

EFFECTS OF MOISTURE, STARCH, AND MICROSTRUCTURE ON THE MECHANICAL PROPERTIES OF MAIZE KERNELS DURING MECHANICAL HARVEST AFTER PHYSIOLOGICAL MATURITY

玉米籽粒生理成熟过程中水分含量、淀粉含量和微观结构对其机械收获时力学性能的影响

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ABSTRACT

This study addressed the issue of high grain breakage rates during mechanical maize harvesting, which significantly compromise grain quality and subsequent storage performance. A comparison was conducted between maize subjected to natural dehydration (CK) and maize treated with a desiccant (SY). The research analysed the moisture content of various plant organs, grain starch composition, and puncture resistance characteristics across three kernel regions during maturation. The results revealed a strong positive correlation between the grain dehydration rate and moisture loss in both the stalk and cob. Desiccant application accelerated grain dehydration and promoted the conversion of branched-chain starch. In both treatments, decreasing kernel moisture content led to the development of a thicker and denser internal cuticle layer, which increased the yield load and elastic modulus in the lateral and apical kernel regions. When kernel moisture content dropped below 25%, the SY group exhibited significantly higher yield load and elastic modulus than the CK group. These findings provide a theoretical foundation for improving kernel impact resistance and reducing grain breakage during mechanical harvesting.

摘要

本文针对玉米机械粒收过程中籽粒破碎率高，严重影响其品质和后续储藏的问题。对自然脱水（CK）和干燥剂处理（SY）两种玉米进行比较。分析了各器官水分、籽粒淀粉含量、籽粒三个部位的膜穿刺性能随成熟时间的变化。结果表明，籽粒脱水速率与穗秆、穗轴极显著正相关。施用脱水剂可加快籽粒脱水与支链淀粉的转化。同组之间，随着籽粒含水率的减少，内部角质层、致密性增加，侧部和顶部的屈服载荷和弹性模量增大，当降至25%以下时，屈服载荷与弹性模量SY组>CK组。本研究可为改善机械收获时的籽粒抗打击性能、降低收获时的破碎率提供理论指导。

INTRODUCTION

Maize is one of the world's three major food crops, with continuously growing global demand in the 21st century due to population growth, improved living standards, and expanding food and agricultural industries. To enhance harvesting efficiency and support large-scale production, the mainstream approach of maize harvesting have transitioned from manual picking to mechanical ear harvesting and finally to mechanical grain harvesting (Wang et al., 2017; Yang et al., 2017).

Grain breakage rate is a critical performance indicator in mechanical maize harvesting. Excessive breakage remains a major challenge, negatively impacting grain quality, storage safety, and economic returns (Li, 2017). Moisture content is widely recognized as a key factor affecting breakage. Studies have shown that breakage rates below 5% can be achieved within a moisture range of 19.0%–24.3% (Shang et al., 2020). Zhao et al. (2020) observed that as the harvest was delayed, moisture content decreased and mechanical strength increased, leading to an initial decline and subsequent gradual rise in breakage rates. Similarly, Wang et al. (2021) reported strong positive correlations between breakage rate, impurity rate, and moisture content, with the lowest breakage occurring at approximately 19.06% moisture.

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To mitigate breakage, strategies such as predictive modelling, variety selection, and desiccant application have been employed to maintain optimal moisture levels during harvest (Huang *et al.*, 2019; Qiao *et al.*, 2024; Fu *et al.*, 2022). For instance, Qiao *et al.* (2022) developed a Radial Basis Function Support Vector Regression (RBF-SVR) model that uses moisture, protein, and starch content to predict damage rates and optimize harvest timing. Their work also highlighted negative correlations between moisture/starch content and most mechanical properties, with regional variations in hardness among the horny endosperm, floury endosperm, and embryo. Wang *et al.* (2019) used puncture tests to reveal varietal differences in moisture content and the role of dry matter in mechanical strength, while Li *et al.* (2018) explored how chemical regulators affect maturity and quality—factors relevant to mechanized harvesting. However, existing studies have primarily focused on dehydration traits, dry matter conversion, or the general effect of moisture on breakage. There remains a lack of in-depth research on how moisture, starch content, and microstructure collectively influence mechanical properties around physiological maturity, especially under desiccant treatment, and the underlying mechanisms are not fully elucidated.

This work examined the maize variety Dongdan 808 planted in Liuyang City (Hunan Province), an area characterized by limited heat resources and slow dehydration rates. By applying desiccants at physiological maturity, the effects of moisture content, starch content, and microstructure on kernel mechanical properties and elucidate their mechanisms have been investigated. The specific objectives were to: (1) Analysed the correlation between kernel dehydration and dehydration in other plant organs during physiological maturity; (2) Evaluated the effect of desiccant application on dehydration rate and kernel quality; (3) Explored how moisture content, starch content, and microstructure affect kernel mechanical properties. This study aimed to provide theoretical and practical insights for reducing breakage rates in mechanical maize harvesting.

MATERIALS AND METHODS

Experimental Design

The experiment was conducted in 2024 in Shashi Village, Shashi Town, Liuyang City, Hunan Province (113°38' E, 28°36' N). The feed maize variety "Dongdan 808", which is most widely cultivated by local farmers, was selected for the experiment. The planting area consists of strip-shaped plots with 65 cm row spacing and 130 cm inter-row spacing, spanning a total length of 90 meters. The experiment included two dehydration treatments: the treated group (SY) using desiccant spray and the control group (CK) treated with water spray. One treatment was replicated five times, comprising 10 plots. Each plot contained 500 plants planted in 30 m² units. Sowing was performed mechanically on March 7, 2024. Organic active acid salt (4-Hydroxy-3-methoxycinnamic acid), provided by Jining Lv Kang Agricultural Products Co., Ltd., was chosen as the desiccant. It was applied at a concentration of 18 g/mu diluted in more than 2 litres of water using an unmanned aerial vehicle (UAV). The application time was at the late grain-filling stage, approaching physiological maturity (when moisture content was about 60%). From the 8th day after desiccant application, samples were taken. The initial sampling interval was two days, adjusted to a one-day delay if rain occurred on the scheduled sampling day. The plant material was divided into eight parts: shank, cob, upper stalk, lower stalk, kernel, husk, upper leaf, and lower leaf. Samples were stored in a 4 °C freezer for later analysis.

Test Items and Methods

Accumulated Temperature Calculation and Moisture Content Prediction Model

After sowing, the growth stages of maize were observed and recorded. When maize was about to enter the physiological maturity stage, the desiccant was applied. During the period of desiccant application, the average temperature was 36°C at the high end and 25°C at the low end. The total precipitation was 78.7 mm, with a corresponding humidity of 54%. No fertilizer was applied to the plants during this period, and irrigation was withheld. Reliance was solely on natural rainfall. Accumulated temperature was calculated following the method of Huang *et al.* (2022).

The accumulated temperature for day "*i*" is:

$$TT_i = T_{mean} - T_{base} \quad (1)$$

The accumulated temperature for a certain period is:

$$TT = \sum TT_i \quad (2)$$

where: TT_i is the accumulated temperature for day "*i*", T_{mean} is the daily average temperature, T_{base} is the lower limit temperature, and TT is the accumulated temperature for a certain period.

This study referred to the research method of Zhao *et al.* (2020) and used the Logistic model for regression analysis. The accumulated temperature after desiccant application (T) was used as the independent variable, and the measured kernel moisture content (W) at each sampling was used as the dependent variable.

Based on the scatter plot distribution of kernel moisture content and accumulated temperature, curves for moisture content versus accumulated temperature were simulated for both experimental (SY) and control (CK) groups to monitor the dynamic dehydration of maize kernels in the late physiological maturity stage. The model is as follows:

$$W = \frac{A_1 - A_2}{1 + \left(\frac{T}{X_0}\right)^P} + A_2 \quad (3)$$

where: A_1 : kernel moisture content at physiological maturity; A_2 : kernel moisture content at the end of dehydration; X_0 and P are model parameters; R^2 : coefficient of determination.

Moisture Content Measurement and Dehydration Rate Analysis

Following the 5-point sampling method, collected plants were divided into eight parts for moisture content testing: kernel, upper leaf on ear, lower leaf on ear, upper stalk on ear, lower stalk on ear, husk, cob, and shank.

$$MC (\%) = \frac{FW - DW}{FW} \times 100\% \quad (4)$$

where MC : moisture content; FW : fresh weight; DW : dry weight.

To quantitatively analyse the dehydration dynamics of different maize organs at various developmental stages, the dehydration rate was calculated using the following formula:

$$ODR [\% / (^\circ\text{C} \cdot \text{d})] = \frac{MC_{prev} - MC_{next}}{AT} \quad (5)$$

where: ODR : organ dehydration rate; MC_{prev} : average moisture content of previous period (%); MC_{next} : average moisture content of subsequent period (%); AT : accumulated temperature between the two periods ($^\circ\text{C} \cdot \text{d}$).

Ear Leaves SPAD Value Measurement

After desiccant treatment, the leaves of the SY group gradually turned yellow, in contrast to those of the CK group. To monitor changes in leaf chlorophyll content, SPAD values were measured using a Konica Minolta SPAD-502 Plus chlorophyll meter (Japan). Based on the effect of the desiccant, SPAD measurements began 8 days after treatment. Because the leaf tips exhibited multiple green-yellow transition zones, resulting in non-uniform readings, SPAD values were measured at the base and middle portions of both the upper and lower ear leaves. Specifically, measurements were taken at 2 inches and 8 inches from the leaf base. For each position, five parallel samples were measured, and the average value was recorded.

Starch Content Measurement

Starch content was determined by dual-wavelength analysis (Zhang *et al.*, 2013).

The puncture performance of maize kernel

A TA.XT.Plus texture analyser (Stable Micro System, UK) was used to assess the puncture performance of maize kernels. The test speed ranged from 0.01 to 40 mm/s. The compression mode was selected, and a needle-tip probe with a tip area of 1 mm² was employed. The probe was loaded at a constant speed of 1 mm/s.

Data processing

The experimental data were sorted out with Microsoft Excel, the analysis was carried out with Origin 2024 software, the correlation analysis was carried out by Pearson method, and the difference significance comparison was carried out by LSD method.

RESULTS

Changes in Maize Plant Moisture Content

Accumulated Temperature and Kernel Moisture Content Changes

The relationship between the time after desiccant application and the accumulated temperature, as calculated from Eqs.(1–3) and presented in Fig. 1, was highly linear, following $Y = 25.2033X$ with a coefficient of determination (R^2) of 0.9926.

These results indicate a strong correlation between accumulated temperature and duration after physiological maturity, highlighting its utility in quantitatively estimating changes in kernel moisture content.

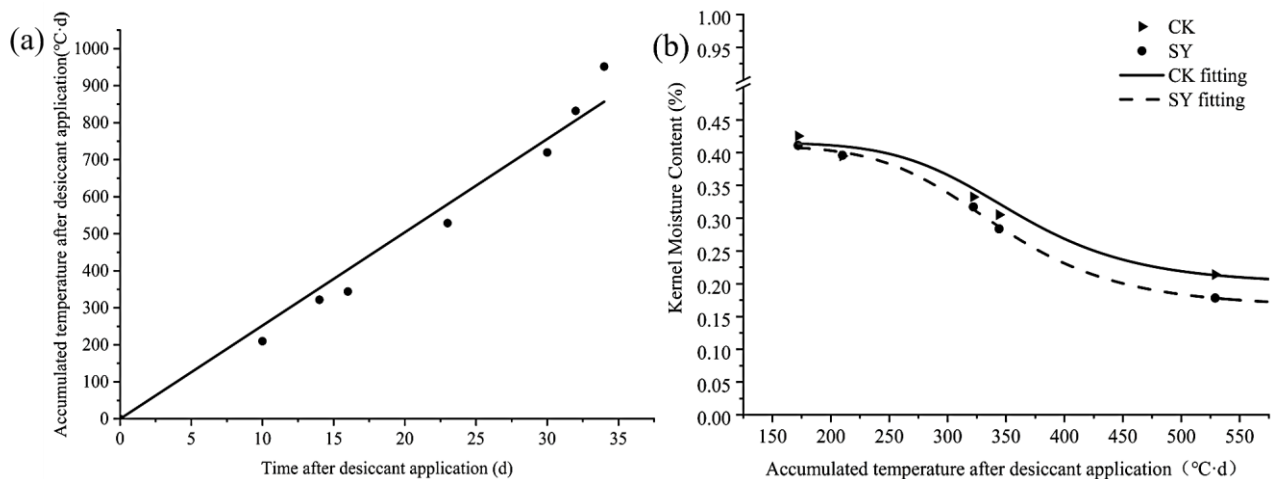


Fig. 1 - Accumulated temperature change after desiccant use

(a) shows the relationship between time after desiccant application and accumulated temperature.

(b) shows the relationship between accumulated temperature and kernel moisture content after desiccant application.

Table 1

Kernel Moisture Content Prediction Model after Desiccant Application

Group	A ₁ (%)	A ₂ (%)	X ₀	P	R ²	I (°C·d) /d	II (°C·d) /d	III (°C·d) /d
SY	41.00	19.89	358.69	6.83	0.9929	333.18/13.22	378.27/15.01	450.56/17.88
CK	41.52	16.41	344.11	6.53	0.9620	364.25/14.45	456.20/18.10	558.03/22.14

Note: (I, II, and III represent the accumulated temperature (°C·d) and the number of days (d) required for the kernel moisture content to decrease to 30%, 28%, and 25%, respectively, after the application of the desiccant.)

As shown in Fig 1(b), the kernel moisture content in both the CK and SY groups followed a pattern of slow decline, followed by a rapid decrease, and subsequent stabilization after physiological maturity. The SY group demonstrated a higher degree of fit ($R^2 = 0.9929$) than the CK group ($R^2 = 0.9620$). Consistent with the prediction model, the CK kernels generally maintained higher moisture content than SY kernels throughout all stages. These results suggest that desiccant application effectively accelerated kernel dehydration during the late physiological maturity period. This observation aligns with the findings of Li *et al.* (2018), who reported that desiccant treatment advanced maize maturity by approximately two days compared to the control.

As shown in Table 1, the predicted results present the accumulated temperature (°C·d) and the number of days required for kernels to reach 30% moisture content after desiccant application. Differences were observed in the dehydration process of kernels during the late physiological maturity stage between the two groups. Previous studies have reported that the moisture content of maize kernels at physiological maturity ranges from 15% to 45%. In this study, 30% moisture content was designated as the threshold for fully physiologically mature kernels, while 25% and 20% were considered optimal moisture contents for mechanical harvesting. The predictions indicated that, to reach 30% moisture content, the CK group required 364.25 °C·d (14.45 days), whereas the SY group required 333.18 °C·d (13.22 days). This translated to the SY group reaching 30% moisture content 1.23 days earlier than the CK group. Regarding 25% moisture content, the CK group required 456.20 °C·d (18.10 days), while the SY group required 378.27 °C·d (15.01 days). Consequently, the SY group reached 25% moisture content 3.09 days earlier. For 20% moisture content, the CK group required 558.03 °C·d (22.14 days), whereas the SY group required 450.56 °C·d (17.18 days). The SY group reached this level 5.04 days earlier.

These results indicate that desiccant application reduced the required effective accumulated temperature during maize physiological maturity. Consequently, it shortened the time needed for kernel moisture content to reach the standards for mechanical harvesting after grain filling.

Moisture Content Changes and Dehydration Rate Analysis of Various Organs

To investigate the relationship between the moisture content of various plant parts and kernels after desiccant treatment, samples were collected at 10, 12, 14, 16, and 23 days following desiccant application. Dynamic changes in moisture content of maize kernels and different plant parts are illustrated in Fig. 2, where (a) represents the CK group and (b) represents the SY group. A significance analysis was conducted to compare moisture content changes among different organs within the same time points for both CK and SY groups.

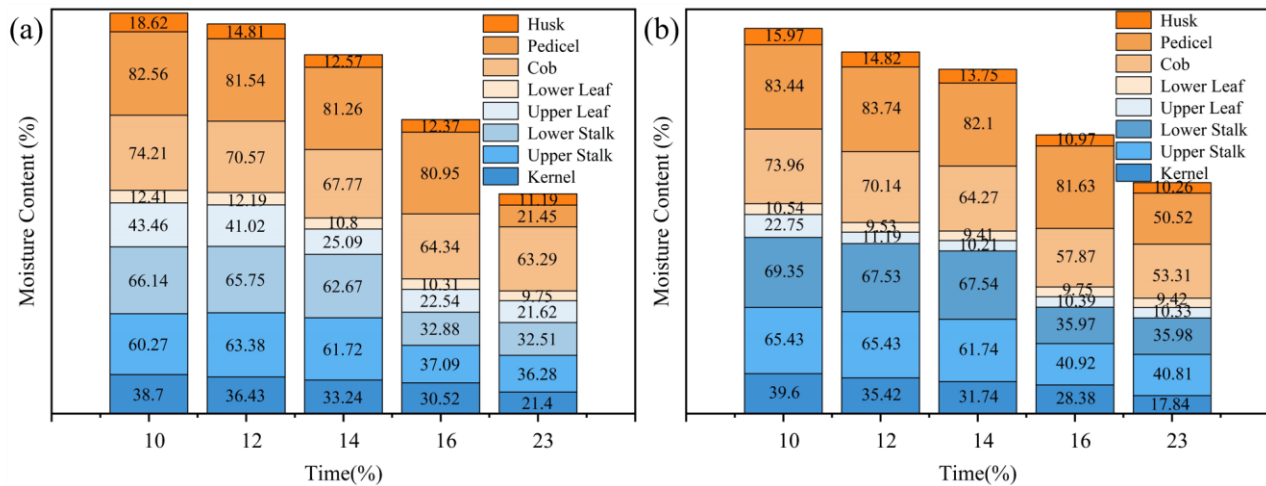


Fig. 2 - Changes in moisture content of various organs after physiological maturity
(a) CK group. (b) SY group

Table 2

Dehydration Rate of Kernels and Various Organs									
Dehydration Rate									
Group	Period	Kernel	Upper Stalk	Lower Stalk	Upper Leaf	Lower Leaf	Cob	Shank	Husk
CK	A	0.0474	0.0258	0.0082	0.0509	0.0044	0.0758	0.0212	0.0795
	B	0.0499	0.0260	0.0481	0.2489	0.0218	0.0438	0.0043	0.0350
	C	0.1234	1.1194	1.3542	0.1160	0.0222	0.1562	0.0141	0.0088
	D	0.0493	0.0044	0.0020	0.0049	0.0031	0.0056	0.3216	0.0064
SY	A	0.0870	0.0000	0.0380	0.2409	0.0211	0.0796	-0.0062	0.0238
	B	0.0576	0.0576	-0.0003	0.0153	0.0019	0.0917	0.0256	0.0168
	C	0.1524	0.9465	1.4350	-0.0085	-0.0156	0.2913	0.0215	0.1260
	D	0.0570	0.0006	-0.0001	0.0003	0.0018	0.0246	0.1909	0.0038

Fig. 2 presents the initial moisture distribution pattern within maize plants. The order of moisture content, from highest to lowest, was: shank, cob, stalk, kernel, upper leaf, husk, and lower leaf. Throughout each monitoring period, the kernel moisture content in the SY group was consistently lower than in the CK group. This difference indicates that desiccant application accelerated kernel dehydration. Furthermore, the moisture content of leaves in the SY group was lower than in the CK group, particularly in the upper leaves, suggesting that the desiccant primarily affected the leaves, accelerating their dehydration. Consequently, leaf dehydration likely affected photosynthesis and nutrient transport in maize, thereby further accelerating kernel dehydration.

To examine the dehydration rate of various maize plant organs during late physiological maturity, the dehydration rates of each organ were calculated based on accumulated temperature and changes in moisture content. As presented in Table 2, samples were collected at 10, 12, 14, 16, and 23 days after desiccant application. The time intervals between adjacent sampling days were designated as A, B, C, and D, respectively. The results showed that the dehydration rate of maize kernels initially increased and then decreased, reaching its maximum between 14 and 16 days after desiccant application. Furthermore, the dehydration rates of both kernels and cobs in the SY group were consistently higher than those in the CK group across all sampling periods. These findings suggest that the desiccant primarily affected cob dehydration, which subsequently accelerated kernel dehydration.

Effect of Kernel Dehydration on Dry Matter Conversion during Late Physiological Maturity

Because maize is rich in starch, the starch contents of the Dongdan 808 maize kernels were measured to assess the impact of desiccant application on grain quality. This analysis was intended to explore the conversion of dry matter from the physiological-mature stage to full maturity following desiccant treatment.

Table 3

Changes in Maize Kernel Starch Content						
Group	Days after Desiccant Application (d)	Kernel Moisture Content (%)	Total Starch (%)	Amylopectin (%)	Amylose (%)	Amylopectin/Amylose Ratio
CK	8	42.50	35±1	29±1	7±1	4.35
	10	38.70	37±2	30±2	7±1	4.05
	12	36.43	39±1	32±1	7±1	4.32
	14	33.24	41±1	32±1	9±1	3.52
	16	30.52	53±2	42±0	11±1	3.82
	23	21.40	69±1	55±1	14±2	4.00
SY	8	41.10	37±1	31±1	6±1	5.17
	10	39.60	38±0	31±2	7±2	4.70
	12	35.42	42±1	35±1	7±0	5.00
	14	31.74	51±1	42±2	8±1	5.08
	16	28.38	53±1	43±2	10±0	4.33
	23	17.84	60±0	50±0	10±0	5.00

Maize kernels are rich in starch; changes in starch content, together with kernel moisture content, can be used to predict optimal harvest time (Qiao *et al.*, 2022). This study examined the effects of natural maturation and desiccant application on starch content by measuring the starch content of maize kernels from physiological maturity to full maturity under both natural and desiccant-induced dehydration conditions. As shown in Table 3, kernel moisture content gradually decreased, while total starch content gradually increased as maize entered the physiological maturity stage. Specifically, from 8 to 14 days after treatment, the SY group showed significantly higher amylopectin content (31%-42%) and total starch content (37%-51%) compared to the CK group (amylopectin: 29%-32%, total starch: 35%-41%). The percentages are expressed as %. In contrast, the amylose content in the SY group (6%-10%) was consistently lower than that in the CK group (7%-14%) across all periods. The percentages are expressed as %.

Compared to CK, the SY group accelerated the conversion of amylopectin during physiological maturity but resulted in a lower final amylopectin content at harvest (CK: 55%, SY: 50%). It also reduced amylose conversion (amylose at harvest: CK: 14%, SY: 10%) and increased the amylopectin-to-amylose ratio (CK: 4, SY: 5).

These results suggest that early desiccant application can increase starch content and accelerate the conversion of low-molecular-weight amylose to high-molecular-weight amylopectin, thereby increasing the amylopectin-to-amylose ratio.

Chlorophyll is an essential catalyst for plant photosynthesis and plays a critical role in maize dry matter accumulation. In maize plants, most chlorophyll is concentrated in the chloroplasts of the leaves. The SPAD index is routinely used as a rapid, non-destructive indicator for leaf chlorophyll content. This study measured SPAD readings on the ear leaf (Table 4). Because the distal tips of the ear leaf senesced eight days after treatment, reliable SPAD readings could not be obtained from those portions. Consequently, measurements were taken at the base and middle of the ear leaf.

Table 4

SPAD Values of Ear Leaves				
Group	Leaf Position	Time (days)	Base Position	Middle Position
CK	Upper Leaf	8	51.36±5.90	39.20±5.44
		10	44.86±2.98	29.54±5.70
		12	35.40±3.22	36.50±5.70
		14	42.18±3.62	15.18±4.20
		16	37.40±5.26	22.86±2.45
	Lower Leaf	8	22.66±6.31	11.82±4.15
		10	12.92±6.07	8.22±0.54
		12	7.80±0.70	7.84±0.86
		14	8.12±1.17	7.98±0.94
		16	7.84±1.4	7.86±1.06
SY	Upper Leaf	8	43.00±5.86	32.20±5.20
		10	9.62±3.28	7.74±2.13
		12	7.10±1.02	8.44±1.71
		14	9.32±0.54	7.80±1.58
		16	5.94±0.80	7.58±1.24
	Lower Leaf	8	9.10±0.86	6.08±3.49
		10	6.10±1.31	6.22±1.53
		12	6.34±0.80	6.40±1.38
		14	5.22±0.76	5.60±1.28
		16	6.50±0.80	6.60±0.88

During the late physiological-maturity stage of maize, SPAD readings generally decreased as the sampling date progressed. At each sampling date, the upper ear leaf exhibited on-average higher SPAD values than the lower ear leaf. Moreover, the average SPAD values at the base of an ear leaf were not lower than those measured at the middle position.

At the same positions, SPAD values in the SY treatment were consistently lower than in the control (CK). Specifically, at 8, 10, 12, 14, and 16 days after treatment (DAT), SPAD values at the base of the upper ear leaf in the SY group were reduced by 16.3 %, 78.6 %, 79.9 %, 77.9 %, and 84.1 %, respectively, relative to CK. Corresponding reductions at the base of the lower ear leaf were 59.8 %, 52.8 %, 18.7 %, 35.7 %, and 17.1 %.

At the middle position of the upper ear leaf, the decreases were 17.9 %, 73.8 %, 76.9 %, 48.6 %, and 66.8 %, while the middle position of the lower ear leaf showed reductions of 48.6 %, 24.3 %, 18.4 %, 29.8 %, and 16.0 %, respectively. These results indicate that early desiccant application reduced the photosynthetic activity of the maize plant during late physiological maturity, which likely impacted starch synthesis and its conversion in the kernels.

Effects of Maize Kernel Dehydration on their Mechanical Properties during Late Physiological Maturity

To investigate how changes in moisture content affected the mechanical properties of different maize kernel parts during dehydration, puncture tests on kernel samples from the SY and CK groups were conducted. These tests were performed at 10, 23, and 34 days after desiccant application, representing varying moisture content levels.

Deformation-load curves, generated by the texture analyser, were used to identify the bioyield point, defined as the first peak load. Needle puncture tests also provided stress-strain curves. From the slope of these curves, an apparent elastic modulus was determined, which together with the yield load at the bioyield point, served as an indicator of kernel hardness.

Table 5

Maize Puncture Test						
Puncture Position	Group	Time (d)	Moisture Content (%)	Yield Load (N)	Elastic Modulus (MPa)	Deformation (mm)
Top	CK	10	38.7	4.75±0.63d	4.29±0.82d	0.95±0.21d
		23	21.4	25.65±1.25c	7.34±0.65d	3.38±0.24a
		34	19.5	49.84±1.45a	23.78±1.91b	2.69±0.60b
	SY	10	39.6	4.21±1.41d	6.49±2.25d	0.69±0.18d
		23	17.8	32.63±1.82b	12.51±0.90c	2.60±0.26bc
		34	13.63	50.19±0.82a	28.09±2.97a	1.93±0.56c
Abdominal	CK	10	38.7	2.10±0.32abc	7.63±1.23c	0.30±0.02bc
		23	21.4	1.72±0.22c	8.27±1.03c	0.72±0.12a
		34	19.5	2.25±0.38abc	12.44±0.36b	0.19±0.03d
	SY	10	39.6	1.98±0.34bc	6.93±0.70c	0.35±0.05b
		23	17.8	2.63±0.53a	11.70±0.99b	0.24±0.02cd
		34	13.63	2.50±0.02ab	17.50±2.59a	0.16±0.02d
Lateral	CK	10	38.7	3.69±0.19c	10.93±1.66c	0.40±0.05c
		23	21.4	30.51±0.82b	27.83±3.62b	0.98±0.15b
		34	19.5	52.03±2.10a	31.40±1.48b	1.06±0.25b
	SY	10	39.6	3.21±0.50c	6.89±1.68c	0.54±0.03c
		23	17.8	31.19±1.88b	28.18±3.90b	0.99±0.16b
		34	13.63	54.45±3.89a	55.75±3.11a	1.35±0.05a

Puncture tests were performed on the lateral, abdominal, and top positions of kernels from both the CK and SY groups. The results showed a significant relationship between kernel moisture content and both the yield load and the elastic modulus obtained from the puncture tests.

As presented in Table 5, within each group, a decrease in kernel moisture content led to an increase in the elastic modulus across all three positions. The yield load for the lateral and top positions also increased as moisture content decreased, whereas the abdominal yield load showed no clear trend. As kernel moisture content declined, the force required to puncture the pericarp at the top and lateral positions increased. When the moisture content dropped to 25%, both the yield load and elastic modulus for all positions in the CK group were lower than those of the SY group.

As is illustrated in Fig. 3, kernels with higher moisture content contained more internal, floury endosperm. This resulted in a softer endosperm and lower kernel hardness, which reduced resistance to compression. As the moisture content decreased, a progressive conversion of the internal floury endosperm into vitreous endosperm was observed, leading to an increased proportion of vitreous endosperm, particularly in the lateral region of the kernel. This structural transformation is clearly illustrated by the representative kernels shown in Fig. 3 on days 16 and 23.

At the same time, the floury endosperm hardened, increasing the yield load required for the top and lateral positions to resist local compression. These findings indicate that maize kernels with lower moisture content are harder and exhibit higher yield loads, reflecting greater resistance to mechanical damage. This enhanced resistance is advantageous for reducing kernel breakage during mechanical harvesting.

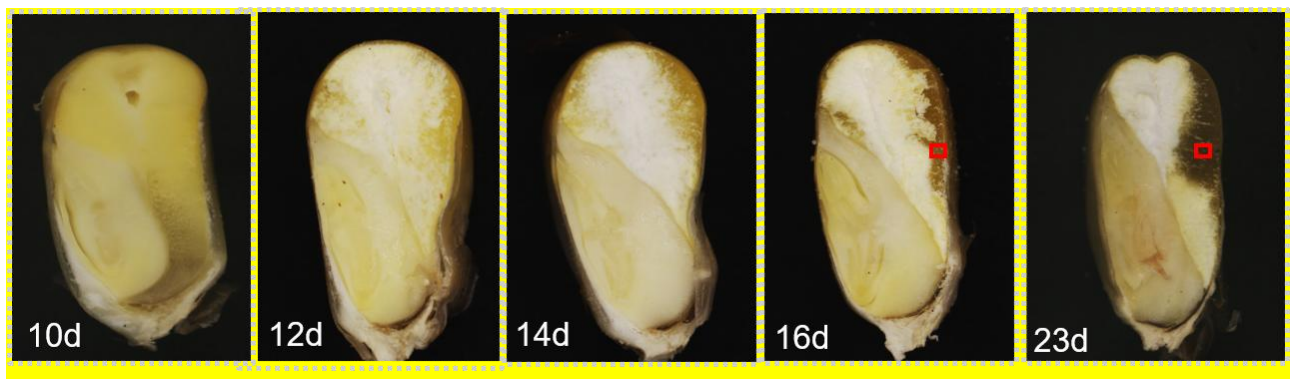


Fig. 3 - Internal changes in the abdominal cross-section of maize kernels in CK group

However, when the changes in moisture content of both groups were examined, the expected pattern of increasing kernel yield load as moisture content decreased did not always hold. Specifically, in the CK group, when kernel moisture was 19.5 %, the yield load at the top was 49.84 N, and at the lateral position it was 52.03 N. In contrast, in the SY group, when kernel moisture was 17.8 %, the yield load at the top was 32.63 N, and at the lateral position it was 31.19 N. Consequently, the two groups did not consistently exhibit an increase in kernel yield load as moisture content declined. Based on the maize-kernel starch data (Table 3), speculated that desiccant application altered the levels of amylopectin, amylose, and total starch, and changed the amylopectin/amylose ratio within the kernels; this likely affected kernel hardness. Such changes may have produced the inconsistent effects of moisture content on mechanical properties observed between the CK and SY groups. These findings suggest that the mechanical properties of maize kernels are influenced not only by moisture content but also by internal dry-matter composition and microstructure.

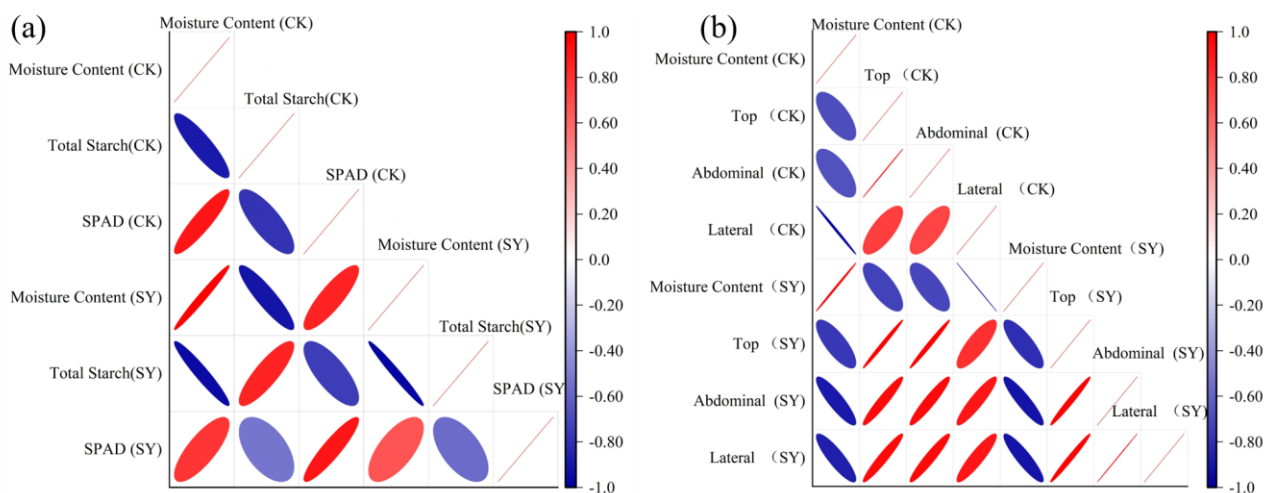


Fig. 4 - Correlation matrix

(a) Moisture content versus SPAD values and starch content.

(b) Moisture content versus elastic modulus of the top, abdominal, and lateral.

In order to illustrate the relationship between moisture content and elastic modulus, as well as the influence of moisture content on SPAD value and starch content, a relationship matrix was made for these variables. The results are shown in Fig. 4 that moisture content is positively correlated with SPAD values ($p < 0.05$), while it is negatively correlated with both total starch content ($p < 0.05$) and the elastic modulus of the various components ($p < 0.05$).

CONCLUSIONS

This work systematically investigated the effects of natural dehydration and desiccant application on the dehydration dynamics, starch metabolism, microstructure, and mechanical properties of maize kernels during the late physiological maturity stage. Key conclusions are as follows: (1) Desiccant treatment effectively accelerated kernel dehydration. A significant positive correlation was observed between kernel dehydration and the dehydration of both the stalk and the cob. (2)

As moisture content decreased, the total starch content in the kernels increased in both the control (CK) and desiccant-treated (SY) groups. Furthermore, desiccant application promoted the conversion of amylopectin, leading to a higher amylopectin-to-amylose ratio (5:4) in the SY group, which indicates notable alterations in starch composition. (3) Concurrently, reduced kernel moisture content resulted in an increased proportion of horny endosperm and microstructural densification, significantly enhancing kernel hardness. These changes suggest that moisture loss induces structural strengthening, thereby improving the kernel's resistance to physical damage during mechanical harvesting. The results of this study offered practical value for maize farmers by providing a scientific basis for optimizing harvest timing and desiccant use. Ultimately, such strategies can help minimize kernel breakage, improve grain quality, increase yields, and reduce post-harvest losses.

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