EFFECTS OF MOISTURE CONTENT ON MECHANICAL CRUSHING PERFORMANCE OF SOYBEAN SEEDS AND ITS APPLICATION IN MECHANIZED HARVESTING

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含水率对大豆种子机械破碎性能的影响及其在机械化收获中的应用

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ABSTRACT

This study addresses the issue of grain crushing during the mechanical harvesting of soybeans, systematically analyzing the effect of moisture content on its mechanical crushing characteristics. Single-factor and multi-factor orthogonal experimental methods were employed to record the grain crushing process through compression tests combined with high-speed camera technology, enabling a quantitative analysis of moisture content, loading speed, compression direction, and their interactions. Field experiments were conducted in five different planting areas. The results confirmed that when the moisture content was controlled within the range of 13% to 17%, the grain crushing force could be maintained at a stable level between 137 N and 182 N, Simultaneously, the crushing rate was reduced to a minimum value of 2.15%±0.43%, generally remaining within a favorable range of 1.09% to 3.34%. The research findings provide a necessary theoretical basis for improving the design of key components of harvesting machinery.

摘要

本研究针对大豆机械收获过程中的籽粒破碎问题，系统分析含水率对其力学破碎特性的影响，采用单因素试验和多因素正交试验方法，通过压缩试验并结合高速摄像技术记录籽粒破碎过程，对含水率、加载速度、压缩方向及其交互作用进行定量分析。在五个不同种植区域开展田间试验，结果验证当含水率控制在 13%-17%范围内时，籽粒压破力能够保持在137N~182N 之间的稳定水平，此时破碎率降至最低值2.15%±0.43%，总体维持在1.09%~3.34%的良好范围内。研究结果为改进收获机械关键部件的设计提供了重要的理论依据。

INTRODUCTION

Soybeans are a vital global source of oil and protein, holding an indispensable role in modern agriculture and the food industry (*Anderson et al., 2019; Mariashibu et al., 2013*). In 2023, the area dedicated to soybean cultivation in China reached 10.47 million hectares, yielding a total of 20.84 million tons. However, this production is insufficient to meet domestic demand, leading to substantial annual imports of 99.409 million tons (*National Bureau of Statistics, 2024; Wang, 2024; National Agricultural and Rural Economic Operation, 2024*). As global demand continues to increase, large-scale mechanized harvesting has become essential for enhancing efficiency and reducing costs.

Nevertheless, high seed breakage rates during mechanical harvesting significantly impact both harvest efficiency and product quality (*Gao et al., 2010; Liu et al., 2017; Fernando et al., 2004*). Research has demonstrated that seed moisture content is a critical factor influencing breakage, as it affects the mechanical properties of seeds and, consequently, their integrity during harvest (*Chen et al., 2010; Krishnan et al., 2014*). Therefore, improving soybean harvest quality, reducing seed breakage rates, and minimizing harvest losses to decrease import dependency have become particularly crucial objectives. Theoretically, lowering seed breakage rates is an effective strategy to enhance harvest quality, with current domestic mechanized harvesting exhibiting an approximate 5% breakage rate, highlighting an urgent need for optimization.

Domestic and international scholars have conducted extensive research that has yielded significant findings regarding the relationship between seed moisture content and mechanical properties. *Waelti et al. (1969)* pioneered the quantification of moisture content's impact on breakage rates through mathematical relationships, establishing a foundation for subsequent research. *Chowdhury et al. (1975),* in corn kernel studies, demonstrated that seed breakage rates increase significantly with rising moisture content, indicating

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that variations in moisture directly influence seed mechanical behavior. *Zhang et al. (2017)* further revealed that the chemical composition and moisture content of soybeans significantly affect their hardness, with moisture levels playing a crucial role in mechanical properties and breakage characteristics. Additionally, *Resende et al. (2013)* investigated the mechanical properties of brown rice and paddy under varying moisture contents, finding enhanced compression resistance at higher moisture levels, which highlights the key role of moisture content in determining the compression resistance of different crops. *Kang et al. (2021)* conducted compression tests to analyze the influence of moisture content on breakage rates across various soybean varieties, further expanding the application of moisture content in soybean harvesting processes. In other crop studies, *Dong et al. (2009)* discovered a negative correlation between moisture and mechanical properties within specific moisture ranges during mechanical tests on rice, providing valuable insights into understanding seed breakage behavior at different moisture contents. *Yang et al. (2015)* studied the friction characteristics of millet seeds, while *Qiu et al. (2019)* explored the effects of millet variety and moisture content on mechanical properties. *Teng et al. (2020)* investigated the influence of external factors on the mechanical characteristics of different soybean varieties. These research outcomes have enriched theories and provided a solid theoretical foundation.

Building on these research foundations, this study employs soybean seed moisture content as the primary experimental variable. Through systematic compression experiments, high-speed imaging technology is innovatively utilized to record seed breakage processes in real time, comprehensively analyzing the effects and interactions of moisture content, loading speed, and force direction on seed breakage rates. Furthermore, by combining field trial data from multiple cultivation regions, the practical impact of moisture content on seed breakage rates is verified, key mechanical properties are identified as evaluation indicators, and ultimately the optimal moisture content range is determined for minimizing breakage rates. Results indicate that controlling moisture content between 13% to 17% can reduce seed breakage rates to 2.15%$\pm$0.43%, which is significantly better than the current mechanized harvesting level of approximately 5%. This research provides a scientific basis for optimizing soybean mechanical harvesting parameters and improving harvest quality, while also offering important theoretical support and engineering references for enhancements in harvesting machinery component design. Ultimately, it achieves the goals of reducing seed breakage rates, minimizing harvest losses, and enhancing soybean harvest quality, contributing to a decreased dependency on soybean imports.

MATERIALS AND METHODS

Experimental Protocol

This study systematically investigates the effects of moisture content, loading speed, and force direction on the breakage characteristics of soybean seeds. Six distinct moisture content levels (8%, 10%, 14%, 19%, 23%, and 27%) were precisely prepared using drying and spray humidification methods. In the compression tests, moisture content, loading speed, and direction were established as experimental variables to comprehensively analyze seed breakage characteristics, with compression failure force serving as the evaluation index. Notably, high-speed imaging technology was employed to capture and record real-time dynamic changes during seed breakage, providing direct evidence for an in-depth analysis of seed breakage characteristics under varying conditions.

To ensure the scientific validity and reliability of experimental data, moisture content adjustments and measurements strictly adhered to the national standard "Grain and Oilseed Inspection - Moisture Determination Method" (GB/T 5497-1985) (*State Administration of Grain and Reserve, 1985*). Additionally, mechanical testing procedures followed to the American Society for Testing and Materials (ASTM) "Standard Practices for Force Calibration and Verification of Testing Machines" (ASTM E4-24) (*ASTM International, 2024*). During the moisture adjustment process, the amount of water to be added or removed was precisely calculated using the equation (1) (*Faryal Fatima et al., 2025*).

$$W = m \times \frac{M_t - M_i}{1 - M_t} \tag{1}$$

where: W represents the target water quantity to be added or removed; m represents the initial sample mass; M_t represents the target moisture content; M_i represents the initial moisture content.

Experimental Equipment

In this experiment, the PM-8188-A moisture meter, manufactured by KETT Corporation, USA (as shown in Figure 1(a)), was utilized to measure the moisture content of the samples. This device maintains a measurement error within ±0.3%, ensuring precise moisture content measurements. To further enhance the reliability and representativeness of the data, each sample was measured five times, and the average value was recorded as the final result.

The mechanical testing system utilizes the Instron 3340 Series single-column tabletop universal testing machine, manufactured by Instron Corporation, USA, as illustrated in Figure 1(b). This equipment provides load and strain measurement accuracy within ±0.5%, ensuring reliable support for the precise acquisition of mechanical data. The testing machine system primarily consists of the following core components: a Force Sensing System that measures the force applied to the sample, equipped with a built-in Force Sensor for accurate force data collection; a Controller that precisely adjusts the loading rate and monitors the entire testing process; and the Computer-Aided Data Acquisition and Display Unit, located on the left side of Figure 1(b), which facilitates real-time data acquisition, display, and storage, thereby making the experimental process and results more intuitive and manageable.

To achieve high-precision recording of the dynamic fracture behavior of soybean grains under applied force, the testing system incorporates a Phantom series high-speed camera manufactured by Vision Research Inc. (VRI), USA, as illustrated on the right side of Figure 1(b). This camera offers a high resolution of 1280×800 pixels and a maximum frame rate of up to 76,000 frames per second, ensuring comprehensive capture of the grain's transient fracture process. Furthermore, the system is equipped with specialized power source and control components to ensure stable operation of the entire setup and facilitate reliable data acquisition.

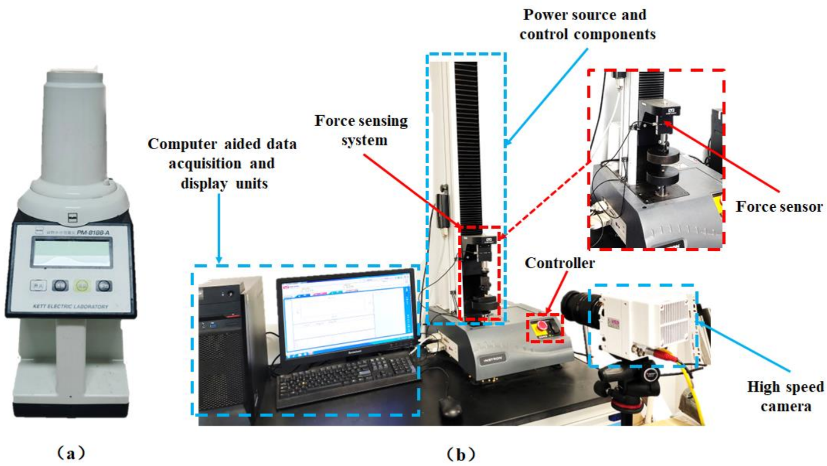

Fig. 1 - Composition of experimental equipment and testing system

(a) PM-8188-A Moisture Meter; (b) Instron 3340 Series Universal Testing Machine and Phantom High-Speed Imaging System.

Experimental Methods and Procedures

In the soybean grain compression test, the stable loading and precise stopping of the upper indenter and fixed platform must be carefully controlled to ensure the reliability of the test data. As illustrated in Figure 2, soybean grains are positioned horizontally at the center of the fixed platform. Through precise manual adjustment, the upper indenter is gradually lowered until the gap between the indenter and the soybean grain is less than 5 mm. This predetermined gap helps form a stable contact surface at the beginning of loading, effectively reducing stress fluctuations caused by rapid loading. During compression, the high-speed camera's angle and position are adjusted to clearly capture the complete fracture process of the soybean grain under compression. This image capture technique not only records the progressive deformation characteristics of the soybean grain but also provides reliable, visual data support for subsequent force analysis and fracture mechanism studies. When irreversible morphological changes in the soybean grain (such as cracking or fracturing) are observed, the downward movement of the upper indenter is immediately stopped to prevent excessive fracturing from interfering with experimental data.

Figure 2 illustrates the force application on soybean grains from different directions, covering three typical modes of compression force application: (a) Vertical Compression, where the upper indenter applies force vertically onto the grain; (b) Lateral Compression, which simulates horizontal lateral compression acting on the grain; and (c) Symmetrical Horizontal Compression, achieving symmetric loading on the grain in the horizontal direction. For each compression mode, the deformation process of the soybean grain between the upper indenter and the fixed platform is visually presented using corresponding mechanical schematic diagrams. The design of these three different loading modes facilitates a comprehensive analysis of the fracturing behavior of soybean grains under various force conditions encountered during actual harvesting. This approach provides systematic experimental support for a multi-perspective analysis of the mechanical properties of soybean grains.

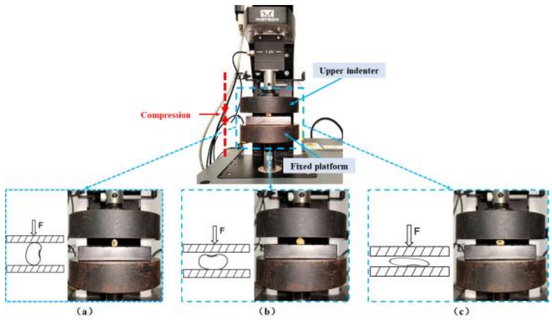

Fig. 2 - Schematic diagram of soybean grain compression loading

(a) Vertical Compression; (b) Lateral Compression; (c) Symmetrical Horizontal Compression.

RESULTS

Analysis of the Single-Factor Effect on Crushing Force

In this experiment, the moisture content of soybean grains, machine loading speed, and compression orientation were selected as the primary test factors, with the crushing force of the grains serving as the evaluation metric. A systematic analysis was conducted to observe the variation patterns of crushing force under different conditions. A single-factor analysis approach was adopted, meaning that while keeping two other test factors constant, the working parameters of the factor under study were adjusted to perform compression tests. This approach enabled an investigation into each test factor's influence on the soybean grains' crushing force.

Based on the Compression Force-Displacement curve in Figure 3 and the staged images of a compression fracture in Figure 4, this study systematically analyzes soybean grains' force variation and fracturing behavior during the Symmetrical Horizontal compression process. High-speed imaging technology was used to fully capture the entire process from initial loading to final fracture, providing an intuitive basis for an in-depth exploration of the compression fracture mechanism of soybean grains. Figure 3 quantitatively displays the changes in crushing force with displacement across different stages. In contrast, Figure 4 presents the morphological evolution and internal structural changes of the grains at five critical moments, making the physical process of compression fracture more visually accessible.

The compression fracture process of soybean grains can be distinctly divided into five characteristic stages. In the initial non-contact stage (0–0.2 mm, Stage 1), as shown in Figure 4(a), the upper platen has not yet made contact with the grain, and the crushing force remains zero. Upon entering the initial contact stage (0.2–0.6 mm, Stage 2), as shown in Figure 4(b), the force-displacement curve exhibits slight fluctuations, and preliminary indentations appear on the grain surface. In the subsequent linear deformation stage (0.6–1.4 mm, Stage 3), as depicted in Figure 4(c), the force continues to increase, minor cracks form within the grain, and the force-displacement relationship shows a significant linear trend, indicating that the grain retains substantial structural rigidity. Upon reaching the unloading stage (1.4–1.6 mm, Stage 4), as illustrated in Figure 4(d), the applied force reaches a critical value (approximately 130–140 N), with prominent internal cracks developing, and localized collapse and separation occur. The crushing force begins to decrease, indicating a gradual loss of the grain's load-bearing capacity. In the final irreversible stage (1.6–1.8 mm, Stage 5), as shown in Figure 4(e), continuous pressure causes internal cracks to expand further, ultimately leading to complete structural failure. The force-displacement curve stabilizes, indicating that the grain has fully entered an irrecoverable fractured state. This process vividly illustrates the complete mechanical behavior of soybean grains, transitioning from elastic deformation to final fracture.

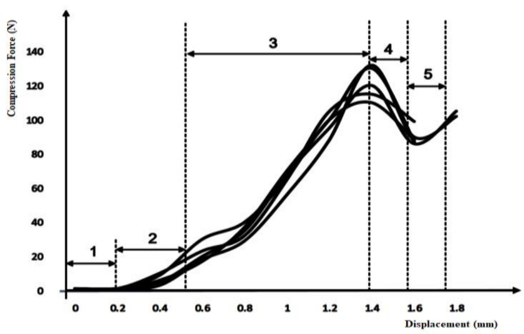

Fig. 3 - Compression Force-Displacement Curve of Soybean Grain

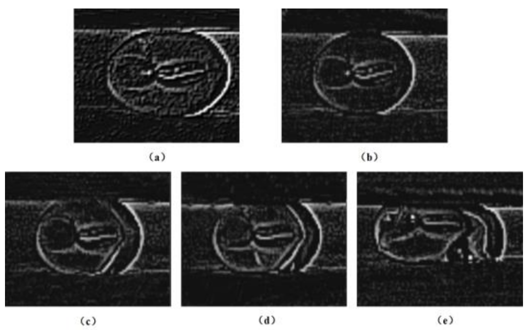

Fig. 4 - Staged images of Soybean Grain Compression Fracture Process

Effect of Moisture Content on Crushing Force

This experiment systematically investigated the impact of six different moisture content levels (8%, 10%, 14%, 19%, 23%, and 27%) on the crushing force of soybean grains, with the loading direction set to Symmetrical Horizontal compression and the loading speed maintained at a constant 30 mm/min. The Moisture Content-Crushing Force curve, is shown in Figure 5, visually depicting the trend in crushing force as moisture content varies. The curve reveals that, under low moisture content (8%), the crushing force reaches approximately 160 N, indicating a denser and harder internal structure with strong brittleness. Consequently, cracks propagate rapidly during compression, requiring a higher crushing force. As the moisture content rises to around 13%, the crushing force peaks at roughly 190 N, before dropping significantly to around 80 N as the moisture content continues to increase to 28%, exhibiting an initial increase followed by a decrease.

This trend is primarily due to changes in the internal structure of the grains caused by increasing moisture content. At lower moisture levels (8%-13%), moderate moisture increases the bonding force between cell walls, enhancing the overall strength of the grain. However, when moisture content rises beyond 13%, excessive water increases the grain's flexibility, leading to more plastic deformation under compression and thus a notable reduction in crushing force. This observation highlights the critical regulatory role of moisture content on the physical properties and compressive strength of soybean grains, offering a theoretical basis for determining optimal moisture levels for harvesting and processing.

Effect of Compression Orientation on Crushing Force

In this experiment, with the moisture content of soybean grains maintained at 14% and a loading speed of 30 mm/min, the influence of three different compression directions—Lateral Compression, Symmetrical Horizontal Compression, and Vertical Compression—on the crushing force was systematically studied. The Compression Direction-Crushing Force curve, plotted shown in Figure 6, clearly illustrates the trend in crushing force according to the compression orientation. From the curve, it can be observed that the crushing force is highest under Symmetrical Horizontal compression (approximately 186 N), followed by Lateral compression (approximately 175 N), and lowest under vertical compression (approximately 162 N). This demonstrates that variations in compression direction significantly impact the compressive strength and mechanical behavior of soybean grains.

The observed differences in crushing force are primarily due to the unique force characteristics and structural properties of soybean grains under each compression orientation. Under Symmetrical Horizontal compression, the platen applies force perpendicular to the cotyledon surfaces, with the direction of force aligned with the cotyledon’s bonding interface. The large contact area and even distribution of force require a higher crushing force to induce fracture. In the Lateral compression state, the compression force directly acts on the cotyledon bond, causing cracks to initiate in the middle area of the cotyledons, leading to localized damage between the seed coat and cotyledons and thus requiring a relatively lower crushing force. In vertical compression, the force is concentrated at the top of the cotyledon bond, leading to a highly localized stress point that results in stress concentration near the embryo, making fracture easier and thus yielding the lowest crushing force.

Effect of Loading Speed on Crushing Force

In this experiment, with the moisture content of soybean grains fixed at 14% and the compression direction set to horizontal, the effect of three different loading speeds (10 mm/min, 30 mm/min, and 45 mm/min) on the crushing force was systematically studied. The Loading Rate-Crushing Force curve, shown in Figure 7, clearly illustrates the trend in crushing force with changes in loading speed. From the curve, it can be observed that at a loading speed of 10 mm/min, the crushing force is the lowest (approximately 140 N), indicating that at slower loading speeds, internal stress propagation within the grain is slower, making the structure more susceptible to damage under sustained pressure, thereby showing lower compressive strength.

As the loading speed increases to 30 mm/min, the crushing force significantly rises to around 185 N, an increase of 32.1%. This indicates that a higher loading rate accelerates stress transmission within the grain, requiring the grain to withstand greater pressure before fracturing. However, when the loading speed is further increased to 45 mm/min, the crushing force slightly decreases (to about 182 N), suggesting that at very high loading speeds, the grain’s load-bearing stress reaches a stable limit, and further increases in loading speed do not significantly enhance crushing force. This finding reveals an optimal range of loading speed for maximizing crushing force: excessively low loading speeds reduce the grain’s compressive performance, while excessively high speeds fail to further increase crushing force.

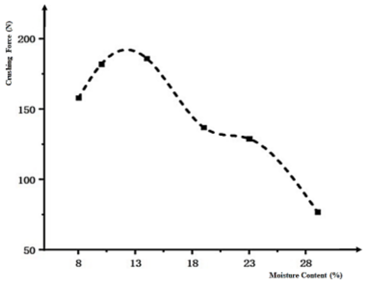

Fig. 5 - Moisture Content-Crushing Force Curve for Soybean Grain

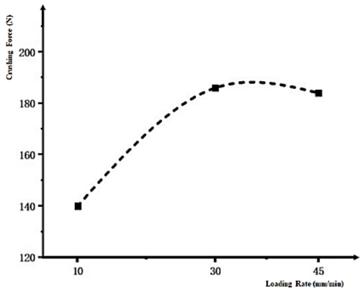

Fig. 6 - Compression Direction-Crushing Force Curve for Soybean Grain

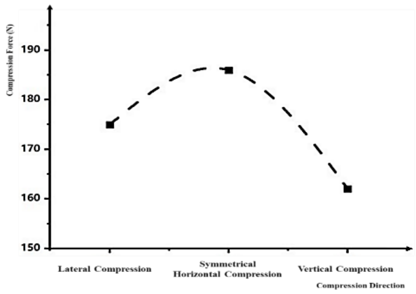

Fig. 7 - Loading Rate-Crushing Force Curve

Interaction Analysis of Multiple Factors Affecting Crushing Force

To investigate the interactive effects of moisture content, compression orientation, and loading speed on the crushing force of soybean grains, a three-factor, three-level regression orthogonal experimental design was adopted in this study, with crushing force Y_1 as the evaluation index. As shown in Table 1, the experiment selected moisture content (A), loading speed (B), and compression orientation (C) as the main influencing factors, each set at three levels: -1, 0, and 1. Specifically, moisture contents were set at 8%, 14%, and 23%; loading speeds at 10 mm/min, 30 mm/min, and 45 mm/min; and compression orientations included vertical compression (2), symmetrical horizontal compression (3), and lateral compression (4). Each experiment was repeated five times, and the average value was used as the final result to ensure data reliability.

Table 2 provides the specific orthogonal experimental scheme and results, comprising 17 test combinations. From the results, it is evident that crushing force Y_1 varies significantly across different combinations of factor levels: the minimum value recorded was 43 N (Test No. 6, with high moisture content, medium loading speed, and vertical compression), while the maximum reached 198 N (Test No. 14, with all factors at the medium level). A comparison of the center point replicates (Test Nos. 13-17) shows that when all three factors are at the 0 level, the crushing force is relatively stable, fluctuating between 176 N and 198 N, with an average of 185.6 N. This suggest that under moderate parameter conditions, soybean grains exhibit good mechanical stability. Furthermore, the results reveal an important pattern: moisture content has the most significant effect on crushing force, followed by loading speed, with compression orientation having a comparatively minor impact. Under low moisture content conditions (-1 level), the crushing force remains generally high regardless of changes in loading speed and compression orientation. As moisture content increases to the 1 level, the crushing force significantly decreases, consistent with the results from the single-factor experiments.

Table 1

Experimental Factor Levels

Level	Factor		
	Moisture Content [%]	Loading Speed [mm/min]	Compression Orientation
-1	8	10	2
0	14	30	3
1	23	45	4

Note: The numbers 2, 3, and 4 represent Vertical compression, Symmetrical Horizontal compression, and Lateral compression, respectively.

Table 2

Orthogonal Experimental Design and Results

Experimental Number	A	B	C	Y_1
1	-1	-1	0	152
2	1	1	0	195
3	-1	0	-1	64
4	1	0	-1	43
5	-1	0	1	89
6	0	1	-1	184
7	0	-1	1	132

Experimental Number	A	B	C	Y_1
8	0	1	1	196
9	0	0	0	186
10	0	0	0	198
11	0	0	0	180

Note: A represents moisture content (%), B represents loading speed (mm/min), C represents compression orientation, and Y_1 represents crushing force (N).

Based on the experimental results in Table 2, variance analysis of crushing force was conducted using Design-Expert 10.0 software. The analysis results indicate that moisture content (A), loading speed (B), compression orientation (C), and their interactions significantly influence the crushing force of soybean grains ($P < 0.0001$), demonstrating that the established model has strong statistical significance. The second-order polynomial model obtained through regression analysis is shown in Equation (2):

$$Y_1 = 185.6 + 31.00 * A - 7.75 * B + 11.00 * C + 26.00 * AB + 1.50 * AC - 2.00 * BC - 63.30 * A^2 + 25.20 * B^2 - 54.80 * C^2 \tag{2}$$

where: A^2, B^2 and C^2 are the quadratic terms of each factor; and AB, AC, and BC are the interaction terms between factors.

From the analysis of the regression coefficients, it can be observed that, in terms of linear effects, the coefficient of moisture content (A) is the largest (31.00) and positive, indicating that moisture content has the strongest positive influence on crushing force. The loading speed (B) coefficient is -7.75, showing a negative correlation with crushing force, while the compression orientation (C) coefficient is 11.00, suggesting a moderate positive impact on crushing force. In terms of interaction effects, the interaction coefficient between moisture content and loading speed ($AB = 26.00$) is the largest, showing a significant synergistic effect between the two. The interaction between moisture content and compression orientation ($AC = 1.50$) is weaker, while the interaction effect between loading speed and compression orientation ($BC = -2.00$) shows a slight antagonistic effect. For the quadratic terms, the absolute value of the moisture content's quadratic coefficient ($A^2 = -63.30$) is the largest, followed by compression orientation ($C^2 = -54.80$), with loading speed ($B^2 = 25.20$) being relatively smaller. This suggests the existence of optimal value points for moisture content and compression orientation concerning their effect on crushing force. This conclusion is corroborated by the specific experimental data.

Table 3

Analysis of Variance (ANOVA) for the Regression Model

Crushing Force (N)					
Variance Source	**Sum of squares**	**degree of freedom**	**mean square**	**F value**	**P value**
Model	44476.06	9	4941.78	78.67	< 0.0001***
A	7688.00	1	7688.00	122.39	< 0.0001***
B	480.50	1	480.50	7.65	0.0279*
C	968.00	1	968.00	15.41	0.0057**
AB	2704.00	1	2704.00	43.05	0.0003***
AC	9	1	9.00	0.14	0.7163
BC	16.00	1	16.00	0.25	0.6293
A^2	16871.12	1	16871.12	268.59	< 0.0001***
B^2	2673.85	1	2673.85	42.57	0.0003***
C^2	12644.38	1	12644.38	201.30	< 0.0001***
Lack of Fit	156.50	3	52.17	0.74	0.5825

*Note: *** indicates $P < 0.001$ (extremely significant), ** indicates $P < 0.01$ (highly significant), and * indicates $P < 0.05$ (significant).*

The ANOVA results in Table 3 show that the factors of moisture content (A), compression orientation (C), and loading speed (B) all have a significant effect on the crushing force of soybean grains. From the F-values in the ANOVA, the overall F-value for the model is 78.67 ($P < 0.0001$), which is far above the critical value required for significance, indicating that the model has a high degree of reliability.

The F-values for the main effects are as follows: moisture content (A) is 122.39 ($P < 0.0001$), compression orientation (C) is 15.41 ($P = 0.0057$), and loading speed (B) is 7.65 ($P = 0.0279$), aligning with their influence on crushing force in the order of moisture content > compression orientation > loading speed. Among the interaction effects, the interaction between moisture content and loading speed (AB) is the most significant, with an F-value of 43.05 ($P = 0.0003$, extremely significant). In contrast, the interactions between moisture content and compression orientation (AC) and between loading speed and compression orientation (BC) are weaker, with F-values of 0.14 ($P = 0.7163$) and 0.25 ($P = 0.6293$), respectively, neither reaching significance ($P > 0.05$).

Examining the sum of squares from the variance sources, the total sum of squares for the model is 44,476.06 with 9 degrees of freedom, and a mean square of 4,941.78, indicating that the model effectively explains the major portion of the variability in crushing force. F-value analysis of the quadratic terms shows that A^2 has the highest F-value (268.59, $P < 0.0001$), followed by C^2 (201.30, $P < 0.0001$) and B^2 (42.57, $P = 0.0003$), all reaching extreme significance levels ($P < 0.001$), demonstrating the strong nonlinear effects of these three factors on crushing force. Specifically, the sum of squares for moisture content (A) is 7,688.00, and the sum of squares for A^2 is 16,871.12, further confirming the significant impact of moisture content on crushing force.The lack of fit sum of squares is 156.50 with 3 degrees of freedom, a mean square of 52.17, and an F-value of 0.74 ($P = 0.5825 > 0.05$), indicating that the lack of fit is not significant, which further validates the reliability of this regression model.

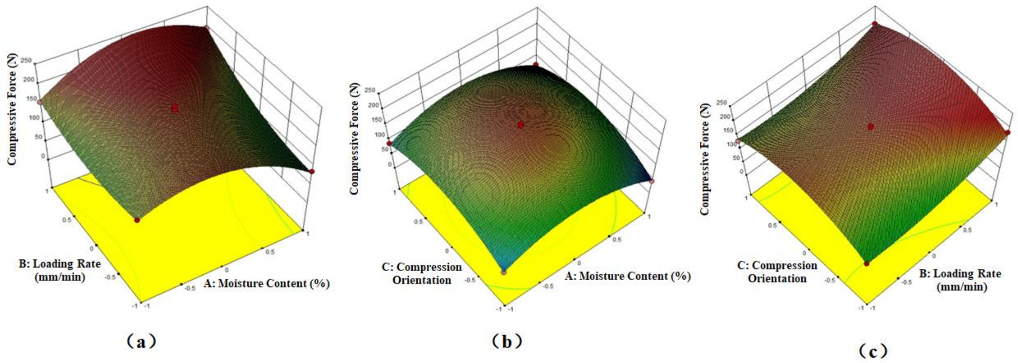

Fig. 8 - Interaction Response Surface of Soybean Seed Crushing Force

(a) Interaction between moisture content and loading speed; (b) Interaction between moisture content and compression orientation; (c) Interaction between compression orientation and loading speed.

Figure 8(a) illustrates the interaction effect between moisture content (A) and loading speed (B) on the crushing force of soybean seeds. When moisture content is fixed, the crushing force of seeds increases gradually with the rise in loading speed (B). This phenomenon can be reasonably explained by the increase in kinetic energy as the loading speed enhances, which in turn raises the crushing force. With a constant loading speed, an increase in moisture content alters the internal structure of the seed, making it softer, which leads to a trend where crushing force first increases and then decreases. As loading speed shifts from high to low levels while moisture content rises, the crushing force initially increases and then decreases noticeably. The response surface plot clearly shows that the maximum crushing force occurs at around 14% moisture content, indicating that a moderate moisture level helps preserve the structural integrity of the seeds. This significant interaction reflects the combined effect of moisture content and loading speed on crushing force.

Figure 8(b) demonstrates the interaction between moisture content (A) and compression orientation (C) on seed crushing force. At a low compression orientation level, an increase in moisture content leads to a decrease in crushing force, which is more pronounced than the effect of loading speed. As compression orientation shifts from a low to a high level, crushing force exhibits a trend of initially increasing and then decreasing. The undulations in the response surface indicate a nonlinear interaction between moisture content and compression orientation, with the interaction effect most evident at a medium compression orientation level. However, variance analysis reveals that this interaction has an F-value of only 0.14 ($P = 0.7163 > 0.05$), suggesting that although a trend is observable on the response surface, its impact is not statistically significant.

Figure 8(c) illustrates the interaction between compression orientation (C) and loading speed (B) on seed crushing force. When the compression orientation is at the 0 level, an increase in loading speed enhances the impact force, thereby increasing the crushing force. When both loading speed and compression orientation reach high and low levels, respectively, the crushing force reaches its peak, as the machine's kinetic energy is maximized under high loading speed, with compression force primarily applied to the cotyledon surface, significantly increasing the crushing force. The response surface's overall shape suggests that compression orientation’s effect becomes more prominent in high-loading-speed regions, highlighting a more significant interaction between the two factors under high-speed conditions. However, variance analysis shows that this interaction's F-value is only 0.25 ($P = 0.6293 > 0.05$), indicating that while observable on the response surface, it lacks statistical significance.

FIELD EXPERIMENT

Field Experiment Design and Preparation

The field experiment was conducted in strict accordance with national standards GB8097-2008 "Test Methods for Harvest Machinery Combine Harvesters" and GB/T 35488-2017 "Monitoring System for Combine Harvesters," ensuring compliance with regulatory requirements. The experiment site was selected at the high-standard soybean farmland testing base in Suixi County, Anhui Province (Figure 9 (b)). This site features fertile soil, well-developed irrigation facilities, and organized field plots, providing ideal conditions for the experiment. As shown in the images, the test plots are well-leveled, with uniform soybean growth and well-supported infrastructure, all contributing to the reliability of the experimental data.

For this experiment, the Lovol Gushen GM80 (4LZ-8M5) grain combine harvester was selected (Figure 9(a)). This model demonstrates strong adaptability and reliable operational performance. As shown in the image, the harvester is well-maintained, with a clean appearance and fully functional operation components.

a) b)

Fig. 9 - Field Experiment Images

(a) GM80 combine harvester used in the experiment; (b) High-standard soybean farmland test base

Field Experiment Procedure

In this field experiment, the experimental area was first divided into five sections, each 10 meters long. On the first day of the experiment, soybean samples were collected from these sections at 8:00, 10:00, 12:00, 14:00, and 16:00, and the moisture content of each sample was manually measured. After that, a harvester was used to harvest the soybeans in each section at a speed of 4.4 km/h. Three groups of samples were randomly taken from the harvested soybeans and placed in sealed bags to prevent moisture changes, as shown in Figure 10, where (a) shows the experimental samples placed in sealed bags, ensuring the representativeness and sealing of the samples. Subsequently, the total mass of the soybean samples in each sealed bag was weighed one by one, and the corresponding weight data was recorded. The breakage rate analysis was conducted for each group of samples, manually selecting the broken soybean seeds from each group (as shown in Figure (b)), and weighing the mass of the broken parts. Figure (c) shows the weighing process of the broken seeds, ensuring the accuracy and reliability of the data. Finally, to determine the crushing condition for each sample group, the crushing rate was calculated using Equation (3)（*Liu et al., 2021*）based on the actual data for each sample:

$$n = \frac{N}{M} \tag{3}$$

where: n represents the crushing rate of the seeds, N denotes the weight of the damaged seeds in the sample, and M is the total weight of the seeds in the sample. By analyzing the crushing rate of samples collected from various sections and time points, along with the sample total weight measurement process shown in Figure 10(d), a large amount of empirical data was obtained. This provides reliable foundational data to support the optimization of soybean harvesting processes and equipment, which is of significant practical importance in reducing seed damage during the harvesting process.

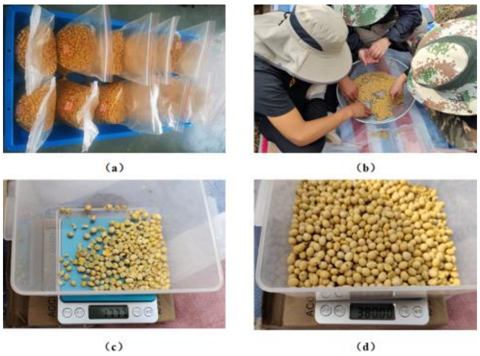

Fig. 10 - Seed Crushing Processing Images

(a) Experimental samples; (b) Selection of damaged seeds; (c) Weighing of damaged seeds; (d) Weighing of samples

Field Experiment Data Analysis and Results

Table 4

Partial Field Experiment Data

NO	Calibrated Moisture Content [%]	Damaged Soybean Mass [g]	Sample Mass [g]	Crushing Rate [%]
1	15.52	3.87	356.61	1.09
2	14.45	6.23	406.54	1.53
3	16.02	9.62	412.65	2.33
4	17.58	8.43	252.36	3.34
5	18.61	16.23	414.62	3.91
6	22.51	17.13	335.24	5.11
7	20.63	17.77	380	4.68
8	16.53	8.84	361.64	2.44
9	20.49	8.19	382.19	2.14
10	19.64	9.03	330.24	2.73
11	16.31	9.97	397.41	2.51
12	15.58	8.05	351.33	2.29

Analysis of the experimental data in Table 4 reveals that moisture content significantly affects seed breakage during mechanized harvesting. When the moisture content exceeds 17%, the breakage rate increases notably. For example, samples numbered 5, 6, and 7 have moisture contents of 18.61%, 22.51%, and 20.63%, with corresponding breakage rates of 3.91%, 5.11%, and 4.68%. In contrast, when moisture content is in the range of 13%-17%, the breakage rate remains low. For instance, samples numbered 1, 2, and 3 have moisture contents of 15.52%, 14.45%, and 16.02%, with breakage rates of only 1.09%, 1.53%, and 2.33%. Furthermore, the total mass of samples ranged from 252.36g to 414.62g, ensuring the reliability and representativeness of the experimental results, providing valuable data support for moisture content control in soybean mechanized harvesting.

In summary, to effectively reduce seed breakage during mechanical harvesting and minimize soybean harvest losses, it is recommended to enhance field environment monitoring before harvest. Harvest timing should be carefully managed, especially during humid weather or when rain is forecasted. Regular monitoring of seed maturity and weather conditions is advised to maintain the moisture content of harvested seeds within the 13%-17% range. Coupled with appropriate harvester settings and precise operating methods, this will significantly reduce the breakage rate, thereby improving harvest quality and reducing post-harvest processing losses.

CONCLUSIONS

Field trials confirm that the optimal moisture content range for harvest is 13%-17%, resulting in the lowest seed breakage rate (2.15% ± 0.43%). To ensure high harvest quality, it is recommended to operate in the afternoon on sunny days, maintain a harvesting speed of 3-5 km/h, keep the drum speed at 400-450 r/min, and regulate the feed rate at 4-6 kg/s. Considering regional differences, the recommended moisture content for southern regions is 14%-16%, while northern regions can maintain a range of 15%-17%. Field trials further verify the significant impact of moisture content on seed breakage rates during mechanical harvesting. Tests conducted across different regions show that seeds with moisture content between 13%-17% exhibit lower breakage rates (1.09%-3.34%). These optimized parameter recommendations provide practical guidance for improving mechanized harvest quality, enhancing efficiency, and reducing harvest losses.

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