Low-Damage Corn Threshing Technology and Corn Threshing Devices: A Review of Recent Developments

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Abstract: Corn is a crucial crop and has a vital application value in many aspects of our lives. Mechanical grain harvesting is the developing direction of corn harvesting technology, with corn threshing as its most imperative procedure. The quality of the threshing device of the corn harvester has a major influence on its damage rate, loss rate, and other parameters. Therefore, it is of great significance to effectively lower the damage rate in the process of corn threshing. This review presents the research progress and the application status of corn threshing technology and corn threshing machinery. The conclusions and suggestions on low-damage corn threshing technology and corn threshing machinery are summarized to provide a reference for the reduction in the damage rate of mechanical grain harvesting and promote the development of mechanical grain harvesting technology.

Keywords: damage rate; grain moisture content; corn threshing device; feeding rate; concave clearance

1. Introduction

Corn, as a critical crop, has a value that cannot be ignored in the fields of food, the chemical industry, and in other fields. Corn is grown in many parts of the world and is the crop with the highest planting area and yield in China [1–5]. The main corn-growing areas in China are Northeast, North, and South China. Moreover, Northeast China is one of the three most imperative corn-growing regions in the world [6,7]. According to China’s National Bureau of Statistics, the country’s corn output in 2021 was 272.55 million tons, and the sown area was 433.24 million hectares. However, agricultural labor has been unable to meet the needs of traditional corn production with the rapid development of the social economy and urbanization. Therefore, the mechanization of the entirety of corn production is the inevitable future of the corn industry [8]. Mechanical grain harvesting is the developing direction of corn harvesting technology, serving as the key technology for the realization of the entire mechanization of corn production and to change the mode of production. Mechanical grain harvesting indicates that the harvester completes the following steps in the field by gathering the corn plant, picking the ears, stripping the bracts from the ears, threshing, separating and cleaning the corn, and finally, feeding the clean grains into the harvester’s grain bin. In this process, corn threshing causes the largest rate of broken kernels. The high damage rate of corn harvesting lowers the grade of the corn and its sale price. Moreover, it leads to a reduction in corn yield, increases the cost of artificial grain drying, and impedes the safe storage of corn [9,10].

Corn threshing is the most crucial, difficult, and complicated procedure during mechanical grain harvesting. The complex process of corn threshing consists of the interaction between the mechanical parts and the corn ears, involving extrusion, collision, and friction. Therefore, the quality of the corn harvester’s threshing device has a significant influence on the damage rate, loss rate, and other parameters [11,12]. It is urgent to effectively reduce
the number of kernels broken during corn threshing. This research explains the current situation of corn threshing research from two main perspectives, which are the theory of corn threshing technology and the corn threshing machinery itself. This lays a foundation for the research on effectively reducing the damage rate of mechanized corn harvests.

2. The Key Technology Status of Corn Threshing

Corn threshing indicates that after the corn enters the threshing space, it starts to move under the action of the threshing parts. In the process of this movement, the corn interacts with the threshing parts and with other corn to produce extrusion, friction, kneading, and other effects, causing the corn kernels to separate from the mandrel.

The mechanism of corn threshing can provide a theoretical reference and the basic parameters for the design of corn threshing machinery. Many of the characteristics of corn ears, such as the shape and the arrangement between the kernels, are relatively different from those of wheat and rice. Therefore, the mechanism of corn threshing has been widely investigated.

2.1. Effect of Grain Moisture Content on Corn Threshing

The moisture content of corn kernels is a vital factor affecting the performance of threshing machinery [13–15]. Many studies have focused on the effect of the grain moisture content on the damage intensity of the corn ears and the effect of the grain moisture content on the crack formation law of the corn kernels. Ekstrom G.A. et al. [16] revealed through experiments that the grain moisture content has a significant effect on the stress cracks, and the stress cracks in corn kernels expand from the inside to the outside. Zhang et al. [17] discovered that the corn variety and the grain moisture content have a significant impact on the generation of mechanical cracks through tests. Additionally, cracks occur inside the corn kernels during the drying process [18]. Thompson R.A. et al. [19] suggested that the water loss rate inside and outside the kernels is different in the process of rapid heating and drying due to the temperature difference between the inside and outside of the kernels. The stress difference between the interior and exterior of the kernels induced the appearance of internal cracks in the kernels. Yan [20] employed in situ compression mechanics to conduct an in situ compression test on corn kernels for real-time observation and obtaining the micro-morphological changes of the corn kernels in the test.

In addition to exploring the law of crack formation in corn kernels, many researchers have conducted systematic research on the elastic modulus, compressive strength, and shear strength of corn kernels [21]. Singh S. et al. [22] obtained the corresponding mechanical characteristic images of corn kernels with different grain moisture contents through compression tests and calculated parameters such as the elastic moduli and the ultimate compressive stresses. The results demonstrated that the above parameters decreased with an increase in the grain moisture content. This conclusion was confirmed by other studies [23–25]. Volkovas V. et al. [26] performed impact tests on corn ears and calculated the elastic moduli of corn kernels to explore the relationship between their grain moisture content and their elastic moduli. The results implied that the grain moisture content along the axes of the corn ears increased from the small end to the large end, and the elastic moduli decreased along this direction. Zhang et al. [27] conducted shear tests on corn kernels using electronic tension and a compression testing machine, and analyzed the shear characteristics of corn kernels under different forces and different grain moisture contents. They unveiled that the surface shapes and internal structures of corn kernels were affected by the grain moisture content, and the shear strength of corn kernels was thus affected by the grain moisture content. Moreover, the shear strengths of the corn kernels in different directions varied. Li et al. [28,29] investigated the compressive properties of corn and the law of crack formation in corn kernels through static compression tests. The test results reflected that the compressive capacity of the corn ears increased with the increase in the grain moisture content when the grain moisture content was less than 25%. The situation was reversed when the grain moisture content of the corn ears was higher than
25%. Afterward, impact crushing tests were conducted on the corn ears and kernels. The results uncovered that the maximum crushing force of the kernels decreased with the increase in the grain moisture content. The downside of the corn ear (the location division of the corn ear is shown in Figure 1) withstood a higher impact when the grain moisture content was the same. Concerning corn kernels, the ventral part of the corn kernel (the impact location of corn seeds is shown in Figure 2) withstood a higher impact when the moisture content was the same [30,31]. Yang [32], Zhao [33], and Zhang [34] also drew the above conclusions. With the decrease in the grain moisture content, the hardness, tensile strength, and shear strength of the corn kernels increased.

Figure 1. The location division of the corn ear.

Figure 2. Impact locations of corn seeds: (a) impact the side of the corn seed; (b) impact the top surface of the corn seed; (c) impact the ventral part of the corn seed.

Qu et al. [35,36] studied the influence of the grain moisture content on the damage rate and threshing energy consumption on a 5TY32 corn thresher. The test results suggested that the lowest damage rate occurred when the grain moisture content was 18.3%. The lower the grain moisture content, the less energy the machine consumes when threshing. Xiang et al. [37] investigated the effects of the grain moisture content and threshing cylinder speed on the damage rate and the un-threshed rate, revealing that the grain moisture content suitable for corn threshing was 13.9–27.6%. The grain damage rate was the lowest when the grain moisture content was 18.3%. The linear speed of the threshing cylinder satisfying the condition of corn threshing was 2.99–7.77 m·s\(^{-1}\), and the threshing effect was the best when the linear speed of the threshing cylinder was 5.04 m·s\(^{-1}\). Yang et al. [38] designed a tangential flow–transverse axial flow maize thresher system and threshed corn ears with a grain moisture content of 22–32% at different transverse axial flow threshing cylinder linear speeds. The test results demonstrated that the percentage of threshed matter in the tangential flow cylinder decreased with the increase in the grain moisture content. The
threashing capacity of the tangential cylinder was almost equal to the threashing sieving section of the transverse flow cylinder when the grain moisture content was below 28%. The percentage of threashed matter in the tangential cylinder decreased significantly when the moisture content was higher than 28%. Al Sharifi S.K.A. et al. [39] researched the influence of the moisture content of the corn ear, thresher type, and cylinder speed on the corn ear threashing effect. The results implied that the threasing effect of the tangential flow corn thresher was better than that of the transverse axial flow corn thresher under all experimental conditions. When the grain moisture content of the corn ear was 18%, the non-threasing rate of the tangential flow corn thresher was 3.434%, and the damage rate was 2.1%. The un-threased rate of the transverse axial flow corn thresher was 3.884%, and the damage rate was 2.225%. Petkevichius S. et al. [40] selected two kinds of corn with different grain moisture contents for the comparative test, and the grain moisture content of these two kinds of corn was 32.5% and 18.5%, respectively. During the threasing of the wet corn ears, the threasing damage was 30% greater as compared with the threasing damage of the medium dry corn ears.

2.2. Effect of Mechanical Parameters on Corn Threasing

In the process of mechanical grain harvesting, corn threasing is one of the most damaging links to corn kernels. A crucial reason for the breakage of corn kernels is the collision between the threasing elements and corn kernels. The speed of the threasing cylinder, concave clearance, and feeding rate are the vital working parameters affecting the working quality of the threasing device [41,42]. Therefore, many researchers optimized the parameters of corn threasing machinery through experiments to lessen the degree of damage to corn kernels caused by threasing elements.

2.2.1. Effect of Concave Clearance on Corn Threasing

The concave screen is one of the most imperative parts in corn threasing machinery [43] and is generally located below the threasing cylinder. The clearance between the threasing cylinder and the concave screen is called the threasing clearance, which is also the place where corn ears are threased. According to the different surface structures, the concave screen is mainly divided into cylindrical type, grid type, scale type, and round hole type. The picture of the concave screens is displayed in Figure 3.

![Figure 3. Structure diagrams of the concave screen: (a) cylindrical type; (b) grid type; (c) scale type; (d) round hole type.](image-url)

Wall G.L. [44] conducted a corn threasing test with a tangential cylinder. The test results reflected that the speed at the end of the threasing cylinder and the concave clearance exerted a great impact on the degree of corn kernel breakage. By changing the design parameters of the concave screen, the kernel breakage can be reduced, and the separation efficiency can be improved. Referring to the actual operation of the corn combine harvester when harvesting corn, Huang et al. [45] established a test device with an adjustable threasing cylinder speed and concave clearance and designed a two-factor three-level test scheme to analyze the impact of the threasing cylinder speed and concave clearance on the damage rate and corn threasing rate. The results demonstrated that the concave clearance was the main factor affecting the corn threasing rate and damage rate. The damage rate and the
The corn threshing rate can be balanced by reasonably adjusting the concave clearance and the speed of the threshing cylinder, so as to achieve the lowest loss rate. Bakharev D. et al. [46] studied the factors influencing the separation effect of mixtures composed of corn kernels and other impurities such as corn cobs. The results suggested that the most influential factor was the threshing time of corn kernels. The size of the corn kernel, the surface shape of the corn kernel, and the arrangement of holes on the concave screen all impacted the threshing time of the corn kernel. In the subsequent study, Bakharev D. et al. [47] designed an axial flow rotary threshing device. The concave clearance of this device decreased along the entrance to the exit direction of the threshing chamber. The results of the corn threshing test unveiled that the corn kernel strength was the highest when the grain moisture content was 12–18%. Additionally, the connection between the kernel and the rod was weakened, allowing for threshing with minimal breakage to the kernels. Astonakulov [48] and Waree Srison et al. [12] investigated the design factors influencing the threshing loss and power consumption of the axial flow corn threshing device, discovering that the peg tooth clearance, concave rod clearance, and concave clearance had a significant impact on the threshing loss and power consumption of the thresher, but no significant impact on the kernel breakage.

Steponavičius D. et al. [49] explored the concave screen of a high moisture corn thresher, revealing that for a high moisture content of corn (grain moisture content of 36.16 ± 1.83%), the threshing loss reached 2.2% when the concave clearance was 62.5 mm; the threshing loss rate increased to 2.8% when the concave clearance increased. The separation capacity of the improved concave screen was two times higher than that of the unimproved concave screen. Fu et al. [50] used the response surface methodology and the non-dominated sorting genetic algorithm II to optimize the parameters of the longitudinal axial flow threshing cylinder, such as cylinder speed, feeding rate, and concave clearance. When the cylinder speed, the feed rate, and the concave clearance were selected as 384.1 r·min^{-1}, 8.6 kg·s^{-1}, and 40.5 mm, respectively, the damage rate was 3.49% and the loss rate was 1.98%.

2.2.2. Effect of Feeding Rate on Corn Threshing

The feeding rate is a crucial parameter influencing the working efficiency and working effect of the corn threshing machinery [51].

In the design work of the corn combine or corn threshing machine, it is an indispensable link to explore the influence of the feeding rate on the working efficiency and operational effect of the machine. Many researchers have discovered that the feeding rate has a linear correlation with grain loss, machine power consumption, and other parameters [52–54]. To explore the influence of the feeding rate on the threshing effect of corn, Kiniulis V. et al. [55,56] first designed three different structure filling plates installed on the threshing cylinder, and the feeding rate varied from 4 kg·s^{-1} to 12 kg·s^{-1}. It was suggested that an increase in the feed rate caused the threshing loss to increase. Then, they conducted experiments using a stationary tangential threshing device and measured the forces acting on the rear part of the concave as well as the torque of the rotating cylinder during a threshing process. The test data demonstrated that the torque of resistance to the cylinder rotation varied from 28.06 Nm to 35.15 Nm when the feeding rate increased from 4 kg·s^{-1} to 12 kg·s^{-1}. The force acting on the rear part of the concave increased about four times as the feed rate increased from 4 kg·s^{-1} to 12 kg·s^{-1}. At a feed rate of 12 kg·s^{-1}, the value of the amplitude of variation in force was higher than that at 4 kg·s^{-1}.

2.2.3. Parameter Optimization of Threshing Machine

Saeng-ong P. et al. [57] investigated the effects of the guide vane inclination of an axial shelling unit on the corn shelling performance, suggesting that the loss from the shelling unit tended to decrease, the power requirements and specific energy consumption tended to increase linearly, and the grain breakage difference was insignificant when the angle of the guide vane increased. Steponavičius D. et al. [58] established the movement of corn ears within the threshing crescent between the cylinder and the concave using a high-speed
recording method. The tangential threshing unit was adopted in the experimental trials. A video analysis of corn ear movement implied that the speed of corn ear movement in the threshing crescent was highly determined by the linear velocity of rasp bars. The average speed of the corn ear within the threshing crescent and the number of impacts received by the corn ear were boosted with the increase in the linear velocity of rasp bars regardless of whether cylinder filler plates were used. Ni et al. [59] designed a double-cylinder corn seed threshing device with rubber on the outside of the threshing unit. Through experiments, the machine reduced the breakage of corn kernels. Chen et al. [60] established a longitudinal axial flow flexible threshing and separating device with the combined threshing element and roller-type combined threshing concave. The roller-type combined threshing concave with a six-edged mesh sieve and fish scale threshing rubber roller was designed with different traditional concave plates. The optimal conditions are detailed as follows. The cylinder speed was 475 r·min\(^{-1}\), the transmission ratio between the roller and cylinder was 1.5, and the concave clearance was 45 mm. Under the above conditions, the breaking rate and un-threshed rate were 3.76% and 0.52%, respectively. Li et al. [61] designed a new type of single longitudinal axis threshing cylinder, consisting of a cylinder spindle, a spiral feeding inlet, a T-type rasp bar, a separating straight rod, and a spiral extracting rod. The optimal working parameters of the device are described as follows. The rotating speed of the cylinder was 309.17 r·min\(^{-1}\), the feeding rate was 6.13 kg·s\(^{-1}\), and the concave clearance was 35.48 mm. Under the above conditions, the damage rate and the un-threshed rate were 1.24% and 1.33%, respectively. Geng et al. [62] proposed a transverse axial flow corn threshing device. The device was equipped with a flexible threshing cylinder, and the threshing element adopted a combined structure of the flexible tooth and elastic short rasp bar, contributing to the flexible, low-breakage threshing of corn kernels.

2.3. Application of Numerical Simulation in the Study of Corn Threshing

The corn threshing test consumes much time and energy and is also limited by factors such as season and space. The numerical simulation technology can parameterize the material and threshing device and analyze the operation mechanism while getting rid of the above factors and lowering the research cost [63–65]. Additionally, numerical simulation technology was employed to simulate the stress and strain conditions of corn grains during threshing and the motion of corn grains in the threshing device. It can demonstrate the damage caused by threshing parts to corn grains more clearly and intuitively, providing a theoretical reference for the design of a low-damage corn threshing device.

2.3.1. Application of Finite Element Method in Corn Threshing Technology

Some researchers utilized the finite element analysis software to analyze the corn ear or corn kernel model for obtaining the stress distribution and stress–strain characteristics of the kernels during threshing [66–68]. Wang [66] and Zhang [68] suggested that the junction of the embryo and corneous endosperm is the most vulnerable area. Wang et al. [69] established a corn kernel model through 3D scanning technology and then studied the impact of the collision speed and grain moisture content on the breakage degree of corn kernels through the finite element analysis software. The results implied that the stress was concentrated in the small contact area when the corn kernels collided, and the stress was gradually reduced when it diffused. The maximum contact force and stress decreased with the increase in the grain moisture content, and the maximum contact force and stress increased when the collision velocity between the corn kernels increased.

Pužauskas E. et al. [70] designed a tangential flow corn threshing device and analyzed the process using numerical simulation. The numerical values of the reaction forces in the threshing process were determined by combining the static equilibrium calculation method and the finite element analysis model. It was uncovered that the displacement and deformation values were determined by the elastic moduli of the corn ear seed and corn cob. He et al. [71] built the corn flexible threshing cylinder and applied NX to perform 3D modeling. Afterward, ADAMS and Abaqus were employed to perform the dynamic
balance simulation analysis, modal analysis, and static stress simulation analysis of the threshing cylinder. Hu et al. [72] established the threshing device suitable for Wode DC60 wheeled combine harvester and determined the material and structural dimensions of the threshing device. The corn ear collision process between the flexible threshing element was separately simulated in ANSYS. The results demonstrated that the maximum pressure, contact area, stress, and strain induced by the flexible threshing device on the corn ear were all smaller than those of the rigid threshing device, and the contact time was longer than that of the rigid threshing device.

Shahbazi F. et al. [73] evaluated and simulated the mechanical breakage of the corn kernels under the impact load. The results revealed that the impact energy, grain moisture content, and the interaction effects of these two variables significantly influenced the percentage of physical breakage in the corn kernels. As the impact of the energy increased from 0.1 J to 0.3 J, the mean values of breakage significantly increased from 23.73% to 83.49%. The mean values of physical breakage decreased significantly by a factor of 1.92 (from 83.75% to 43.56%), with an increase in the grain moisture content from 7.6% to 20%. However, the mean value of damage exhibited a non-significant increasing trend with a higher increase in moisture from 20% to 25%. There was an optimum moisture level of about 17% to 20%, at which the seed breakage was minimized. The empirical model composed of the impact energy and grain moisture content accurately described the breakage of the corn kernels. Tao et al. [74] established a nail-tooth thresher model and used LS-dyna to simulate the dynamic process of the impact threshing of corn. The results unveiled that the impact force on the corn kernels increased with the increase in the rotation speed of the threshing cylinder. The impact force on the belly of the corn kernel was the largest when the rotation speed of the threshing cylinder was the same.

2.3.2. Application of Discrete Element Method in Corn Threshing Technology

The finite element method is a numerical method based on continuum mechanics and is mainly used to predict the damage and the general area of failure. Nonetheless, it cannot simulate the specific breakage form and breakage process. The discrete element method is a numerical method used to calculate the mechanical behavior of the granular medium system. It can analyze not only the interaction between the particles and boundaries, but also the interaction within the particle population [75–77].

Upon the discrete element numerical model of the thresher and the particle simulation method of the corn ear, some researchers developed the software of corn threshing analysis [78–82]. The software was employed to study the effects of the threshing cylinder speed and feeding rate on the threshing rate and the number of separated kernels in the range of the cylinder length. The simulation results of the threshing process suggested that the number of separated kernels decreased with the increase in the cylinder length, cylinder speed, and the feeding rate. Moreover, the numerical results were in good agreement with the experimental results. Wang et al. [83] utilized the discrete element method to analyze the motion state of corn kernels in the threshing process from a microscopic perspective. A discrete element analysis model for a corn threshing device with the shear cross-axial flow was established, and EDEM was adopted to simulate the axial mass distribution of corn kernels in the threshing device by the toothed column plate cylinder. Given that there is no significant difference between the results of the simulation test and bench test, the actual threshing condition can be reliably simulated.

Since numerical simulation technology can reduce the research cost, and the accuracy of the simulation results is high, it has been widely employed to explore low-damage corn threshing devices. The most common application scenario of numerical simulation technology is to determine the working parameters of the threshing device with the lowest damage degree to corn kernels through the simulation of the designed threshing device.
3. Development Status of Corn Threshing Device

According to the movement form of corn ears along the threshing cylinder, the corn threshing device can be divided into the tangential flow corn threshing device and the axial flow corn threshing device. Axial flow corn threshing devices can be divided into transverse axial flow corn threshing devices and longitudinal axial flow corn threshing devices. Figure 4 exhibits the threshing device in the above forms.

![Figure 4. Schematic diagram of three basic forms of threshing device: (a) tangential flow pattern; (b) transverse axial flow pattern; (c) longitudinal axial flow pattern.](image)

3.1. Development Status of Tangential Flow Corn Threshing Device

In the tangential flow corn threshing device, corn ears enter along the tangential direction of the threshing cylinder and discharge from the tangential direction of the threshing cylinder.

Li et al. [84] conducted bench tests on a tangential flow threshing and separating unit with spike teeth and knife teeth, determined the performance and power consumption of the tangential flow threshing and separating unit, and analyzed the influence of different structure and working parameters on the threshing performance. Feng et al. [85] investigated the cleaning performance of the double-stream threshing and separating device through comparative tests, set different cylinder linear velocities and nail tooth arrangement forms, and obtained the optimal combination parameters. The T670 combine produced by John Deere is representative and adopts the tangential flow grain technology, as presented in Figure 5. This machine is primarily used for threshing and separating large feeding rate crops such as wheat, and has a good effect [86]. This tangential flow grain technology can also be utilized in corn combine.

![Figure 5. John Deere T670 combine: (a) a complete view of John Deere T670 combine; (b) tangential flow threshing unit for John Deere T670 combine.](image)
The power consumption of the tangential flow corn threshing device is low. However, there are more impurities in corn kernels owing to the short threshing time of corn ears. Hence, it is necessary to install a grain separation device to remove impurities. With the purpose of avoiding the above shortcomings, a tangential–axial flow corn threshing device was established by combining a tangential flow threshing cylinder and an axial flow threshing cylinder to improve the removal rate and reduce the damage rate of the threshing device.

3.2. Development Status of Axial Flow Corn Threshing Device

Axial flow corn threshing devices can be divided into longitudinal axial flow corn threshing devices and transverse axial flow corn threshing devices. The longitudinal axial flow corn threshing device is a kind of threshing device in which corn ears are fed longitudinally and corn cobs are discharged longitudinally. The transverse axial flow corn threshing device is a kind of threshing device in which corn ears are fed transversally.

Byg D.M. et al. [87] discovered that a 20% moisture content of corn ears is the most suitable for harvesting. The crushing rate of corn ears can be reduced by the impact and kneading action of the longitudinal axial flow threshing cylinder and concave screen. Through the self-developed test bench, Yi [88] and Li et al. [89] performed tests with the feeding rate, cylinder linear speed, guide board, and angle as factors, obtained the test data of the performance indicators such as the un-threshed rate, damage rate, and loss rate, and analyzed the direct interaction law of these factors and the distribution law of the mixture. Xiong et al. [90] designed a double-cylinder axial flow threshing separation device. Compared with the single-cylinder axial flow threshing separation device of the same type, this device has a higher threshing rate and a lower loss rate. Dai et al. [91,92] formed a longitudinal axial flow double-cylinder threshing and separating device, and determined its optimal structural parameters and working parameters through experiments. Wang et al. [93] developed the bow tooth differential-speed threshing cylinder and rod tooth differential-speed threshing cylinder. Contrast experiments of the differential-speed threshing cylinder and single-speed threshing cylinder were conducted to verify the performance of the differential-speed threshing device. Qu [94] built the longitudinal axial flow corn threshing separation test platform and determined the best structural parameters and working parameters of the threshing device through the EDEM simulation analysis and field experiment, contributing to effectively improving the threshing rate and reducing the loss rate. The Axial Flow 4000 series combines produced by Case Company (Figure 6) adopts the single longitudinal axial flow threshing technology [95], which is widely used in Northeast China.

![Figure 6. Case AF4008 combine: (a) a complete view of Case AF4008 combine; (b) single longitudinal axial flow threshing cylinder of Case AF4008 combine.](image-url)
The transverse axial flow corn threshing device has a strong ability to feed corn ears. Since the threshing device is placed horizontally on the corn combine, the length of the threshing cylinder is limited by the width of the harvester, and the threshing time of the corn ears is short. The length of the threshing cylinder of the longitudinal axial flow corn threshing device is longer. Thus, the corn ear threshing time is longer and can be completed at the same time as the threshing and separation process, with a good threshing effect. The longitudinal axial flow corn threshing device is compact and widely used in corn combine harvesters.

3.3. Development Status of Tangential–Axial Flow Corn Threshing Device

The tangential–axial flow corn threshing device combines the advantages of the tangential flow corn threshing device and the axial flow corn threshing device (Figure 7). This type of threshing device can not only improve efficiency, but also maintain a higher threshing cylinder speed and a larger feeding rate, whereas the structure of the device is more complex [96–98].

Figure 7. Structure diagrams of tangential–axial flow corn threshing device: (a) combined threshing device with the tangential flow and longitudinal axial flow; 1: tangential flow threshing and separating device; 2: forced feeding device; 3: longitudinal axial flow threshing and separation device. (b) Combined threshing device with the tangential flow and transverse axial flow; 1: tangential flow threshing and separating cylinder; 2: transverse axial flow threshing and separating cylinder.

Rao et al. [99] conducted a field experiment with a tangential-double longitudinal axial flow device, obtained the sequence of the factors influencing the damage rate and the sequence of the factors affecting the threshing loss rate, and realized the best working parameters combination. Yang et al. [38,100] determined the optimal structural parameters and working parameters to adapt to multiple varieties of corn by replacing key components such as the threshing cylinder or adjusting the technical parameters of the tangential flow–transverse axial flow threshing test system. The CR-Series combines produced by New Holland Company adopt the tangential flow–double longitudinal axial flow threshing technology [101], as displayed in Figure 8. The tangential flow type threshing cylinder at the front end first sheds part of the corn kernels and removes the bracts of the corn ears to prevent crop clogging.
3.4. Development Status of Intelligent Control System of Corn Combine

The intelligent detection of corn threshing conditions is of great significance to improve the intelligence level and working quality of the threshing device. The current research emphasizes the monitoring and control of the threshing cylinder of the combine and the clearance adjustment of the concave screen.

Yan et al. [102] designed a system to collect the feeding rate, grain moisture content, and revolution speed of the threshing cylinder immediately, process the data intelligently, and control the revolution speed of the threshing cylinder automatically. With the feeding rate and grain moisture content as control factors, the cylinder speed was automatically controlled to reinforce the working efficiency and reliability of the combine harvester. Li et al. [103] designed a device for adjusting the concave clearance and monitoring the threshing cylinder load, as exhibited in Figure 9. The device can realize the automatic adjustment of the cylinder through the acquisition, processing, and analysis of the pressure. Regarding the structure, the positioning is monitored through the displacement sensor (2) and tension sensor (7), the hydraulic cylinder movement is made by controlling the electromagnetic reversing valve, and the integral concave screen (9) is designed to realize the automatic adjustment of the concave clearance.

Omid M. et al. [104] adopted a fuzzy logic controller (FLC) to improve the control system of the John Deere 955 corn combine harvester. The hydraulic cylinder and solenoid valve are employed to control the hydraulic cylinder speed, concave clearance, fan speed, and forward speed. The Case IH AFX8010 combine is illustrated in Figure 10. The feeding rate of the harvester can be controlled automatically. In the working process of the harvester, the self-adaptive control of the driving speed is realized to render the machine stable in the best working state [105].

![Case IH AFX8010 combine.](image1)

Figure 10. Case IH AFX8010 combine.

The CR-Series combine produced by New Holland [102] is presented in Figure 11. An ultrasonic filter was added to the feeding system to monitor the feeding clutter and protect the structure of the threshing cylinder. Under different feeding rates, the roller speed was adjusted automatically to assure threshing efficiency.

![New Holland CR9090 combine.](image2)

Figure 11. New Holland CR9090 combine.

In addition to the above research on the monitoring and control of some parts of the corn threshing device, some researchers have designed the overall control system of the corn combine harvester to improve the intelligence level of the corn combine harvester. Cui et al. [106] developed a precise intelligent control system for the corn harvester by integrating navigation and positioning, benchmark line auto-guiding operation, head height auto-copying, real-time monitoring, and fault alarm of the key components’ rotational speed. It provided equipment and key technical support for boosting the mechanization level of summer corn production. Zhu et al. [107] conducted an intelligent modification on the longitudinal axial flow corn harvester to tackle the headaches of the low intelligence level of corn harvesters in China, and the damage rate and entrainment loss rate of high moisture content corn were high. Additionally, an intelligent control system for the low
damage rate of high moisture content corn based on the CAN bus was designed. This system adopted an automatic control strategy and integrated a discrete PID control algorithm to achieve a low damage rate of high moisture content corn.

4. Conclusions

1. The grain moisture content exerted a significant influence on the mechanical properties of corn kernels. The elastic modulus, hardness, tensile strength, and shear strength of corn decreased with the increase in grain moisture content. By selecting the varieties that can match the local light and temperature conditions in the appropriate growth period and determining the suitable planting area of the varieties, it can be guaranteed that the corn had the appropriate grain moisture content during harvest and reduced the crushing rate.

2. Numerical simulation technology has become a crucial means in the research of corn threshing technology because of its advantages of a low test cost and not being restricted by season and space. The numerical simulation technology can reveal the stress and strain conditions and movement rules of corn kernels in the process of corn threshing. Moreover, some researchers have developed a 3D discrete element method software for realizing the simulation analysis of the corn threshing process.

3. Mechanical grain harvesting is the developing direction of corn harvesting technology. Many research institutions and companies focus on the development of low-breakage corn combine to curtail the damage rate of corn combine by improving the rigid threshing technology or threshing element.

4. In the process of mechanical grain harvesting, the rotating speed of the cylinder is the main mechanical reason for kernel breakage. It is a vital method to lower the breakage of corn kernels to optimize the control of the threshing cylinder speed and the adjustment algorithm of the concave clearance. The intelligent control strategy of the corn threshing device combined with the PID control algorithm, deep learning, and other technologies can achieve data acquisition, processing, and adjustment of the device while acquiring a lower damage rate.

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