DESIGN AND EXPERIMENTAL STUDY OF THE THRESHING DEVICE FOR A 4YZ-2 CORN KERNEL HARVESTER

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4YZ-2型玉米籽粒收获机脱粒装置设计与试验

Pu LI[1], Rongwei FAN[2], Ziyu MA[2], Qiaochu SHI[2], Bang JI*[2]

[1] Hunan Mechanical and Electrical Polytechnic, Changsha/China;

[2] Hunan Agricultural University, College of Mechanical and Electrical Engineering, Changsha/China;

Tel: +86 17375860294; E-mail: 619741039@qq.com

Corresponding author: 369370030@qq.com (Bang Ji)

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***Keywords:** corn kernel harvester; threshing device; flexible arc-shaped bar teeth; round steel bar concave screen; hilly regions*

ABSTRACT

To address grain breakage and high losses associated with elevated grain moisture during corn harvesting in hilly regions, this study analyzes the threshing process and proposes a flexible threshing device composed of flexible arc-shaped bar teeth and a round steel bar concave screen. Discrete element simulations using EDEM were conducted to evaluate the contact forces between corn ears and the flexible threshing device, in comparison with a conventional rigid device. The aim was to verify the performance of the proposed design. Field comparative tests were subsequently performed to assess the operational performance of both flexible and rigid threshing devices. The results show that, compared with the rigid device, the flexible device reduces kernel breakage by 3.25 percentage points and kernel loss by 2.88 percentage points. These findings provide a useful reference for the design and application of corn kernel harvesters in hilly regions.

摘要

针对丘陵地区玉米籽粒收获过程中籽粒含水率高导致籽粒破碎和损失大等问题。本文对脱粒过程进行力学分析，设计一种由"柔性弧面杆齿+圆钢栅条凹板筛"组成的柔性脱粒装置。通过 EDEM 软件对脱粒装置进行模拟仿真，探究柔性脱粒装置与传统刚性脱粒装置对玉米果穗接触力的数值大小，验证所设计的柔性脱粒装置性能。进行了柔性和刚性脱粒装置田间对比试验，试验结果表明：与传统刚性脱粒装置相比，籽粒破碎率下降了 3.25 个百分点，籽粒损失率下降了 2.88 个百分点，为丘陵地区玉米籽粒收获机提供了参考。

INTRODUCTION

Corn (Zea mays) constitutes one of humanity's principal staple crops and represents the highest-yielding cereal grain globally. It serves multiple essential functions, including its use as food, animal feed, and an industrial raw material, thereby occupying a pivotal role in agricultural production *(Basuki et al., 2020)*. Presently, mechanized corn harvesting can be delineated into two primary methodologies: direct kernels harvesting and cob harvesting. Cob harvesting encompasses a series of intricate processes, such as cob removal, husking, bin collection, transportation, drying, threshing, and cleaning. This multifaceted operation entails numerous operational steps, resulting in escalated costs. Conversely, direct kernels harvesting employs corn kernel combine harvesters that adeptly perform cutting, threshing, and cleaning simultaneously in a single operational pass. This approach significantly mitigates labor demands, reduces operational costs, enhances efficiency, and increases overall productivity *(Zhang et al., 2025, Lontseva et al., 2022)*. With the incessant advancement of the corn industry, direct kernels harvesting is emerging as the prevailing trend in mechanized corn harvesting *(Xu et al., 2025, Vlădut et al., 2023)*. However, in hilly regions, the use of corn kernel combine harvesters faces significant challenges *(Mu et al., 2025)*. The complex and undulating terrain characteristic of such areas complicates the maneuverability of large combine harvesters. Furthermore, the constraints imposed by the terrain limit the levels of mechanization achievable, resulting in substantially lower mechanization rates in comparison to flatland regions. In addition, high moisture content observed in certain hilly locales contributes to increased kernel loss and breakage during the harvesting process.

These challenges significantly impede the advancement of the corn industry in hilly regions. Consequently, the development of a threshing device specifically designed for corn kernel combine harvesters operating in these challenging terrains is imperative. Such innovation is crucial not only for enhancing the mechanization levels of direct corn kernel harvesting in these areas but also for promoting the holistic development of the corn industry and safeguarding food security *(Li et al., 2023)*.

To address significant losses and kernel breakage associated with direct corn kernel harvesting, extensive research has been conducted by scholars worldwide. The American Case AF series corn kernel combine harvester employs several advanced features, including an AFX single longitudinal axial flow threshing drum, flexible threshing technology, multiple concave sieves, a conical feed head, a 360-degree separation design, and adjustable drum cover deflector plates. Collectively, these features significantly expand the separation area, enhance the efficiency of threshing and separation, and concurrently reduce kernels loss rates. In their research, *Wang et al., (2021)*, designed a low-loss variable-diameter threshing drum, wherein the diameter progressively increases from the front to the rear within the main threshing section. This configuration enhances the cob-holding capacity of the section, promotes flexible contact between cobs, and diminishes the forces acting between kernels and between kernels and the cob core. Such modifications facilitate easier cob threshing while minimizing kernel breakage. Furthermore, *Wang et al., (2020)*, optimized the design of plate teeth into claw-like structures by simulating manual bending and rubbing of corn cobs to enhance the cob gripping force. They utilized flexible materials such as resilient resin and nylon, in conjunction with torsion springs, to mitigate the impacts of rigid kernels. Their innovative design features flexible hammer-claw threshing elements that not only reduce breakage rates but also improve overall threshing efficiency.

In summary, contemporary corn kernel harvesters are predominantly large-scale machines designed for operation on expansive, flat terrain. In contrast, their use in hilly and mountainous regions presents several challenges, including large machine size, limited maneuverability during turning and field access, and poor adaptability to uneven terrain. Accordingly, this study aims to reduce kernel breakage and loss during corn threshing by developing a flexible threshing device for a corn kernel harvester specifically adapted to such conditions.

MATERIALS AND METHODS

Overall structure and working principle

Overall Structure

The 4YZ-2 corn kernel harvester consists of several key components, including a non-row-specific corn header, a grain conveying wheel, a conveying chute, a threshing chamber, and a chassis system. A schematic representation of the machine is shown in Figure 1, and the main structural parameters are listed in Table 1.

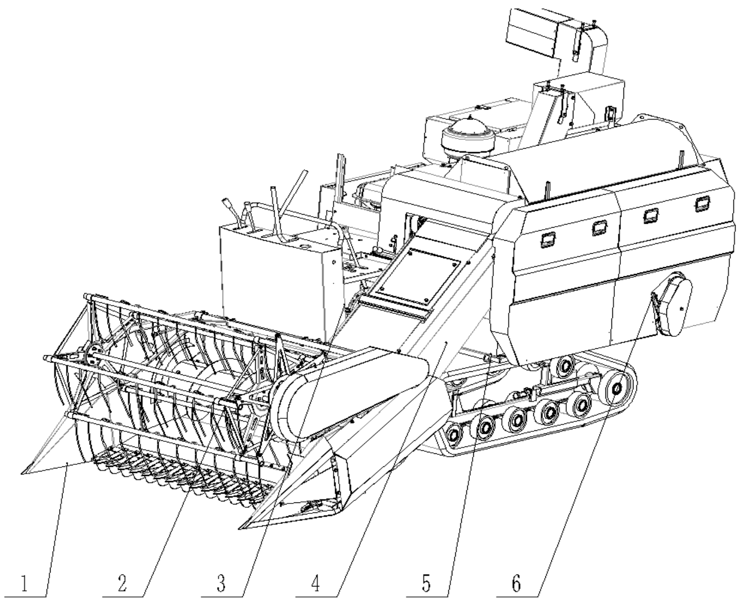


Fig. 1 – Schematic diagram of the overall structure of the 4YZ-2 type corn kernel harvester

1 - Non-row-specific corn header; 2 - Grain conveying wheel; 3 - Cab; 4 - Conveying chute; 5 - Chassis system; 6 - Threshing chamber.

Table 1

Main parameters of the 4YZ-2 corn kernel harvester

Parameters	Numerical value
Structural form	Crawler-mounted
Total mass/ Kg	1250
Overall dimensions (length × width × height)/ mm	3450×1650×1950
Rated power/ Kw	18.4
Feed rate/ Kg/s	1.6
Cutting width/ mm	1350
Ground clearance/ mm	210
Track width/ mm	280
Concave wrap angle/ °	200
Threshing drum diameter/ mm	370
Threshing drum length/ mm	1350
Number of harvested rows	2
Cleaning method	Air-screen cleaning
Threshing method	Longitudinal axial flow
Grain conveying wheel type	Eccentric
Screw conveyor type (cutting table)	Screw conveyor
Cutting blade type	Standard type III

Working principle

The 4YZ-2 corn kernel combine harvester is designed to perform stalk cutting, conveying, threshing, and cleaning in a single pass. During operation, corn stalks are cut by the cutter bar and conveyed to the header auger. The header auger then transports the crop material, including ears and stalks, through the conveying chute to the threshing device. Within the threshing unit, the ears undergo kernel separation through the combined action of threshing elements and the concave screen *(Chelladurai et al., 2026)*. The separated kernels, together with residual plant material, fall into the cleaning chamber for further processing. In this chamber, impurities and cob fragments are removed by the combined action of a vibrating screen and a cleaning fan, while the cleaned kernels are conveyed by the grain auger to the grain tank.

Key component design

Threshing component design

During the threshing process, the interaction between the kernel and the threshing teeth can be divided into two stages: elastic deformation and fracture *(Le et al., 2025; Kruszelnicka et al., 2024)*. Due to the complex composition of materials within the threshing drum, the analysis is simplified by considering the kernel as the primary research object. Based on Hertzian contact theory, the collision process between the threshing teeth and the kernel is analyzed to establish a mechanical model for quantifying kernel damage *(Xu et al., 2008)*. This analysis enables the determination of the critical crushing velocity at which the kernel undergoes fracture.

$$V_0 = \left[\frac{10.2\Pi^5 Q^5 R_y^2}{1000 m E^{*4}} \right]^{\frac{1}{2}}$$

As indicated in the equation above, modifying the shape and material of threshing elements is crucial for reducing kernels breakage rates and enhancing threshing quality, thereby improving harvesting efficiency when these elements interact with corn kernels under consistent working parameters *(Li et al., 2020, Su et al., 2018)*. Conventional cylindrical bar teeth exhibit a relatively limited contact area with corn kernels, which leads to substantial rigid impacts on corn cobs during the threshing process. To mitigate kernel breakage, a design was proposed incorporating flexible arc-shaped bar teeth, as illustrated in Figure 2. This innovative design effectively increases the contact area with corn kernels and diminishes the shearing forces exerted on them. Furthermore, the application of a polyurethane rubber coating on the rod teeth surfaces transforms rigid impacts into more flexible interactions during direct kernels harvesting. This modification not only extends the collision duration with the kernels but also contributes to a reduction in kernel breakage rates.

Fig. 2 - Flexible arc-shaped bar tooth

Design of the round steel bar concave screen

During the threshing process, the separation of kernels from the cob is achieved through the combined action of the threshing elements and the concave screen. This process enables the effective separation of kernels from the bulk material *(Steponavičius et al., 2023)*. Due to the complex composition of materials within the threshing drum, the ear was selected as the primary object of analysis for simplification. When the ear interacts with the concave screen, force analysis indicates that, as shown in Figure 3, kernel separation occurs under the combined effects of gravitational force, shear force exerted by the concave screen, and impact force generated by the threshing elements *(Fan et al., 2019)*.

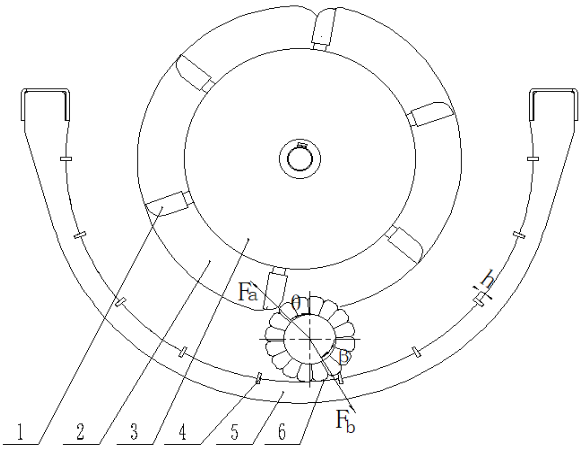


Fig. 3 – Schematic diagram of the interaction between the threshing elements, concave screen, and corn ear

1 - Threshing bar teeth; 2 - Spiral blades; 3 - Spoke disc; 4 – Concave bars; 5 - Concave screen mounting bracket; 6 - Corn ear.

$$F_a cos\theta = F_b cos\beta + G \quad (1)$$

$$F_a = \frac{(F_b cos\beta + G)}{cos\theta} \quad (2)$$

$$F_a = \frac{(F_b cos\beta + G)}{cos\theta} \quad (3)$$

$$cos\theta \approx \frac{R-h}{R} \quad (4)$$

$$F_a = \left(\frac{RF_b cos\beta + RG}{(R-h)} \right) \quad (5)$$

$$\tau = \frac{F_a}{A} \quad (6)$$

$$\tau = \left(\frac{RF_b cos\beta + RG}{A\left(R - h\right)} \right) \tag{7}$$

where:

F_a is the shear force exerted by the concave screen on the corn ear, [N]; F_b is impact force exerted by the threshing element on the corn ear, [N]; G is gravitational force of the corn ear, [N]; r is radius of the corn ear, [mm]; h is the height of the concave bar, [mm]; θ is the angle between the shear force and the direction of gravity, [°]; β is the angle between the impact force and the direction of gravity, [°]; A is the contact area between the concave screen and the corn ear, [mm²]; τ is the shear strength exerted by the concave screen on the corn ear, [MPa].

The preceding equations indicate that, when the impact angle between the threshing element and the direction of gravity, as well as the ear weight, ear radius, and concave bar height, are held constant, increasing the contact area between the concave screen and the ear, together with a reduction in threshing drum speed, can effectively reduce the kernel breakage rate and improve threshing performance. Conventional bar-type concave screens are characterized by sharp edges on their surfaces, which generate significant shear forces during the threshing process. When the kernels have high moisture content, their critical shear strength decreases, leading to increased kernel breakage *(Tan et al., 2023)*. To address these issues, a round steel bar concave screen was designed (Fig. 4). This structure features smooth cylindrical bars without sharp edges, thereby increasing the contact area between the concave screen and the ear and reducing mechanical damage to the kernels. In addition, part of the original bar structure is retained to limit the passage of impurities, such as stalks and cobs, into the cleaning system.

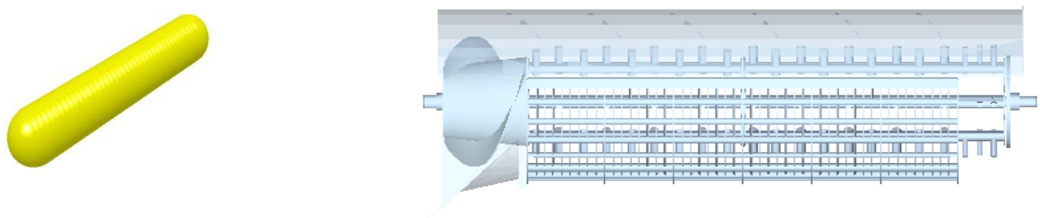
Fig. 4 – Round steel bar concave screen

Discrete element simulation and experimental evaluation of the threshing device

This study employs the Discrete Element Method (DEM) to simulate the performance of the designed flexible threshing device. The contact forces acting on corn ears are analyzed and compared between conventional cylindrical bar teeth and flexible arc-shaped bar teeth. In addition, the effects of different concave screen structures—conventional bar-type concave screens and round steel bar concave screens—are evaluated. The simulation results are further validated through experimental tests to assess the effectiveness of the proposed flexible threshing device.

Establishment of the simulation model

Prior to simulation, a discrete element model was developed to represent the geometric characteristics of the corn ear. For computational efficiency, the model was simplified based on its fundamental dimensions and constructed using a multi-sphere particle representation. Specifically, the corn ear model was generated by aggregating forty spherical particles *(Wang et al., 2023)*, as shown in Fig. 5a. To improve computational efficiency, the threshing device model was simplified by removing non-essential components. The resulting geometry was exported in Parasolid (x_t) format and imported into EDEM for simulation. The simplified model of the threshing device is shown in Fig. 5b.



（a） *Simplified simulation model of corn ears* （b） *Simplified model of the threshing device*

Fig. 5 – Simulation model

Simulation parameter settings

After importing the model into EDEM, the material properties of the threshing device and the corn ear particle model were defined. According to previous studies *(Li et al., 2020; He, 2019)*, the Hertz-Mindlin (no-slip) contact model was adopted, and the corresponding parameters are listed in Table 2. The operating parameters were set as follows: a threshing drum rotational speed of 900 r/min, a threshing gap of 30 mm, and a feed rate of 1.6 kg/s. The feeding duration was 2 s, and the total simulation time was 2.5 s. During the simulation, both the operating parameters and the particle contact parameters were kept constant, while different threshing components were evaluated using the discrete element method.

Table 2

Simulation contact parameters

Parameters	Numerical value
Density of corn/ Kg/m³	1197
Poisson’s ratio of corn	0.4
Shear modulus of corn/ MPa	13.7
Density of steel / Kg/m³	7000
Poisson’s ratio of steel	0.3
Shear modulus of steel / MPa	7000
Density of polyurethane/ kg/m³	0.331
Poisson’s ratio of polyurethane	22.1
Shear modulus of polyurethane / MPa	1072
Corn-steel restitution coefficient	0.709
Corn-steel static friction coefficient	0.351
Corn-steel rolling friction coefficient	0.01
Corn-polyurethane restitution coefficient	0.29
Corn-polyurethane static friction coefficient	1.05
Corn-polyurethane rolling friction coefficient	0.01
Corn-corn restitution coefficient	0.182
Corn-corn static friction coefficient	0.431
Corn-corn rolling friction coefficient	0.078

Field Trials

Test conditions and equipment

The field experiments were conducted in Liuyang City, Hunan Province, China. A strip intercropping system with a soybean–corn planting pattern of 3:2 was adopted. The corn variety used in the experiment was Dongdan 808. The planting spacing was 12 cm, with a row spacing of 39 cm, and the minimum ear height was 120 cm. Harvesting operations were performed using the test corn kernel harvester at a forward speed of 0.5 m/s over a test length of 20 m. At the time of harvesting, the kernel moisture content was 27.8%. The field test of the corn kernel harvester is shown in Fig. 9.

Fig. 9 - Field experiment

Test criteria and methods

The kernel breakage rate and kernel loss rate were selected as evaluation indices. A comparative analysis was conducted between the proposed flexible threshing device, featuring flexible arc-shaped bar teeth combined with a round steel bar concave screen, and a conventional rigid threshing device equipped with cylindrical bar teeth and a conventional bar-type concave screen. Both devices were installed on a 4YZ-2 corn kernel combine harvester for testing. Prior to the experiment, well-grown plots were selected and divided into test sections of 20 m in length. The combine harvester was operated at a forward speed of 0.5 m/s. A tarpaulin was installed at the rear straw outlet to collect all discharged material after threshing. After each test, the kernels lost at the discharge outlet were collected, and samples of the discharged kernels were taken. For each sample, 900 g of kernels was selected, and broken kernels were manually separated and weighed. Each test was repeated three times, and the average values were calculated.

The calculation formulas are given as follows:

$$S_P = \frac{W_P}{W_Y} \times 100\% \tag{8}$$

$$S_S = \frac{W_S}{W_Z} \times 100\% \tag{9}$$

where:

W_P is the mass of broken kernels, [g]; W_Y is the total mass of sample kernels, [g]; W_S is the mass of kernels lost at the discharge outlet, [g]; W_Z is the total mass of collected kernels, [g].

RESULTS AND DISCUSSION

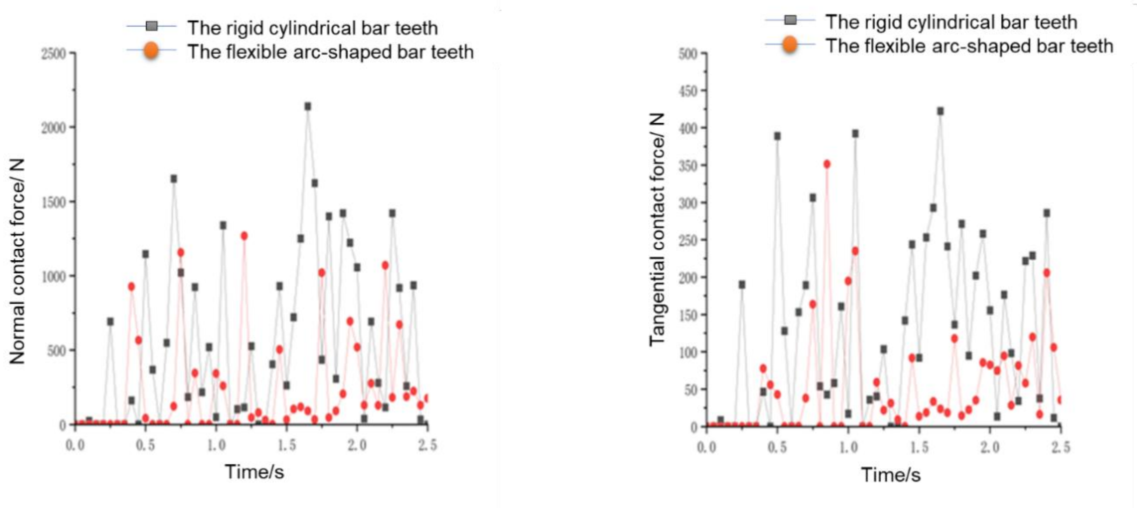
Analysis of simulation results

The simulation results for different threshing components are presented in Table 3. The normal and tangential contact forces exerted by the flexible arc-shaped bar teeth on corn ears are significantly lower than those generated by rigid cylindrical bar teeth, with reductions of 44.2% and 64.3%, respectively. This reduction is primarily attributed to the increased contact area between the flexible arc-shaped bar teeth and the corn ear, which reduces stress concentration and shear effects. In addition, the polyurethane coating applied to the tooth surfaces transforms rigid impacts into more compliant interactions, thereby reducing kernel breakage. The force-time relationship for corn ears under different threshing elements is shown in Fig. 7. During the threshing process, the contact force generated by cylindrical bar teeth exhibits significant fluctuations. At the moment of impact, localized stress concentrations may occur, resulting in high instantaneous peak forces. The peak contact force produced by the cylindrical bar teeth is higher than that of the flexible arc-shaped bar teeth. Consequently, under identical operating conditions, kernels are more susceptible to breakage when rigid teeth are used, leading to a higher breakage rate.

Table 3

Contact forces of different threshing components

Threshing element type	Normal contact force / N	Tangential contact force / N
Rigid cylindrical bar teeth	1135.4	224.4
Flexible arc-shaped bar teeth	633.2	80



(a) Normal contact force *(b) Tangential contact force*

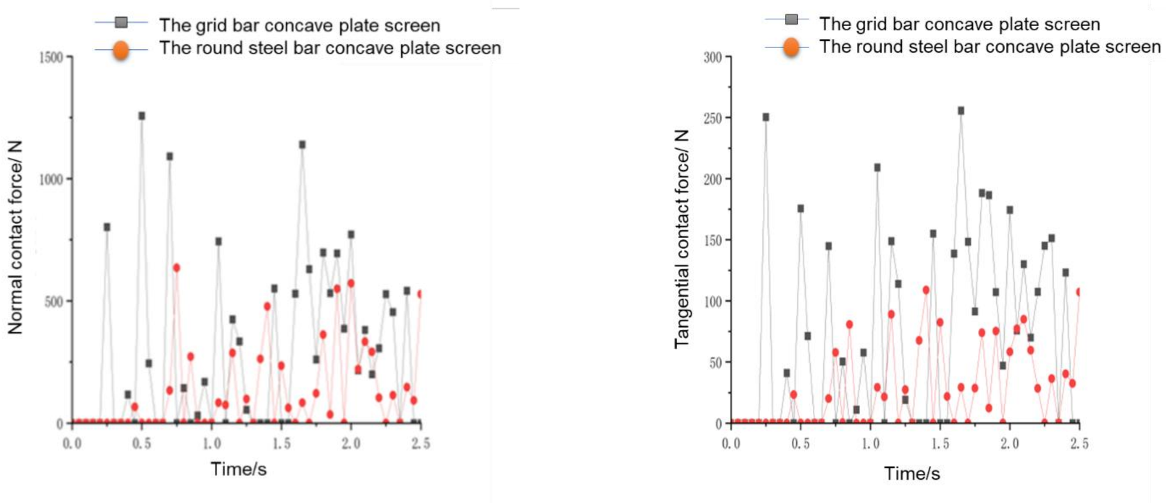
Fig. 7 - Contact force–time curves for different threshing elements

The simulation results for different concave screen designs are presented in Table 4. The normal and tangential contact forces exerted by the round steel bar concave screen on corn ears are significantly lower than those generated by the conventional bar-type concave screen, with reductions of 43.3% and 58.2%, respectively. This difference is mainly attributed to the presence of sharp edges on the bars of the conventional concave screen. During threshing, these edges increase shear interactions between the concave screen and the material, resulting in smaller contact areas and localized stress concentrations. Consequently, the intensity of impacts and the resulting contact forces acting on the corn ears are higher. The force-time relationship for corn ears under different concave screen designs is shown in Fig. 8. The conventional bar-type concave screen exhibits higher peak contact forces compared to the round steel bar concave screen. As a result, kernels are more prone to breakage under identical operating conditions, leading to increased kernel damage.

Table 4

Contact forces for different concave screen designs

Concave plate screen type	Normal contact force / N	Tangential contact force / N
Conventional bar-type concave screen	660.2	150.4
Round steel bar concave screen	374.2	62.9



(a) Normal contact force *(b) Tangential contact force*

Fig. 8 - Contact force–time curves for different concave screen designs

Analysis of field test results

The comparative test results are presented in Table 5. The results show that the flexible threshing device, incorporating flexible arc-shaped bar teeth and a round steel bar concave screen, achieves an average kernel breakage rate of 3.54% and a kernel loss rate of 2.71%. In contrast, the conventional rigid threshing device, equipped with cylindrical bar teeth and a bar-type concave screen, exhibits average kernel breakage and loss rates of 6.79% and 5.59%, respectively. Compared with the rigid device, the flexible threshing device reduces kernel breakage by 3.25 percentage points and kernel loss by 2.88 percentage points. These results demonstrate that the proposed flexible threshing device effectively reduces kernel damage and loss during corn harvesting.

Table 5

Field test results

Test no.	Flexible threshing device		Traditional rigid threshing device	
	Breakage rate	Loss rate	Breakage rate	Loss rate
1	3.29%	2.49%	6.78%	5.33%
2	3.82%	2.79%	7.05%	5.81%
3	3.52%	2.85%	6.54%	5.64%
Average	3.54%	2.71%	6.79%	5.59%

CONCLUSIONS

(1) Based on the design of the 4YZ-2 corn kernel combine harvester, a flexible threshing device was developed, incorporating flexible arc-shaped bar teeth and a round steel bar concave screen. The flexible arc-shaped bar teeth reduce impact forces acting on the kernels and increase the contact duration, while the round steel bar concave screen increases the contact area between the concave screen and the ear, thereby reducing kernel breakage.

(2) Discrete element simulations using EDEM showed that the normal and tangential contact forces exerted by the flexible arc-shaped bar teeth on corn ears were significantly lower than those of rigid cylindrical bar teeth, with reductions of 44.2% and 64.3%, respectively. Similarly, the round steel bar concave screen produced lower normal and tangential contact forces than the conventional bar-type concave screen, with reductions of 43.3% and 58.2%, respectively.

(3) Field comparative tests demonstrated that, compared with the rigid threshing device, the flexible threshing device reduced the kernel breakage rate by 3.25 percentage points and the kernel loss rate by 2.88 percentage points. These results confirm the effectiveness of the proposed design in reducing kernel damage and loss, and provide a useful reference for corn kernel harvesting in hilly regions.

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REFERENCES

[1] Basuki M., Aprilyanti S., Azhari, Madagaskar (2020). Design of Corn Thresher, *IOP Publishing - Journal of Physics: Conference Series*, 1500, 012075, Indonesia/Sumatera Selatan.

[2] Chelladurai D.D. (2026). *Machines of the Farm. Theory and Practice, Chapter 10 - Machines for crop harvesting*, pp. 231-262. Academic Press. Paperback ISBN: 9780443329067; eBook ISBN: 9780443329074

[3] Fan, C.L., Cui, T., & Zhang, D.X. (2019). Design and Test of Low-damage Combined Corn Threshing and Separating Device (低损伤组合式玉米脱粒分离装置设计与试验). *Transactions of the Chinese Society for Agricultural Machinery,* Vol. 50(04), pp. 113-123, Beijing/China.

[4] He, Ke., (2019). Design and Experiment on Flexible Threshing Device for Corn *(玉米柔性脱粒装置设计与试验)*. [D] *Shandong University of Technology*, Shandong/China

[5] Kruszelnicka W., Leda P., Tomporowski A., Ambrose K. (2024). Breakage behavior of corn kernels subjected to repeated loadings, *Powder Technology*, volume 435, 119372, Bydgoszcz/Poland

[6] Le, L., Yang, Z., & Nie, J.S. (2025). Optimization Design of Tangential Flow Transverse Axial Flow Double Drum Maize Threshing Device. *INMATEH-Agricultural Engineering,* Vol. 77(03), pp. 647-662, Bucharest/Romania.

[7] Li, H. B., Chen, L. W., & Zhang, Z. Y. (2023). A Study on the Utilization Rate and Influencing Factors of Small Agricultural Machinery: Evidence from 10 Hilly and Mountainous Provinces in China. *Agriculture-Basel,* Vol. 13(1). pp. 51. Jiangsu/China

[8] Lontseva I., Sennikov V, (2022). Improving the Efficiency of Combine Harvesters, *Fundamental and Applied Scientific Research in the Development of Agriculture in the Far East (AFE-2021) - Agricultural Innovation Systems*, Volume 1, Conference proceedings, pp. 415-423;

[9] Li, X. Y., Du, Y. F., Guo, J. L., & Mao, E. R. (2020). Design, Simulation, and Test of a New Threshing Cylinder for High Moisture Content Corn. *Applied Sciences-Basel,* Vol. 10(14). pp. 4925. Beijing/China

[10] Li, X. Y., Du, Y. F., Mao, E. R., Zhang, Y. A., Liu, L., & Guo, D. F. (2023). Design and experiment of corn low damage threshing device based on DEM. *International Journal of Agricultural and Biological Engineering,* Vol. 16(3), pp. 55-63. Beijing/China

[11] Mu, Z.Q., Z, B., & Tian, K.P. (2025). Current status and technical challenges of corn mechanized harvesting in the southwestern hilly and mountainous regions (西南丘陵山地玉米机械化收获现状与技术挑战). *Journal of Chinese Agricultural Mechanization,* Vol. 46(11), pp. 331-335+343.Nanjing/China

[12] Steponavicius, D., Kemzuraite, A., Puzauskas, E., Domeika, R., Grigas, A., & Karalius, D. (2023). Shape Optimization of Concave Crossbars to Increase Threshing Performance of Moist Corn Ears. *Agriculture-Basel,* Vol. 13(5). pp. 983. VMU.

[13] Su, Y., L, H., & Xu, Y. (2018). Optimization and Experiment of Spike-tooth Elements of Axial Flow Corn Threshing Device (轴流式玉米脱粒装置钉齿元件优化与试验). *Transactions of the Chinese Society for Agricultural Machinery,* Vol. *49*(S1), pp. 258-265.Beijing/China

[14] Tan, Y.F., Chen, L., Hu, S., & Wang, J. (2023). Design and experiment of longitudinal-axial flow flexible bent-tooth soybean thresher (纵轴流柔性弯齿式大豆脱粒装置的设计与试验). *Acta Agriculturae Zhejiangensis,* Vol. 35(12), pp. 2954-2965.Sichuan/China

[15] Vlădut N.-V., Ungureanu N., Biris S.St., Voicea I., Nenciu F., Găgeanu I., Cujbescu D., Popa L.- D., Boruz S., Matei G., Ekielski A., Teliban G.C. (2023). Research on the identification of some optimal threshing and separation regimes in the axial flow apparatus, *Agriculture.* 13(4):838, Section: Agricultural Technology. Bucharest/Romania

[16] Wang, Z. B., Wang, Z. W., & Zhang, Y.P. (2020). Design and Test of Longitudinal Axial Flexible Hammer-claw Corn Thresher (纵轴流柔性锤爪式玉米脱粒装置设计与试验). *Transactions of the Chinese Society for Agricultural Machinery,* Vol. 51(S2), pp. 109-117. Shandong/China

[17] Wang, Z.D., Cui, T., & Zhang, D.X. (2021). Design and Experiment of Low Damage Corn Threshing Drum with Gradually Changing Diameter (玉米收获机低损变径脱粒滚筒设计与试验). *Transactions of the Chinese Society for Agricultural Machinery,* Vol. 52(08), pp. 98-105. Beijing/China

[18] Wang, Z.W., Wang, Q.H., Ming, J.R., & Zhang, C. (2023). Design and experiment of vertical corn threshing device (立式玉米脱粒装置设计与试验)*. Journal of Chinese Agricultural Mechanization,* Vol, 44(06), pp. 105-113.

[19] Xu, J., J. C., & Chen, Q. (2025). Research And Development of an Integrated Header for Soybean Corn Combined Harvesters Adapted to Strip Intercropping. *INMATEH-Agricultural Engineering,* Vol, 76(02), pp. 58-68.

[20] Xu, L.Z., L, Y.M., Ding, L.F. (2008). Contacting mechanics analysis during impact process between rice and threshing component (水稻谷粒与脱粒元件碰撞过程的接触力学分析). *Transactions of the Chinese Society of Agricultural Engineering,* Vol, (06), pp. 146-149.

[21] Zhang, H.F., L, G.Z., Zhang, D.M. (2025). Limitations of Varieties on Mechanized Harvesting of Maize Grains and Thoughts on Specialized Variety Breeding (玉米子粒机械化收获的品种制约及专用品种选育思考). *Journal of Maize Sciences*, pp. 1-9. Henan/China