rotary blades, as shown in Fig. 3, in which, the forward vertical rotary blade and reverse vertical rotary blade differ in opposite blade directions.

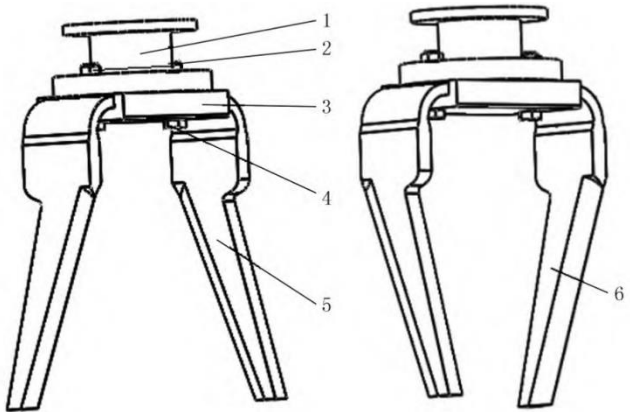

Fig. 3 - Forward vertical rotary units and reverse vertical rotary units
1 - Blade box base; 2 - Bolt; 3 - Blade box; 4 - Nut; 5 - Forward vertical rotary blade; 6 - Reverse vertical rotary blade

Structural Design of The Vertical Rotary Blade

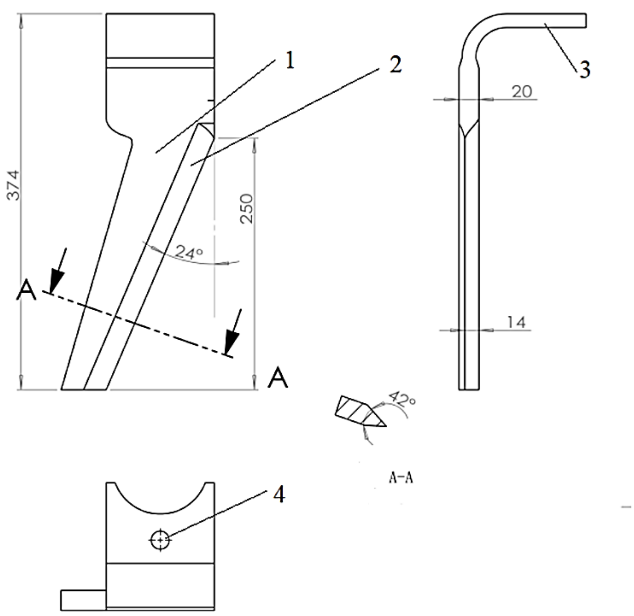

Fig. 4 - Structure of the forward vertical rotary blade
1 - Blade body; 2 - Cutting edge; 3 - Blade handle; 4 - Bolt hole

The vertical rotary blade is the execution part of the vertical rotary tiller, which is designed as shown in Fig. 4. In order to avoid deformation and breakage of the vertical rotary blade in work, it is necessary to ensure that the mechanical properties of the vertical rotary blade meet the work requirements. The material used in the designed blade is 65 Mn steel, and it is quenched and heat-treated to improve the hardness of the cutting edge and the comprehensive mechanical properties. To reduce cutting resistance and power consumption, the cutting edge of the vertical rotary blade is skewed at a certain angle to achieve a sliding cutting effect. Previous studies have reported that power consumption decreases when the sliding cut angle ranges between 22° and 55°. Accordingly, an angle α=24° was selected in the present work. The cutting edge of the designed blade is offset toward the outside of the blade body, being 6 mm from the outer side and 14 mm from the inner side. This configuration ensures that, during rotation in the soil, the blade body engages soil already fragmented by the cutting edge, thereby reducing soil resistance against the blade.

Finite Element Analysis of Vertical Rotary Blade Based on ANSYS Workbench

In SolidWorks software, the 3D model of the forward vertical rotary blade is saved in Parasolid format, and then imported into ANSYS Workbench software (*Jiang et al., 2013, Irsel, 2022*). The bending deformation of the vertical rotary blade mainly comes from the reaction force generated by the blade body penetrating the soil, which acts vertically on the blade body and causes the bending deformation of the blade (*Zhang et al., 2022; Zhang et al., 2024*). The force schematic of the blade body when penetrating the soil is presented in Fig.5, where *A* is the starting point of the vertical rotary blade, *B* is the bottom of the vertical rotary blade, *b* is the total length of the blade body, q is the vertical homogeneous load on the blade body, and w_B is the deformation value at the blade bottom.

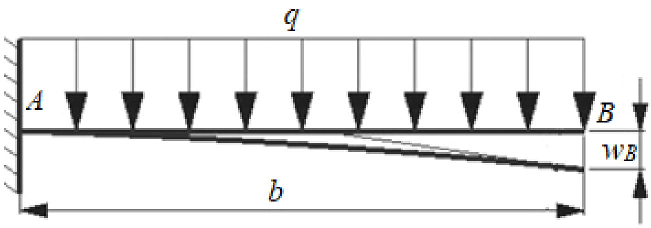

Fig. 5 - Force diagram of the blade body

The maximum force τ_{max} perpendicular to the blade body is:

$$\tau_{\max} = F_{\max} \sin \eta_{\max} = 561 \times \sin 42^{o} \approx 389N \tag{1}$$

where, $F_{\max}$ is maximum tangential resistance encountered by the vertical rotary blade, N; $\eta_{\max}$ is maximum cutting angle of the vertical rotary blade, °.

The area A_1 applied by $\tau_{\max}$ on the blade body is 11246 mm^2, so the maximum pressure $P_{\max}$ is:

$$p_{\max} = \frac{\tau_{\max}}{A_1} \approx 3.46 \times 10^4 \, Pa \tag{2}$$

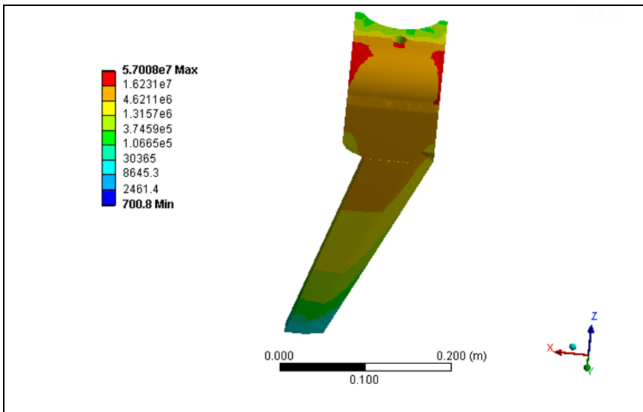

Fig. 6 - Stress distribution of the blade

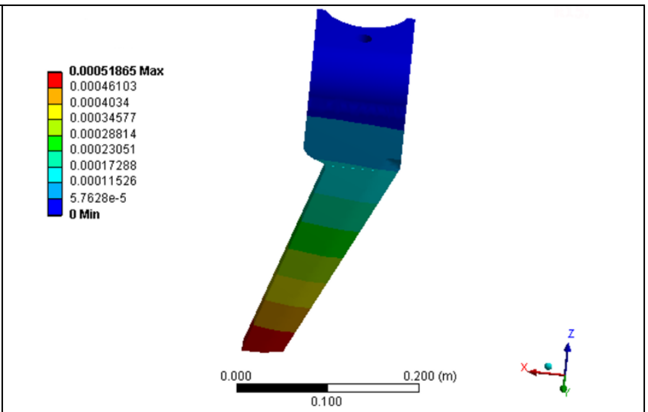

Fig. 7 - Deformation distribution of the blade

The vertical rotary blade model was sequentially defined with material properties, meshed, and constrained. A pressure load of 34600 Pa was then applied to the blade body. The resulting stress distribution is shown in Fig. 6, while the corresponding deformation distribution is presented in Fig. 7.

From Fig. 6 and Fig. 7, it can be concluded that the vertical rotary blade experiences a maximum stress of 57 MPa at the top arc and at the bolt hole. The maximum deformation of the blade occurs at the bottom of the blade tip, with a maximum deformation of 5.19×10^{-4}m. The material of the vertical rotary blade is 65Mn whose yield strength limit is $\sigma_s = 430$ MPa.

Taking the safety factor $n_s = 1.5$, the allowable stress $[\sigma]$ is:

$$[\sigma] = \frac{\sigma_s}{n_s} = 286 \text{ MPa} \tag{3}$$

The maximum stress suffered by the blade is 57 MPa < 286 MPa. The permissible deformation of 65Mn is 1.36×10^{-3}m, while the maximum deformation of the blade is 5.19×10^{-4}m＜1.36×10^{-3}m. Therefore, the vertical rotary blade can satisfy the strength demand during work.

Discrete Element Simulation Analysis

Aiming to investigate the influence of the rotational speed and forward speed for the vertical rotary blade on the soil fragmentation rate, EDEM software is utilized to simulate the operation process of the vertical rotary blade. A vertical rotary unit (including two blades) is selected as the model and imported into EDEM software.

The rotational speed of the blade and the forward speed of the machine are selected as the influencing factors for the simulation experiment. The forward speed is set to 0.45 m/s, 0.70 m/s, and 1.00 m/s, with corresponding blade rotational speeds of 309 r/min, 411 r/min, and 450 r/min, respectively. A series of orthogonal simulation experiments was subsequently conducted.

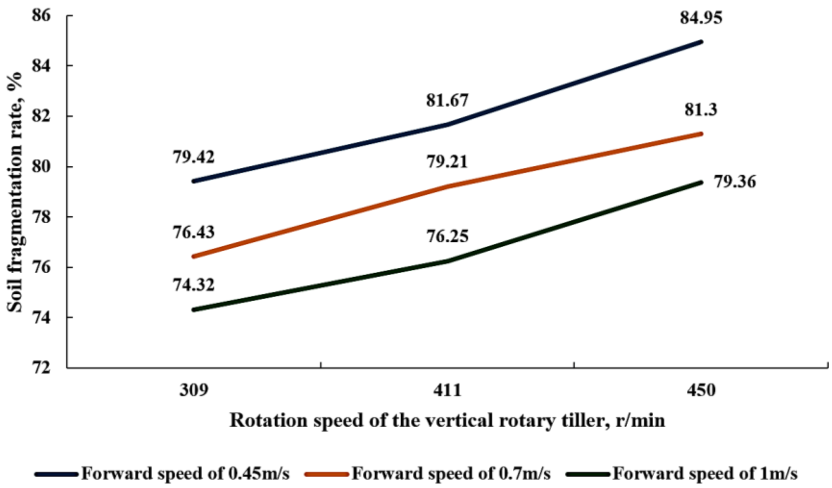

Fig. 8 - Simulation results of soil fragmentation rate

After each orthogonal experiment, the proportion of soil particles with the longest edge less than 40 mm is calculated in the post-processing module, which is the soil fragmentation rate (*Du et al 2020*). The simulation results under different working conditions are presented in Fig. 8. Through data analysis, it can be concluded that the forward speed is negatively correlated with the soil crushing rate, while the rotational speed of blades is positively correlated with the soil fragmentation rate. Therefore, a lower forward speed and a higher rotational speed should be selected for the vertical rotary blade during work.

Field Trials

Test conditions: The prototype vertical rotary tiller developed in this study was subjected to field testing in an experimental plot characterized by loamy soil with a moisture content of 16.7%. The prototype had dimensions of 1995 mm in width, a tillage depth of 250 mm, and a loosening depth of 350 mm, and was operated with a tractor providing 88.2 kW of power. During the testing phase, the tractor's forward speed was maintained at 0.45 m/s, while the blade rotational speed was set to 411 r/min. A visual overview of the field experiment is provided in Fig. 9.

Evaluation indexes: referring to NY/T 2456-2013 Technical Specifications for Quality Evaluation of Rotary Tillers (*NY/T 2456-2013 2013*), in combination with the actual working situation, the rotary tillage depth, stability coefficient of rotary tillage depth, soil fragmentation rate, and fuel consumption are adopted as the evaluation indexes for rotary tillers.

Fig. 9 - The field experiment of the prototype

Test scheme: in compliance with the testing requirements outlined in the national standard GB/T 5668-2017 Rotary Tillers (*GB/T 5668-2017 2017*), our prototype underwent a series of evaluations. The experimental setup consisted of five groups, each covering a distance of 20 meters. Within the scope of each trial, key evaluation indexes were measured and subjected to rigorous validation of the prototype's performance.

RESULTS

Test Results

The results of the field trials are presented in Table 1. The findings indicate that the tillage depth after the experiment is stable, ranging from 251 mm to 255 mm, with a mean depth of 253 mm. The stability coefficient of tillage depth is between 92.23 % and 93.94 %, averaging at 92.87 %. The soil fragmentation rate after the experiment is relatively pretty, ranging from 79.90 % to 82.38 %, with an average value of 81.28 %.

Table 1

Results of the field trials for prototype

	Tillage depth (mm)	Variation coefficient (%)	Stability coefficient (%)	Soil fragmentation rate (%)	Fuel consumption (g/kW·h)
1	251	7.51	92.49	80.06	18580
2	254	6.87	93.13	80.84	18364
3	254	6.98	93.02	83.36	18398
4	252	7.38	92.62	84.29	18411
5	254	6.91	93.09	77.85	18562
Average	253	7.13	92.87	81.28	18463

Comparative Test and Analysis

To substantiate the enhanced performance of the deep vertical rotary tiller crafted in this research, a comparative evaluation was undertaken against the prevalent ZBJQ-5 vertical rotary tiller available in the market. The ZBJQ-5 model, which is outfitted with 12 vertical rotary blades and 4 subsoiling shovels, has a tilling width of 1980 mm. The tests were conducted under uniform conditions, with a tractor power of 88.2 kW, a forward speed of 0.45 m/s, and a blade rotary speed of 411 r/min. The comparative test outcomes for the ZBJQ-5 vertical rotary tiller are detailed in Table 2.

Table 2

Comparative test results

	Average tillage depth (mm)	Stability coefficient (%)	Soil fragmentation rate (%)	Average fuel consumption (g/kW·h)
ZBJQ-5 tiller	205	89.92	72.53	19474
Tiller in this study	253	92.87	81.28	18463

Table 2 indicates that, in comparison to the ZBJQ-5 vertical rotary tiller, the average rotary tillage depth of the tiller designed in this study has increased by 47 mm. Additionally, the stability coefficient of tillage depth has improved by 2.95%, and the soil fragmentation rate has also risen by 12.06%. Moreover, under identical test conditions, the average fuel consumption was reduced by 3.55%. These results demonstrate the newly designed vertical rotary tiller exhibits superior working performance compared to the existing ZBJQ-5 tiller. These improvements are advantageous for root systems of crops, as they enhance the soil's capacity to retain water, moisture, and air permeability, which promotes a favorable environment for crop planting and growth.

Discussion

Further comparison with existing literature shows that, relative to the inner-curve-angle vertical rotary blade proposed by *Liu et al. (2017)*, the asymmetrical blade designed in this study (6 mm outward offset and 14 mm inward offset) demonstrates notable improvements based on finite element analysis. Specifically, the maximum stress was reduced by 17.52%, while tillage resistance decreased by 12.47%. Extensive testing further indicated a slight reduction in average fuel consumption, consistent with the findings of *Zhai et al. (2022)*, who reported that blade angle significantly affects energy efficiency. Compared with the Y-type vertical rotary tiller developed by *Zhang (2016)*, the bevel–cylindrical gear combination applied in this study achieved a 26.72% reduction in torque fluctuation. Additionally, relative to the spiral cutter that reached a soil fragmentation rate of 78% *(Yang et al., 2023)*, the optimized blade geometry in this study attained 81.28%, surpassing the optimal tillage standard of 75% proposed by *Bogunovic (2017)*. Under identical soil conditions (loamy soil, 16.7% moisture content), the working depth stability coefficient reached 92.87%, significantly exceeding the 85.2% reported by *Tian (2023)* for a strip-tilling cultivator. These results demonstrate that this research advances the technical development of vertical rotary tillers.

The deep vertical rotary tiller designed is ideally suited for plain areas. It may present challenges when applied to hilly areas. Therefore, in future research, flexible design methods can be introduced to design a deep vertical rotary tiller that meets the agronomic requirements of hilly areas.

CONCLUSIONS

(1) Ansys Workbench was employed to simulate the tiller's working state. The simulations revealed that the deformation and stress levels of the vertical rotary tiller fall within acceptable limits, signifying its capability to fulfill the operational demands.

(2) By simulating the operation process using EDEM software, it was found that the forward speed of the equipment and the rotational speed of the rotary blade have an impact on the soil fragmentation rate. Consequently, it is recommended to opt for a lower forward speed combined with a higher rotational speed to optimize the tilling process.

(3) The field test results highlight the vertical rotary tiller's impressive performance, characterized by an average tillage depth of 253 mm, a tillage depth stability coefficient of 92.87%, and a soil fragmentation rate of 81.28%, which meet the requirements of national standards GB/T 5668-2017.

(4) Compared to the existing ZBJQ-5 vertical rotary tiller on the market, the machine designed in this study demonstrates a 47 mm increase in rotary tilling depth, a 2.95% improvement in tilling depth stability coefficient, a 12.06% enhancement in soil fragmentation rate, and a 3.55% reduction in average fuel consumption. The vertical rotary tiller developed through this research unambiguously demonstrates its superior operational capabilities.

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REFERENCES

[1] Bai, Z.T., Li, Z.J., Li, L., Li, P.F., Gong, P., Wang, T., Fan, J.L. & Liu, H.G. (2024). Deep vertical rotary tillage reduced soil salinity and improved seed cotton yield and water productivity under limited irrigation in saline-alkaline fields. *Industrial Crops and Products,* 218, 118943.

[2] Bogunovic & Kisic. (2017). Compaction of a clay loam soil in Pannonian region of Croatia under different tillage systems. *Journal of Agricultural Science and Technology,* 19 (2), 475-486.

[3] Chandrashekar, Reddy, H.K.V. & Singh, J. (2021). Evaluation of power tiller operated vertical rotary plough for tillage. *Indian Journal of Ecology,* (6), 48.

[4] GB/T 5668-2017. (2017). *Rotary tillers (GB/T5668-2008 旋耕机)*. Beijing: Standardization Administration of China.

[5] Du, X.W., Yang, X.L., Pang, J. & Ji, J.T. (2020). Design and test of automatic detection platform for soil fragmentation rate in rotary tillage. *International Journal of Agricultural and Biological Engineering,* 13 (5), 40-49.

[6] Gjoka, F., Shkurta, E. & Kasa, E. (2024). Soil compaction and maize yield in various plowing systems from a sustainability perspective *12th ed. Farm Machinery and Processes Management in Sustainable Agriculture (FMPMSA)*, Univ Life Sci, Lublin, POLAND, 159-164.

[7] Hu, R.W., Zheng, B.F., Liu, Y.J., Peng, S.G., Gong, J., Li, J.H., Qin, T., Liang, J.S., Xiong, K.L., Shao, L.J., Zheng, Z.Y., Yi, Z.X., Zhou, Q.M. & Li, J. (2024). Deep tillage enhances the spatial homogenization of bacterial communities by reducing deep soil compaction. *Soil & Tillage Research,* 239, 106062.

[8] Huang, S., Islam, M.U. & Jiang, F. (2023). The effect of deep-tillage depths on crop yield: A global meta-analysis. *Plant Soil and Environment,* 69 (3), 105-117.

[9] Irsel, G. (2022). Bevel gears strength calculation: Comparison ISO, AGMA, DIN, KISSsoft and ANSYS FEM methods. *Journal of the Chinese Society of Mechanical Engineers,* 43 (1), 315-323.

[10] Jiang, X.J., Zhu, Y.S., Hong, J., Zhang, Y.Y. & Kan, Q.H. (2013). Constitutive model for time-dependent ratchetting of ss304 stainless steel: Simulation and its finite element analysis. *Journal of Theoretical and Applied Mechanics,* 51 (1), 63-73.

[11] Liu, F., Mi, Y., Liao, N., Di, M., Liu, Y. & Liu, H. (2017). Research design of vertical rotary cultivator and experiment *(立式旋耕机研究设计与试验)*. *Journal of Agricultural Mechanization Research,* 39 (11), 81-84.

[12] NY/T 2456-2013. (2013). *Technical specifications for quality evaluation of rotary tillers (NY/T 2456-2013 旋耕机质量评价技术规范标准)*. Beijing: Ministry of Agriculture of the People's Republic of China.

[13] Tarverdyan, A.P., Sargsyan, S.F. & Altunyan, A.V. (2017). Investigation results of kinematic and dynamic indicators of tiller with vertical rotation axis in orchards soil cultivation. *Annals of agrarian science,* 15 (2), 163-168.

[14] Tian, Y. (2023). *Design and test of vertical strip rotary cultivator in straw return mode (秸秆归行模式下立式条带旋耕机设计及试验)*. Master Thesis. Jilin Agricultural University.

[15] Yang, J.J., Tan, W.J., Han, J.R., Li, F.M. & Zhang, F. (2022). Distribution pattern of rainwater in soil under vertical deep rotary tillage in dryland farmland. *Agricultural Water Management,* 273, 107891.

[16] Yang, W., Xiao, X., Pan, R.H., Guo, S.Y. & Yang, J. (2023). Numerical simulation of spiral cutter-soil interaction in deep vertical rotary tillage. *Agriculture-Basel,* 13 (9), 1850.

[17] Zhai, S., Shi, Y., Zhou, J., Liu, J., Huang, D., Zou, A. & Jiang, P. (2022). Simulation optimization and experimental study of the working performance of a vertical rotary tiller based on the discrete element method. *Actuators*, 342.

[18] Zhang, C. (2016). *Development of Y shape vertical rotary cultivator (Y 型立式旋耕机的研制)*. Master Thesis. Henan Agricultural University.

[19] Zhang, X.Y., Hu, X., Zhang, L.X. & Kheiry, A.N.O. (2024). Simulation and structural parameter optimization of rotary blade cutting soil based on SPH method. *International Journal of Agricultural and Biological Engineering,* 17 (3), 82-90.

[20] Zhang, X.Y., Zhang, L.X., Hu, X., Wang, H., Shi, X.B. & Ma, X. (2022). Simulation of soil cutting and power consumption optimization of a typical rotary tillage soil blade. *Applied Sciences-Basel,* 12 (16), 8177.