EXPERIMENTAL STUDY ON THE SHEAR MECHANICAL PROPERTIES OF CORN ROOT STUBBLE

/

玉米根茬的剪切力学性能实验研究

Hongjie YI[1], Xinzhu LIU*[1], Qiang HE[1], Zhen CHEN[1], Jianan DU[1], Lei XING[1]
[1] College of Mechanical Engineering, Jiamusi University, Jiamusi, Heilongjiang,154007, China
Tel: +8618845485459; E-mail: 18845485459@163.com

DOI: https://doi.org/10.35633/inmateh-78-107

***Keywords:** Corn stubble, shear mechanical properties, moisture content, loading speed, fiber saturation point, stubble crushing device, shear stress analysis*

ABSTRACT

The shear mechanical properties of corn stubble are fundamental to the design of high-efficiency crushing and stubble management equipment. However, the combined effects of moisture content and loading speed on these properties remain insufficiently characterized. In this study, maize root stubble (cv. 'Heyu 23') samples were collected and subjected to shear tests using a DDL 300 electronic universal testing machine under three moisture content levels (50–80%) and four loading speeds (5–50 mm/min), with 10 replicates per condition (total n = 120). The coefficient of variation (CV) ranged from 17.6% to 42.3%, indicating moderate to high variability depending on the test conditions. The shear stress exhibited a nonlinear, moisture-dependent response. The maximum shear stress (2.17 MPa) occurred at high moisture content (70–80%) and a medium loading speed (20 mm/min), while the minimum value (1.26 MPa) was observed at moderate moisture content (60–70%) and a low loading speed (10 mm/min). A critical moisture threshold of approximately 65% (fiber saturation point) was identified, below which brittle behavior dominates, and above which viscoelastic and lubricating effects prevail. These findings provide quantitative support for the design and operational parameter optimization of maize root stubble crushing equipment, particularly for cutting–kneading combined mechanisms and bionic stubble cutters.

摘要

玉米秸秆的剪切力学性能是高效粉碎和秸秆处理设备设计的基础。然而，含水率和加载速度对这些性能的综合影响仍缺乏充分的研究。在本研究中，采集了玉米秸秆（品种为和玉23）样本，并使用DDL - 300电子万能试验机进行了剪切试验。研究了三个含水率组（50% - 60%、60% - 70%和70% - 80%）和四种加载速度（5、10、20和50毫米/分钟），每个条件重复10次（共计120个样本）。变异系数（CV）范围为17.6%至42.3%，其中在含水率为70% - 80%、加载速度为10毫米/分钟时变异系数最小（17.6%），表明重复性最高；在含水率为60% - 70%、加载速度为50毫米/分钟时变异系数最大（42.3%），表明稳定性最差。剪切应力呈现出与含水率相关的非线性响应。最大剪切应力（2.17兆帕）出现在含水率为70% - 80%、加载速度为20毫米/分钟时，而最小剪切应力（1.26兆帕）出现在含水率为60% - 70%、加载速度为10毫米/分钟时。研究确定了一个临界含水率阈值，约为65%（纤维饱和点），低于该阈值时，秸秆表现出脆性特征；高于该阈值时，粘弹性和润滑效应占主导。这些研究结果为玉米秸秆粉碎设备的设计和运行参数优化提供了定量基准，特别是对于切割揉搓组合机构和仿生秸秆切割器。

INTRODUCTION

Corn (*Zea mays L.*) stands as one of the world's most vital cereal crops, serving as a cornerstone for food security, animal feed, and industrial raw materials (*Pei et al., 2026*). The Heilongjiang Province, a member of the world's three major "Golden Corn Belts", contributes significantly to this output. However, this high productivity is accompanied by a massive amount of agricultural residue, particularly corn stubble. Following mechanical harvesting, which is the predominant method of harvest, cornfields are left with 6-10 cm high stubble. This stubble, characterized by a thicker stem base, denser fiber arrangement, and higher lignin content compared to upper straw, poses a unique challenge for decomposition (*Che et al., 2024; Zhao et al., 2017*).

The incorporation of crop residues into the soil is a mainstream strategy for enhancing soil organic matter and fertility, aligning with policies like the “Heilongjiang Black Soil Protection and Utilization Regulations”. However, the effective management of corn stubble is critical. Inefficiently processed stubble can harbor soil-borne pathogens, reduce soil microbial activity, and exacerbate weed and disease issues in subsequent cropping cycles (*Ramm et al., 2024; Tursun et al., 2016*). Stubble management is typically conducted in two seasons: autumn and spring. Autumn stubble management, occurring during the ~30-day window post-harvest before soil freeze, benefits from higher stubble moisture content. While this condition increases tool wear and energy consumption, it promotes soil moisture conservation and offers a longer window for straw decomposition over winter, significantly enhancing organic matter accumulation. Conversely, spring management, during the ~20-day post-thaw period, processes drier stubble, which is easier to fragment and allows for immediate seedbed preparation. However, this approach risks competing with planting schedules and leads to soil moisture loss, potentially compromising spring soil moisture content (*Singh et al., 2024*).

Recognizing that the robust basal stalk of the corn stubble is the most challenging component to fragment, researchers have extensively studied its mechanical properties to inform the design of high-efficiency crushing devices.

For instance, Liu et al. investigated the axial compression, radial compression, and bending characteristics of corn stalks (*Liu et al., 2026*), while Li et al. focused on the shear mechanical properties of silage corn stalks (*Li S.B. et al., 2024*). Other studies have explored the crushing mechanical properties, the compression and bending of fresh stalks, and the tensile and shear characteristics of corn stalk rind (*Ramm et al., 2024*). Despite these efforts, existing straw crushers, predominantly of the single-action chaffing or hammer-milling type, often fail to produce the fine particles (generally ≤2 mm) required for rapid composting or the fragmented stubble (≤10 cm) needed for field incorporation. A critical research gap remains: the design of a dedicated stubble crushing device that integrates sequential cutting and kneading actions, and the comprehensive optimization of its material conveying and production performance.

Therefore, the overarching goal of this study is to experimentally characterize the shear mechanical properties of corn stubble under varying moisture content and loading speed conditions, thereby providing quantitative benchmarks for the design and operation of stubble crushing devices. The specific objectives are: (1) to accurately measure the maximum shear stress of corn stubble across three moisture content ranges (50–60%, 60–70%, and 70–80%) and four loading speeds (5, 10, 20, and 50 mm/min); (2) to evaluate the repeatability and stability of these measurements using the coefficient of variation (CV); (3) to identify the critical moisture threshold (fiber saturation point) at which the shear mechanical behavior transitions from brittle to viscoelastic-dominated; and (4) to elucidate the interactive effects of moisture content and loading speed on shear stress, thereby providing practical recommendations for selecting operational parameters (e.g., cutting speed and timing) for stubble management equipment. The findings are expected to directly inform the design of cutting-kneading combined mechanisms and bionic stubble cutters, without overextending into detailed device prototyping or discrete element modeling, which are beyond the present scope.

MATERIALS AND METHODS

This section details the materials and procedures used to characterize the shear mechanical properties of corn stubble, providing essential parameters for the design and optimization of the stubble crushing device.

Test material preparation

The corn stubble (Zea mays L. cv. ‘Heyu 23’), a widely cultivated variety in the Jiamusi region, was selected as the test material. In early April 2025, a total of 200 stubble samples were collected from a single field with uniform growth conditions (plant spacing: 10 cm; row spacing: 20 cm). To ensure sample consistency, only straight, undamaged, and pest-free stubble specimens from the same growth cycle were chosen. The samples were carefully cleaned to remove soil and fibrous roots, retaining only the 10 cm basal stalk segment above the main root crown (Fig. 1, 2). The prepared samples were stored in a cool, shaded location to minimize moisture loss prior to testing. The moisture content of the collected stubble samples was measured and found to range from 52.19% to 77.96%, representing the typical autumn harvest conditions in the region.

Fig. 1 - Corn root residue

Fig. 2 - Corn root stubble after soil removal and weed removal

Equipment and Instrumentation

The primary equipment used for the shear tests included:

Universal Testing Machine: A DDL-300 electronic universal testing machine (Changchun Testing Machine Research Institute Co., Ltd., China), equipped with a custom straight-knife-edge shear fixture (blade thickness: 2 mm). The machine has a maximum compressive/shear force capacity of 300 kN, operates at 220 V, and provides a displacement accuracy of ±0.5% of the indicated value.

Drying Oven: A 101-1 type digital display forced-air drying oven (Hebi San De Instrument Co., Ltd., China), with a 220 V operating voltage, 2 kW rated power, and an adjustable temperature range of 0 to 300°C.

Measurement Tools: A digital vernier caliper (accuracy: 0.02 mm) and an electronic precision balance (accuracy: 0.0001 g) were used for dimensional and mass measurements, respectively. Standard scissors and other auxiliary tools were used for sample preparation.

The experimental setup is illustrated in Figures 3 and 4. All tests were conducted under controlled laboratory conditions at a constant temperature of 20°C and relative humidity between 25% and 40%.

Fig. 3 - Electronic Universal Testing Machine

Fig. 4 - Digital Display Forced-Draft Drying Cabinet

Experimental design and procedure

Shear tests were conducted using a custom-designed fixture to securely clamp the corn stubble specimens. The shearing point was consistently positioned at 2–9 cm above the main root crown (i.e., the basal stalk) to represent the primary cutting zone in field stubble management. All tests were performed under controlled environmental conditions at a constant temperature of 20°C and a relative humidity range of 25%–40%.

Due to the presence of nodes and the inherently non-uniform diameter of corn stubble—characterized by an approximately elliptical cross-section—a systematic measurement protocol was adopted. For each specimen, the diameter was measured at three distinct positions (upper, middle, and lower sections). At each position, two orthogonal diameter measurements were taken, yielding a total of six measurements per specimen. The average of these six values was calculated and recorded as the representative diameter for that specimen.

The experimental design incorporated two independent variables: moisture content and loading speed. Three moisture content groups were established: Group Ⅰ (50%–60%), Group Ⅱ (60%–70%), and Group Ⅲ (70%–80%). Within each moisture content group, four loading speeds were applied: 5, 10, 20, and 50 mm/min. To account for natural variability and to ensure statistical reliability, each combination of moisture content and loading speed was replicated 10 times. This resulted in a total of 120 individual shear tests (3 moisture levels × 4 loading speeds × 10 replicates). During each test, the DDL-300 universal testing machine automatically recorded the force-displacement curve, from which the maximum shear force was extracted for subsequent analysis.

RESULTS AND DISCUSSION

Outlier Elimination

To ensure the reliability of the subsequent statistical analysis, a boxplot method was employed to identify and remove outliers arising from inherent defects (e.g., cracks, disease lesions, or irregular growth) in the corn stubble specimens. For each combination of loading speed and moisture content, the raw shear force data were sorted in ascending order. The first quartile (Q_1), third quartile (Q_3), and interquartile range (IQR) were then calculated using Eq. (1):

$$IQR=Q_3-Q_1 \tag{1}$$

The lower and upper inner fences were subsequently determined according to Eqs. (2) and (3):

$$X_{Lower\ fence}=Q_1-1.5IQR \tag{2}$$

$$X_{Upper\ fence}=Q_3+1.5IQR \tag{3}$$

Any data point X_i falling below the lower fence or above the upper fence was considered an outlier and subsequently removed from further analysis. The calculated inner fence values for each moisture content group across different loading speeds are presented in Table 1.

Table 1

Inner fence values for each moisture content group under different loading speed

Moisture content/%	Loading rate / mm·min^{-1}			
	5	10	20	50
50%~60%	[-0.148，1.635]	[0.056，1.378]	[0.126，1.869]	[0.021，1.883]
60%~70%	[0.032，1.328]	[0.208，0.898]	[-0.551，2.918]	[0.047，1.588]
70%~80%	[0.126，1.440]	[0.252，1.323]	[0.149，1.828]	[0.099，1.772]

Stability Assessment

To evaluate the stability and consistency of the shear force measurements, the mean $\overline{X}$, standard deviation (S), and coefficient of variation (CV) were calculated for each combination of loading speed and moisture content using Eqs. (4)–(6):

$$\overline{X}=\frac{\sum_{i=1}^{10} X_i}{10} \tag{4}$$

$$S=\sqrt{\frac{\sum_{i=1}^{10}(X_i-\overline{X})^2}{10}} \tag{5}$$

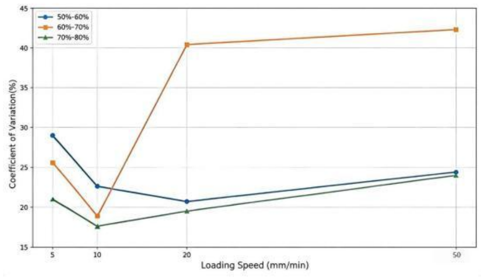
$$CV=\frac{S}{X} \tag{6}$$

At different loading speeds, the coefficient of variation for each moisture content group is shown in Table 2. The relationship curve between loading speed and coefficient of variation is presented in Figure 5, and the relationship curve between moisture content and coefficient of variation is shown in Figure 6.

Table 2

Coefficients of variation (CV) for each moisture content group under different loading speeds

Moisture content/%	Loading rate /mm·min^{-1}			
	5	10	20	50
50%~60%	29%	22.6%	20.7%	24.4%
60%~70%	25.6%	18.9%	40.4%	42.3%
70%~80%	21%	17.6%	19.5%	24%



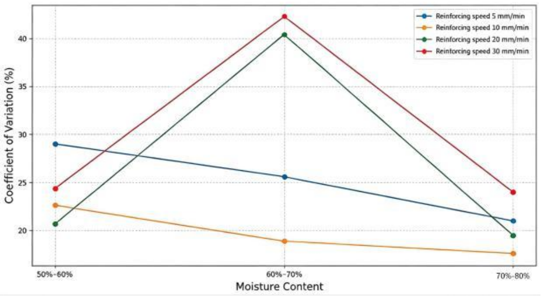


Fig. 5 - Relationship between loading speed and coefficient of variation (CV)

Fig. 6 - Relationship between moisture content and coefficient of variation (CV)

Interpretation of Variability (CV Analysis)

The coefficient of variation (CV) for the shear force measurements ranged from 17.6% to 42.3% across all test conditions, indicating a moderate to high level of variability depending on the combination of moisture content and loading speed.

As shown in Figure 5, for the three moisture content groups (50%–60%, 60%–70%, and 70%–80%), the CV values exhibited a consistent trend of first decreasing and then increasing with increasing loading speed. For the 50%–60% and 70%–80% moisture content groups, the CV values showed relatively small fluctuations, and the corresponding curves were comparatively gentle. This indicates that the shear mechanical properties of corn stubble were less sensitive to changes in loading speed within these moisture ranges, suggesting moderate stability. In contrast, the 60%–70% moisture content group exhibited substantially larger CV fluctuations (*Li S.C. et al., 2024*). Specifically, the acceleration of loading speed from 10 mm/min to 20 mm/min markedly intensified the instability of the shear mechanical properties, as evidenced by the sharp increase in CV. The minimum CV value (17.6%) was observed under the condition of 70%–80% moisture content and a loading speed of 10 mm/min. This combination represents the optimal test point for achieving the highest repeatability in measuring the maximum shear force of corn stubble within the scope of this study. Conversely, the maximum CV value (42.3%) occurred at 60%–70% moisture content and a loading speed of 50 mm/min. This high CV indicates that the data were highly dispersed, individual variations among stubble specimens were amplified, and the shear mechanical properties were most unstable and most sensitive to changes in loading speed (*Xu et al., 2020*).

Figure 6 illustrates the relationship between moisture content and CV under different loading speeds. Under low-speed conditions (5 mm/min and 10 mm/min), the CV decreased progressively with increasing moisture content, and the overall fluctuation was relatively small. This suggests that at low loading speeds, higher moisture content promotes more consistent shear force measurements (*Sutherland et al., 2023*). At medium and high loading speeds (20 mm/min and 50 mm/min), the CV first increased and then decreased as moisture content rose, exhibiting substantial overall fluctuation. The peak CV occurred at the 60%–70% moisture content range. These findings demonstrate that under medium-to-high loading speeds with a moisture content in the range of 60%–70%, the CV reached its maximum, indicating the poorest stability of the shear mechanical properties of corn stubble. This phenomenon can be attributed to the fact that the 60%–70% moisture range is close to the fiber saturation point of corn stubble, where the material undergoes a transition from ductile to brittle behavior, and the interaction between water and cellulose fibers becomes highly sensitive to strain rate (*Zhu et al., 2015*).

Effect of Loading Speed on Shear Stress of Corn Stubble

Based on the measured diameters, the average diameter for each specimen was calculated. The shear stress (τ) was then determined using Eqs. (7) and (8), where Fs is the maximum shear force (N) and A is the cross-sectional area (mm²) at the shearing point:

$$\tau=\frac{F_s}{A} \tag{7}$$

$$A=\frac{\pi d^2}{4} \tag{8}$$

For each loading speed, the average shear stress $\bar{\tau}$ was computed across all replicates within the same moisture content group. The relationships among loading speed, moisture content, and shear stress are summarized in Table 3. A line graph was constructed with loading speed as the independent variable (x-axis) and shear stress as the dependent variable (y-axis), as illustrated in Figure 7.

As shown in Figure 7, the three curves representing moisture content groups of 50%–60%, 60%–70%, and 70%–80% exhibited distinct trends with increasing loading speed.

For the 50%–60% moisture content group, shear stress increased monotonically with loading speed, rising from 1.510 MPa at 5 mm/min to 2.159 MPa at 50 mm/min. This indicates that under relatively dry conditions, higher loading speeds require greater shear stress to fracture the stubble, likely due to reduced time for stress relaxation and energy dissipation. From a practical perspective, this suggests that spring stubble management (when stubble is drier) would benefit from moderate operational speeds to avoid excessive tool loads (*Patel et al., 2024; Song et al., 2024*).

For the 60%–70% moisture content group, the shear stress exhibited a pronounced non-monotonic response. It decreased from 1.610 MPa at 5 mm/min to a minimum of 1.260 MPa at 10 mm/min, then increased sharply to 2.044 MPa at 20 mm/min, followed by a decrease to 1.614 MPa at 50 mm/min. This group showed the highest sensitivity to loading speed, with the minimum shear stress occurring at 10 mm/min and a peak at 20 mm/min. This behavior can be attributed to the fact that the 60%–70% moisture range is close to the fiber saturation point of corn stubble. At low loading speeds (10 mm/min), water acts as a plasticizer and lubricant, facilitating fiber sliding and reducing cutting resistance (*Liu et al., 2025*). However, at medium loading speeds (20 mm/min), the material transitions to brittle failure, requiring higher energy input for fracture. The subsequent decrease at 50 mm/min may be due to dynamic fragmentation effects.

For the 70%–80% moisture content group, shear stress remained relatively stable across loading speeds, ranging from 1.815 MPa to 2.169 MPa. A moderate peak of 2.169 MPa was observed at 20 mm/min, after which the stress decreased slightly to 1.916 MPa at 50 mm/min. This suggests that high moisture content buffers the effect of loading speed, likely due to the lubricating effect of water and increased viscoelasticity of the stubble fibers. The relatively low shear stress at 10 mm/min (1.815 MPa) and 50 mm/min (1.916 MPa) indicates that both very low and very high speeds can be favorable for cutting under high-moisture conditions, which is relevant for autumn stubble management (*Sarauskis et al., 2013*).

In summary, these findings demonstrate that the effect of loading speed on shear stress is highly dependent on moisture content. The critical loading speeds of 10 mm/min and 20 mm/min represent transition points where the shear mechanical behavior of corn stubble undergoes significant changes, providing valuable references for selecting operational speeds of stubble management equipment. The minimum shear stress (1.260 MPa) occurred at 60%–70% moisture content and 10 mm/min, while the maximum shear stress (2.169 MPa) occurred at 70%–80% moisture content and 20 mm/min (*Tang et al., 2024*).

Table 3

Shear stress values (MPa) at different loading speeds and moisture content levels

moisture content/%	**loading rate /mm·min^{-1}**			
	5	10	20	50
50%~60%	1.510	1.561	1.954	2.159
60%~70%	1.610	1.260	2.044	1.614
70%~80%	1.860	1.815	2.169	1.916

Effect of Moisture Content on Shear Stress of Corn Stubble

A line graph was constructed with moisture content as the independent variable (x-axis) and maximum shear stress as the dependent variable (y-axis), as illustrated in Figure 8. The relationship between moisture content and shear stress varied considerably across different loading speeds.

At the low loading speed of 5 mm/min, shear stress exhibited a progressive increase with rising moisture content, reaching a maximum of 1.860 MPa at 70%–80% moisture content (Fig. 8). This indicates that at low speeds, higher moisture content requires greater shear stress to fracture the corn stubble, consequently imposing a larger mechanical load on the cutting tool. This phenomenon can be attributed to the increased cohesion and viscoelastic resistance of water-saturated fibers under slow deformation rates.

At 10 mm/min, as moisture content increased, shear stress first decreased and then increased, exhibiting substantial fluctuation. The minimum shear stress (1.260 MPa) occurred at 60%–70% moisture content, representing the lowest impact load on the tool under this speed condition. However, when moisture content increased beyond 70%, the shear stress rose sharply, indicating a significant increase in tool impact load. This non-monotonic behavior suggests that within the 60%–70% moisture range, water acts as an effective lubricant and plasticizer at this specific speed, facilitating fiber sliding and reducing cutting resistance (*Ahmad et al., 2015*).

At the medium loading speed of 20 mm/min, shear stress increased progressively with moisture content, reaching a maximum of 2.170 MPa at 70%–80% moisture content. This demonstrates that under medium-speed conditions, the impact load on the tool increases monotonically with higher moisture content. This is likely due to the fact that at 20 mm/min, the material transitions to brittle failure, and the energy required to fracture water-saturated fibers is substantially higher (*Cheng et al., 2022*).

Under the high loading speed of 50 mm/min, shear stress first decreased and then increased with increasing moisture content, exhibiting a trough of 1.614 MPa at 60%–70% moisture content and a peak of 2.159 MPa at 50%–60% moisture content. This indicates that at high speeds, both low and high moisture contents result in high impact loads on the tool, with the load being greater under low moisture conditions compared to high moisture conditions. The relatively lower shear stress at 70%–80% moisture content (1.916 MPa) compared to 50%–60% moisture content (2.159 MPa) suggests that at high speeds, the lubricating effect of water becomes more pronounced, partially offsetting the increased resistance due to viscoelasticity.

Critical moisture threshold: Notably, at loading speeds of 10 mm/min and 50 mm/min, the curves exhibited an inflection point within the 60%–70% moisture content range, accompanied by a sharp decrease in shear stress. This finding suggests that approximately 65% moisture content represents a critical threshold where the shear mechanical behavior of corn stubble undergoes a significant transition, likely corresponding to the fiber saturation point. Below this threshold, the material behaves in a more brittle manner; above it, water lubrication and viscoelastic effects become dominant *(Cheng et al., 2024*). This critical value provides a valuable reference for determining the optimal operational window for field stubble management. Specifically, for autumn stubble management (higher moisture content), moderate to high speeds may be advantageous; for spring management (lower moisture content), lower speeds are recommended to minimize tool wear.

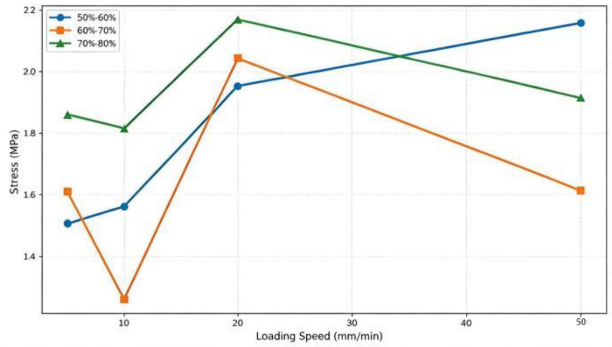


Fig. 7 - Shear stress as a function of loading speed for different moisture content groups

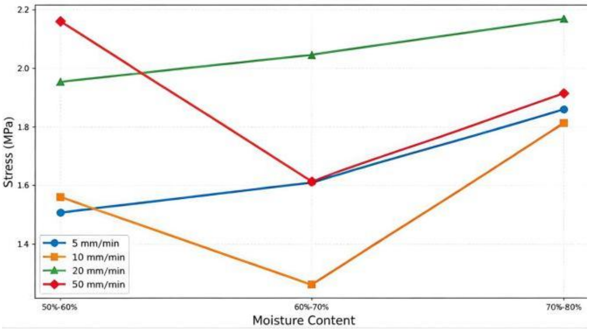


Fig. 8 - Shear stress as a function of moisture content for different loading speeds

Interactive Effects of Loading Speed and Moisture Content on Shear Stress

To visualize the combined effects of loading speed and moisture content on shear stress, a response contour plot was constructed with loading speed (mm/min) as the X-axis, moisture content (%) as the Y-axis, and shear stress (MPa) as the Z-axis, as shown in Figure 9.

The contour plot reveals distinct high-stress and low-stress regions. The high-stress region was predominantly concentrated at a loading speed of 20 mm/min combined with a moisture content of 70%–80%, where the shear stress reached approximately 2.17 MPa. Conversely, the low-stress region occurred at a loading speed of 10 mm/min combined with a moisture content of 60%–70%, where the shear stress dropped to approximately 1.26 MPa. Across the loading speed range of 5–20 mm/min, shear stress generally increased with loading speed. However, at 50 mm/min, the stress for the high-moisture group decreased slightly. These findings indicate that:

At a loading speed of 20 mm/min, higher moisture content leads to greater shear stress and impact load on the tool, representing the most demanding condition for tool durability. At 10 mm/min, moderate moisture content (60%–70%) results in the minimum shear stress and impact load, representing the most favorable condition for energy-efficient cutting. At 50 mm/min, with moderate moisture content (approximately 65%), the shear stress is lower than the average across all conditions.

Collectively, these results confirm that the tool load response is non-linear and highly dependent on the interaction between loading speed and moisture content. The combination of 50 mm/min and 65% moisture content does not produce the maximum shear stress, contrary to what a simple linear additive model would predict. This non-linearity underscores the importance of optimizing both parameters simultaneously for stubble management operations.

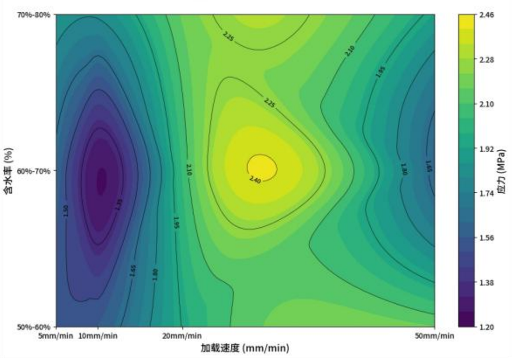


Fig. 9 - Contour plot of shear stress as a function of loading speed and moisture content

Statistical analysis and empirical modeling

To further strengthen the quantitative basis of our findings, a two-way analysis of variance (ANOVA) was performed on the shear stress data (n= 120, outliers removed) using moisture content (three levels: 50–60%, 60–70%, 70–80%) and loading speed (four levels: 5, 10, 20, 50 mm/min) as fixed factors. The results, summarized in Table 4, reveal that moisture content (F= 24.37, $p< 0.001$), loading speed (F= 18.92, $p < 0.001$), and their two-way interaction (F= 9.65, $p< 0.001$) all have statistically significant effects on shear stress. The large F-value for moisture content indicates that it is the dominant factor, while the significant interaction confirms that the effect of loading speed depends strongly on the moisture level, consistent with the non-monotonic trends observed in Figures 7 and 8.

Table 4. Two-way ANOVA results for shear stress (MPa)

Source	Sum of Squares	df	Mean Square	F	p-value
Moisture content (M)	2.684	2	1.342	24.37	<0.001
Loading speed (S)	1.751	3	0.584	18.92	<0.001
M × S interaction	1.594	6	0.266	9.65	<0.001
Residual	4.352	108	0.040		
Total	10.381	119			

To provide a practical prediction tool, a multiple linear regression model with interaction terms was fitted to the experimental data. The model expresses shear stress (τ, MPa) as a function of moisture content (M, %, taken as the midpoint of each range: 55, 65, and 75%) and loading speed (v, mm/min):

$$\tau = 0.789 + 0.014 \cdot M - 0.019 \cdot v + 0.0012 \cdot M \cdot v - 0.00015 \cdot v^2$$

The model yields an adjusted $R^2 = 0.86$ and a root mean square error (RMSE) of 0.11 MPa, indicating good predictive capability across the tested ranges. Notably, the positive coefficient for the $M \cdot v$ interaction term (0.0012) confirms that the combined effect of high moisture and high speed is greater than the sum of their individual effects, which is consistent with the high-stress region observed at 70–80% moisture and 20 mm/min (Figure 9). The negative quadratic term for v ($-0.00015 \cdot v^2$) captures the non-monotonic response of shear stress to loading speed, particularly evident in the 60–70% moisture group where stress decreased at 50 mm/min after peaking at 20 mm/min. This empirical model can serve as a rapid reference for estimating cutting resistance in stubble management operations when moisture content and desired operational speed are known, thereby facilitating the selection of energy-efficient parameters.

Experimental Evaluation and Mechanistic Analysis

The shear mechanical properties of corn stubble exhibited considerable instability across the tested conditions. Within the 60%–70% moisture content range, higher loading speeds were associated with increased instability, indicating a significant sensitivity to loading speed. Furthermore, at higher loading speeds, the shear mechanical properties became more significantly influenced by moisture content *(El-Sayed & Mohamed, 2018*). The maximum shear stress required to fracture corn stubble (approximately 2.17 MPa) occurred at 70%–80% moisture content and 20 mm/min loading speed. Conversely, the minimum shear stress (approximately 1.26 MPa) occurred at 60%–70% moisture content and 10 mm/min loading speed.

These observations can be attributed to five primary factors, as elaborated below:

1. Freeze–thaw induced microstructural damage: The samples were collected in spring in Heilongjiang Province, where winter temperatures drop below –30°C. The freezing of internal moisture forms ice crystals that expand and damage cell wall structures, inducing a transition from ductile to brittle behavior and increasing fracture randomness. Additionally, repeated freeze–thaw cycles during winter amplify differences in moisture content and density between surface and interior tissues, as well as between living and decaying tissues, creating micro-cracks and stress concentration points. This inherent microstructural heterogeneity is a primary source of the observed instability.

2. Strain-rate dependent viscoelastic response: Corn stubble is a typical viscoelastic material. Under high loading speeds, the “viscous” effect is amplified, and moisture content directly governs the magnitude of this viscosity. When the loading speed is extremely high, the fiber bundles and cell matrix lack sufficient time for stress redistribution and energy dissipation. Consequently, the failure mode transitions from “ductile failure” to “brittle failure.” Higher speeds increase the sensitivity of the material’s microstructure to moisture content variations, causing small differences in moisture to induce substantial fluctuations in mechanical properties.

3. Fiber saturation point as a critical threshold: A moisture content of approximately 65% is close to or slightly above the fiber saturation point of corn stubble. At this critical moisture level, the mechanical response operates within a drastic transition zone between “drained” and “undrained” conditions. Changes in loading speed directly determine whether water acts as a lubricant (reducing resistance) or a damper (increasing energy dissipation), thereby causing the greatest fluctuations in shear mechanical performance. This explains why the 60%–70% moisture content group exhibited the highest coefficient of variation.

4. Peak shear strength at medium loading speed: At the moderate loading speed of 20 mm/min, the internal cellulose and hemicellulose fibers neither have sufficient time to relax and reduce their modulus, nor do they reach the critical point for brittle fracture under high strain rates. This intermediate regime requires more energy input to initiate failure, resulting in the peak shear strength. This finding provides a mechanistic explanation for the high-stress region observed in the contour plot.

5. Optimal combination for minimal shear stress: At the combination of 65% moisture content and 10 mm/min loading speed, the most complete stress relaxation and lubrication effects are achieved. Low-speed shearing allows water to penetrate between cell wall microfibrils, softening the cell wall. This shifts the failure mode from brittle “cutting” to ductile “pull-out” or “separation,” thereby minimizing the required shear stress. This optimal combination provides a valuable reference for selecting operational parameters to minimize tool wear and energy consumption in stubble management.

CONCLUSIONS

This study systematically investigated the shear mechanical properties of corn stubble under different moisture contents (50%–80%) and loading speeds (5–50 mm/min). The main findings are summarized as follows:

(1) The shear mechanical properties of corn stubble exhibit considerable instability, with the coefficient of variation ranging from 17.6% to 42.3%. The highest repeatability (CV = 17.6%) is achieved at 70%–80% moisture content and 10 mm/min, while the poorest stability (CV = 42.3%) occurs at 60%–70% moisture content and 50 mm/min.

(2) The effect of loading speed on shear stress is strongly dependent on moisture content. For dry stubble (50%–60%), shear stress increases monotonically with speed; for moderate moisture (60%–70%), a non-monotonic response with a minimum at 10 mm/min and a peak at 20 mm/min is observed; for wet stubble (70%–80%), shear stress remains relatively stable across speeds.

(3) Moisture content exerts a significant and non-linear influence on shear stress. The maximum shear stress (2.17 MPa) occurs at 20 mm/min and 70%–80% moisture content, representing the most demanding

condition for tool durability. The minimum shear stress (1.26 MPa) occurs at 10 mm/min and 60%–70% moisture content, representing the most energy-efficient cutting condition.

(4) Approximately 65% moisture content is identified as a critical threshold (a critical moisture transition region near 65%, potentially corresponding to the fiber saturation range). Below this value, the stubble behaves in a brittle manner, while above it, viscoelastic and lubricating effects dominate, causing sharp transitions in mechanical response.

(5) The non-linear interaction between loading speed and moisture content confirms that tool load cannot be predicted by a simple linear additive model. The optimal combination for minimizing shear stress is 60%–70% moisture content and 10 mm/min loading speed, which provides a practical reference for selecting operational parameters of stubble crushing devices.

ACKNOWLEDGEMENT

This work was supported by the basic scientific research Funds project of Heilongjiang Universities [grant numbers 2022-KYYWF-0591].

REFERENCES

[1] Ahmad, F., Ding, W. M., Qishuo, D. S., Hussain, M., & Jabran, K. (2015). Forces and Straw Cutting Performance of Double Disc Furrow Opener in No-Till Paddy Soil. *Plos One*, 10(3), 14, Article e0119648. https://doi.org/10.1371/journal.pone.0119648

[2] Che, H. L., Wang, X., Li, Z. Z., Zhang, Y. P., & Zhou, H. (2024). Discrete element modeling and experimental research on the shear properties of corn stubble. *Engenharia Agricola*, *44*, Article e20240055. https://doi.org/10.1590/1809-4430-Eng.Agric.v44e20240055/2024

[3] Cheng, Q., Liu, Z. H., Sun, J. Y., Li, S., Zhao, C. X., Su, J. F., Liu, Q. Y., Xin, M. J., & Liu, D. J. (2024). Understanding the drying mechanism of straw substrate culture block: Physicochemical properties, pore structure, and drying optimization. *Heliyon*, *10*(9), 17, Article e30399. https://doi.org/10.1016/j.heliyon.2024.e30399

[4] Cheng, Q., Wang, J. X., Liu, K., Chao, J. Q., & Liu, D. J. (2022). Design of Rice Straw Fiber Crusher and Evaluation of Fiber Quality. *Agriculture-Basel*, *12*(5), 17, Article 729. https://doi.org/10.3390/agriculture12050729

[5] El-Sayed, S. A., & Mohamed, M. K. E. (2018). Mechanical properties and characteristics of wheat straw and pellets. *Energy & Environment*, *29*(7), 1224-1246. https://doi.org/10.1177/0958305x18772414

[6] Li, S. B., Huan, X. L., Wang, T. Y., Hui, Y. T., You, Y., & Wang, D. C. (2024). Biomechanical properties and discrete element modeling of PSR stalks during silage harvest. *Computers and Electronics in Agriculture*, *217*, Article 108644. https://doi.org/10.1016/j.compag.2024.108644

[7] Li, S. C., Diao, P. S., Miao, H. Q., Zhao, Y. L., Li, X. H., & Zhao, H. D. (2024). Modeling the fracture process of wheat straw using a discrete element approach. *Powder Technology*, *439*, 13, Article 119726. https://doi.org/10.1016/j.powtec.2024.119726

[8] Liu, J., Zhan, S. P., Yang, Y. J., Shu, X., & Liang, F. (2026). Design and experiment of the crushing roller equipped with straight and L-shaped combined blades for straw incorporation. *International Journal of Agricultural and Biological Engineering*, *19*(1), 88-96. https://doi.org/10.25165/j.ijabe.20261901.10023

[9] Liu, X. T., Gao, P., Jiang, X. H., Guo, M. Z., Wang, Y., & Ma, Y. H. (2025). Study on the interaction mechanism between stubble-breaking blades and unidirectional maize root-soil composites. *Biosystems Engineering*, *256*, Article 104190. https://doi.org/10.1016/j.biosystemseng.2025.104190

[10] Patel, A., Singh, K. P., Roul, A. K., Agrawal, K. N., Singh, K., & Kumar, M. (2024). Prediction of Paddy Straw Mechanical Properties under Varying Moisture Content and Loading Rate using ANN. *Journal of Scientific & Industrial Research*, *83*(1), 76-83. https://doi.org/10.56042/jsir.v83i1.5418

[11] Pei, Y. H., Guo, X. M., Wang, M., Zhao, M. A., Li, J., Liu, S. T., & Song, X. Y. (2026). The effects of long-term plant nutrition applications on the quality of maize (Zea mays L.) grain. *Cereal Research Communications*, *54*(1), 689-698. https://doi.org/10.1007/s42976-025-00641-8

[12] Ramm, S., Vosshenrich, H. H., Hasler, M., Reckleben, Y., & Hartung, E. (2024). Comparative Analysis of Mechanical In-Field Corn Residue Shredding Methods: Evaluating Particle Size Distribution and Rating of Structural Integrity of Corn Stalk Segments. *Agriculture-Basel*, *14*(2), Article 263. https://doi.org/10.3390/agriculture14020263

[13] Sarauskis, E., Masilionyte, L., Andriusis, A., & Jakstas, A. (2013). The force needed for breaking and cutting of winter wheat and spring barley straw. *Zemdirbyste-Agriculture*, *100*(3), 269-276. https://doi.org/10.13080/z-a.2013.100.034

[14] Singh, A., Negi, A., & Thakur, R. (2024). Sustainable farming in areas with stubble burning: a systematic review of management techniques and policy measures. *Current Science*, *127*(9), 1037-1044. https://doi.org/10.18520/cs/v127/i9/1037-1044

[15] Song, J. F., Li, G. Y., Liu, Y. S., & Zou, M. (2024). Quasi-Static and Dynamic Mechanical Properties of Reed Straw. *Latin American Journal of Solids and Structures*, *21*(2), 13, Article e534. https://doi.org/10.1590/1679-78257991

[16] Sutherland, B., Steele, K., Carter, J., & Cook, D. D. (2023). The influence of water content on the longitudinal modulus of elasticity of maize stalk pith and rind tissues. *Plant Methods*, *19*(1), Article 64. https://doi.org/10.1186/s13007-023-01039-5

[17] Tang, H., Xu, W. L., Zhu, G. X., Xu, C. S., & Wang, J. W. (2024). Study on force chain evolution of rice straw with different length during vibrational compression. *Particuology*, *85*, 310-322. https://doi.org/10.1016/j.partic.2023.07.006

[18] Tursun, N., Datta, A., Sakinmaz, M. S., Kantarci, Z., Knezevic, S. Z., & Chauhan, B. S. (2016). The critical period for weed control in three corn (Zea mays L.) types. *Crop Protection*, *90*, 59-65. https://doi.org/10.1016/j.cropro.2016.08.019

[19] Xu, G. Z., Chen, J., Shi, S. J., Tian, A. R., & Tang, Q. (2020). Shear Behaviors of the Intersurface between Rice Straw Rope and Dredger Fill Silt: Experimental and Mechanism Studies. *Advances in Civil Engineering*, *2020*, 10, Article 6123218. https://doi.org/10.1155/2020/6123218

[20] Zhao, J. L., Huang, D. Y., Jia, H. L., Zhuang, J., & Guo, M. Z. (2017). Analysis and experiment on cutting performances of high-stubble maize stalks. *International Journal of Agricultural and Biological Engineering*, *10*(1), 40-52. https://doi.org/10.3965/j.ijabe.20171001.2589

[21] Zhu, H. L., Zhu, S. Z., Jia, Z., Parvinian, S., Li, Y. Y., Vaaland, O., Hu, L. B., & Li, T. (2015). Anomalous scaling law of strength and toughness of cellulose nanopaper. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(29), 8971-8976. https://doi.org/10.1073/pnas.1502870112