








Mechanical properties and integrity of stored corn grains after continuous and intermittent drying

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Abstract

This study aimed to evaluate the influence of continuous and intermittent drying during the storage time on mechanical properties and integrity of corn. For intermittent drying, five rest times (0, 4, 8, 12, and 16 h) and four storage times (0, 90, 180, and 270 days) were used. The corn grains harvested at a moisture content of 0.34 ± 0.001 kg kg⁻¹ dry basis (db) were dried in a fixed-layer experimental dryer set at a temperature of 100 °C and an air flow rate of $1.5 \text{ m}^3 \text{ min}^{-1} \text{ m}^{-2}$ until they reached a moisture content of 0.16 ± 0.03 kg kg⁻¹ db. For intermittent drying, the process was interrupted at a moisture content of 0.22 ± 0.02 kg kg⁻¹ db and resumed after resting. Tests for electrical conductivity, rupture force, deformation, energy required for rupture, and modulus of toughness and hardness were conducted. Grain integrity is better maintained when the grain has been dried with a longer rest time and stored for short periods; compressive strength exhibits the same behavior as integrity, but hardness, energy for rupture, and the modulus of toughness are not influenced by storage time, and grain deformation was not affected by the rest and storage times.

Keywords: *Zea mays* L.; rest time; electrical conductivity; compressive strength.

Practical Application: An alternative to physical integrity maintenance of corn grains stored.

1 INTRODUCTION

The use of high temperatures during grain drying not only shortens the effective drying time, but also compromises the physical quality and nutritional composition of agricultural products. In addition, part of the energy supplied is lost through exhaustion, thereby reducing the efficiency of the drying process (Kumar et al., 2016). The adoption of high temperature is common in storage units, mainly at the peak of harvest, to reduce the flow of wet product, which becomes a serious problem in terms of quality.

Assar et al. (2016) observed an increase in drying air temperature with an increase in evaporation and water diffusion to the surface of rice grains. However, this positive correlation may have negative effects, including the emergence of cracks and fissures that compromise the mechanical properties of these products. This can be minimized via intermittent drying (Mabasso et al., 2020), which involves the intermittent supply of drying air and different rest times (Nishiyama et al., 2006).

This technique enables to guarantee the diffusion and standardization of water on the grain surface, facilitating its removal by diluting the moisture gradient generated in continuous drying.

In addition to contributing to maintaining product quality, intermittent drying is more energy efficient (Allaf et al., 2014; Foroughi-Dahr et al., 2015; Lima et al., 2016; Mabasso et al., 2021).

Knowing the mechanical properties and moisture content of agricultural products during storage is essential in preserving their quality and minimizing possible damage (Shir-mohammadi et al., 2018; Tarighi et al., 2011). Since damage reduces storage potential, it is important to adopt measures that guarantee the physical integrity of stored grains, which can be determined according to their resistance to an applied force by measuring the rupture force, hardness, energy required for rupture, and elastic modulus of grains (Feng et al., 2019), in addition to cellular analyses such as electrical conductivity (Coradi et al., 2019).

Several studies have investigated the mechanical properties of agricultural products from a quality preservation standpoint, with an emphasis on different moisture contents (Abdel Mak-soud, 2009; Esehaghbeygi et al., 2009; Resende et al., 2013; Tarighi et al., 2011). There has been less focus on the temperature of drying air (Abasi & Minaei, 2014) and its relationship with rest times in storage, and although several studies mention quality,

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their focus is primarily on the efficiency of the drying process and/or its immediate effects (Filippin et al., 2018; Franco et al., 2020; Mabasso et al., 2020; Mabasso et al., 2021; Oliveira et al., 2022; Park et al., 2018; Zhao et al., 2018).

Knowledge of the immediate effect of intermittent drying techniques must be complemented with the storage potential, as a consequence of pressure reduction at the peak of harvest and the adoption of processes that contribute to the maintenance of grain quality during the storage time. Most of studies about this topic do not discuss about mechanical properties with a focus on intermittent drying and storage time, and so only few studies focus on drying temperature, while a lot of studies mainly discuss about the effect of continuous drying by moisture content reduction. As such, this study aimed to assess the compressive strength of stored corn grains subjected to continuous and intermittent drying at different rest times.

2 MATERIALS AND METHODS

This study was conducted in a completely randomized design in a 5×4 factorial scheme with four repetitions, corresponding to five rest times (0, 4, 8, 12, and 16 h), where 0 represents continuous drying and 4 represents storage times (0, 90, 180, and 270 days).

Following manual harvesting and threshing, corn grains of the Cargo TL cultivar with an initial moisture content of 0.34 ± 0.001 kg kg⁻¹ dry basis (db) were placed in a transparent polyethylene container in a cooling chamber at 5 °C for 72 h in order to ensure a uniform moisture content throughout the grain mass. Moisture content was determined in triplicate by the gravimetric method in a forced air oven at 103 ± 1 °C for 72 h (ASABE, 2007).

This was followed by drying in a fixed-bed experimental dryer, using a system with temperature and air flow controls. Drying was carried out at 100 °C and air flow rate of 1.5 m³ min⁻¹ m⁻². The grain volume and initial depth of the grain layer were 0.035 m³ and 0.124 m, respectively.

To prevent the formation of moisture and temperature gradients during the drying process, the grains were turned regularly, at 10-min intervals, and water removal was also monitored. The monitoring was carried out using three perforated polyethylene bags, each containing 100 g of grains, placed randomly in the grain mass. For continuous drying process, monitoring was continued until a final moisture content of 0.16 ± 0.03 kg kg⁻¹ db, and in the remaining treatments, it was carried out in two stages, the first up to 0.22 ± 0.02 kg kg⁻¹ db and the second until 0.16 ± 0.03 kg kg⁻¹ db, followed by a rest period.

For the rest of the process, the hermetical and sealed expanded polystyrene box was used to simulate silo conditions and prevent interference from the external environment as much as possible. Temperature and relative humidity in the grain mass were measured throughout rest using an HT-4010 digital data logger, capable of instant measurements and equipped with an internal storage system that enables data to be transferred to a computer via the HT Communication software. The 100-L expanded polystyrene box was adapted to a length, width, and height of 0.51, 0.30, and 0.16 m, respectively, for a total volume of 24.48 L (24.48×10^{-3} m³).

A thickness of 0.15 m was established for all the sides of the box, equivalent to a grain mass thickness of 1.011 m. This ratio was obtained based on the electrical conductivity of the material (0.02 W m⁻¹ °C⁻¹) and corn grains (0.16 W m⁻¹ °C⁻¹) under moisture content and temperature (Leila et al., 2019; Suleiman & Rosentrater, 2016).

After drying, the corn grains were stored in metal containers with perforated lids covered to allow air circulation and mimic silo storage conditions. Storage lasted for 270 days (9 months), with four assessment times (0, 90, 180, and 270 days).

2.1 Electrical conductivity

Electrical conductivity was measured via the mass method, using four samples of 50 grains in four repetitions, with mass determined on a digital balance accurate to 0.01 g. Grain mass, water volume, time, temperature, and the execution protocol for the methodology were in line with the recommendations of Vieira and Krzyzanowski (1999).

2.2 Physical characteristics of the grains

Four repetitions of 10 corn grains were selected for uniaxial compression tests (Abasi & Minaei, 2014; Tarighi et al., 2011). Each grain was measured using a digital pachymeter accurate to 0.01 mm. The average equivalent volume of the grains was determined considering their shape as spheroid (Equation 1) and based on previous tests. These were conducted using the displacement of a low-density (0.658 g mL⁻¹) liquid (hexane), which is difficult for the grains to absorb. This produced statistically equal results, validating the equations for the study conditions (Abasi & Minaei, 2014).

$$V_e = \frac{\pi abc}{6} \quad (1)$$

Where:

V_e : the equivalent volume of the corn grain (mm³);

a, b, and c: long, central, and short axes of the corn grain (mm), respectively.

2.3 Rupture force

To obtain the stress-strain curves, the grains were submitted to uniaxial compression tests in a TA HD Plus texture analyzer with a 750 N load cell. Testing was carried out with the grains in their normal resting position, adopting 1 mm as the maximum strain value and 0.20 mm s⁻¹ as the test speed, as obtained in stability tests. The stress-strain curves were used to determine the rupture point of the corn grain. The point of rupture is a sudden drop in the increasing stress values and occurs simultaneously to a crack or fissure in the grain.

2.4 Absorbed energy

The energy absorbed (E) or necessary for deformation corresponds to the area under the stress-strain curve during loading, as per Equation 2 (Tarighi et al., 2011).

$$E = \frac{F_r \cdot D}{2} \quad (2)$$

Where:

F_r : the rupture force;

D: deformation at the rupture point of the grain.

2.5 Modulus of toughness

The methodology described by Abasi and Minaei (2014) was used to determine the modulus of toughness, as the energy required for material rupture or the total energy per unit volume absorbed by the material until rupture point (Equation 3).

$$P = \frac{\int F \cdot dx}{V_e} \quad (3)$$

Where:

P: the modulus of toughness (mJ mm^{-3});

F: the compression force (N);

dx: the deformation (m);

V_e : the equivalent volume of the corn grain (mm^3).

2.6 Hardness

Hardness is the ratio of compression force and deformation at the point of rupture, in accordance with Equation 4 (Olaniyan & Oje, 2002).

$$Q = \frac{F_r}{D} \quad (4)$$

Where:

Q: the grain hardness (N mm^{-1});

F_r : the rupture force (N),

D: the deformation at the point of rupture (mm).

2.7 Statistical analysis

The data were analyzed using the SigmaPlot 11.0 software. Regression models were set up and analyzed based on data trends using F-tests at 5% probability for the coefficients and coefficient of determination (R^2). Pearson's correlations were also performed, using the Student's t-test at 5% significance.

3 RESULTS AND DISCUSSION

During storage, temperature ranged from 19.0 to 30.27 °C with an average of 25.54 °C and relative humidity from 79.27 to 84.64% with an average of 82.76%. High temperatures coincide with low relative humidity values, which agree with the greater capacity of air to retain water vapor. In general, intergranular relative humidity varied during storage due to the hygroscopicity of grains, which either lose or absorb water until the equilibrium moisture content is reached according to the storage conditions.

Moisture content declined as storage time increased, regardless of the rest time applied during drying. There was a slight variation in moisture content for rest times of 4–16 h in relation to the continuous drying process, which ranged from 14.18±0.44 to 12.27±0.79%.

In general, grain characteristics were not influenced by rest time during drying or by storage time (Table 1). According to Abasi and Minaei (2014), this is vital in determining mechanical properties or resistance and directly influences the deformation and rupture force of grains.

Stress-strain values depend on the size of the material submitted to compression, whereby the larger the grain, the greater the force needed to generate the same deformation and, consequently, the greater the rupture force of the grain (Couto et al., 2002).

Table 1. Average values of physical characteristics of corn grains for different storage and rest times.

RT (h)	um (g)	a (mm)	b (mm)	c (mm)	d _e (mm)	V _e (mm ³)
0	0.396	12.61	9.44	4.35	8.02	86.44
4	0.390	12.35	9.23	4.37	7.92	83.08
8	0.397	12.42	9.31	4.40	7.97	84.97
12	0.394	12.38	9.24	4.40	7.95	84.05
16	0.392	12.29	9.29	4.35	7.91	82.91
CV (%)	12.307	6.01	6.88	7.23	4.29	12.75
ST (days)	um (g)	a (mm)	b (mm)	c (mm)	d _e (mm)	V _e (mm ³)
0	0.412	12.65	9.48	4.42	8.08	88.31
90	0.381	12.22	9.20	4.30	7.84	80.61
180	0.397	12.48	9.31	4.45	8.01	86.18
270	0.387	12.29	9.22	4.34	7.88	82.07
CV (%)	12.307	6.01	6.88	7.23	4.29	12.75

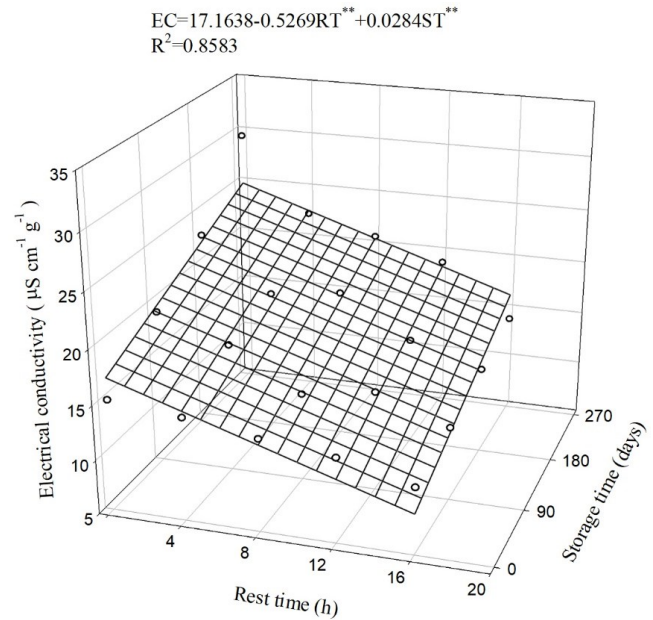
RT: rest time; ST: storage time; um: unit mass of the grain; a, b, c: long, central, and short axes of the grain; d_e: equivalent diameter; V_e: equivalent volume of the grain.

Grains should be grouped uniformly to ensure that their size does not influence mechanical properties (Gunasekaran & Paulsen, 1985), as shown in Table 1.

The corn grain's electrical conductivity increased with storage time and decreased at longer rest times (1). This is expected because intermittent drying helps maintain cellular integrity of membrane (Shirmohammadi et al., 2018), whereas storage time compromises it (Coradi et al., 2019). However, there was a greater variation in electrical conductivity for rest time (0.53) than for storage (0.03), demonstrating the importance of intermittent drying in maintaining grain quality, regardless of storage time.

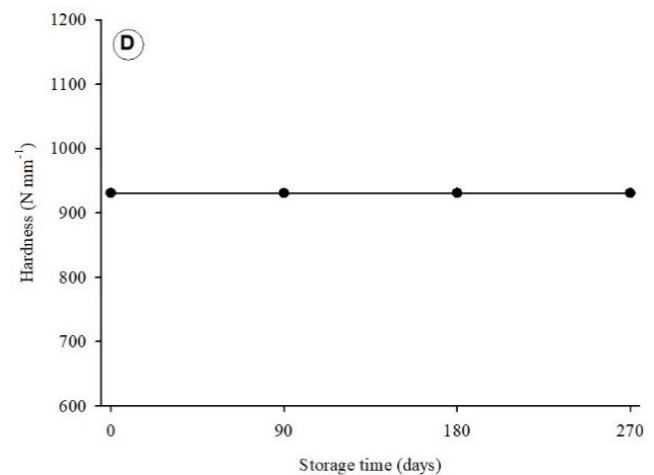
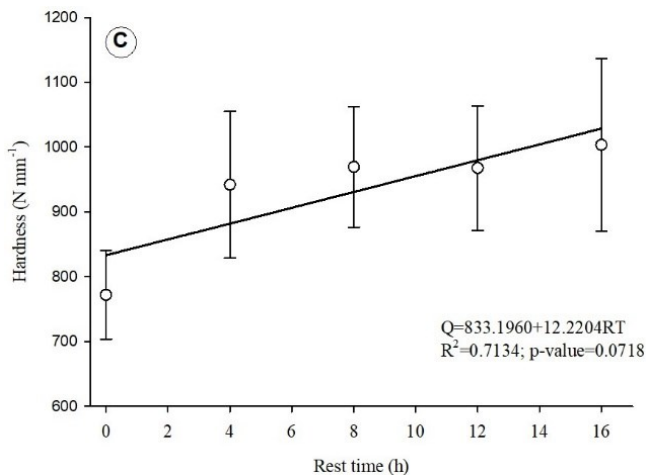
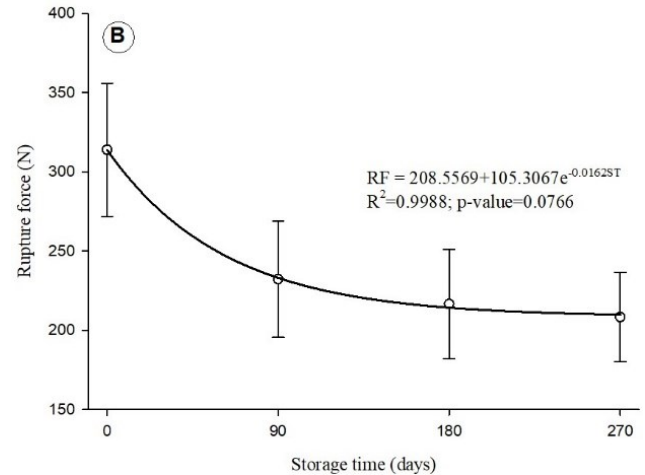
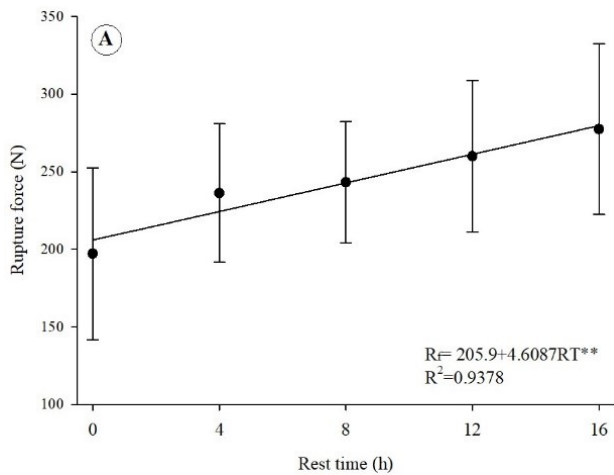
Similar results were obtained by Coradi et al. (2019), who assessed the effect of different storage conditions and observed greater membrane degradation and cell disorganization during storage due to the increase in average electrical conductivity of grains.

Rupture force was influenced by storage time and the rest time during drying (Figures 2A and 2B). Longer rest times promoted greater grain resistance; however, during storage, grains became more susceptible to rupture. Water loss during drying results in loss of volume. The continuous supply of hot air increases internal pressure, and the grain expands, which can



**Significant at $p < 0.01$.

Figure 1. Effect of rest and storage times on electrical conductivity of corn grains.



**Significant at $p < 0.01$.

Figure 2. Effect of rest time on (A, C) rupture force and harness and (B, D) storage time on rupture force and harness.

cause cracks or fissures owing to its limited expansion capacity to resist stress, making it less resistant with continuous drying or short rest times (Lima et al., 2016; Mabasso et al., 2020).

Abasi and Minaei (2014) assessed the effect of different temperatures on the mechanical properties of dried corn grains in continuous process and concluded that an increase in drying air temperature exacerbated cracks and fissures and less energy was needed for rupture, negatively affecting storage potential. Vergara et al. (2018) found that intermittent drying reduced damage and improved the storage potential of corn seeds.

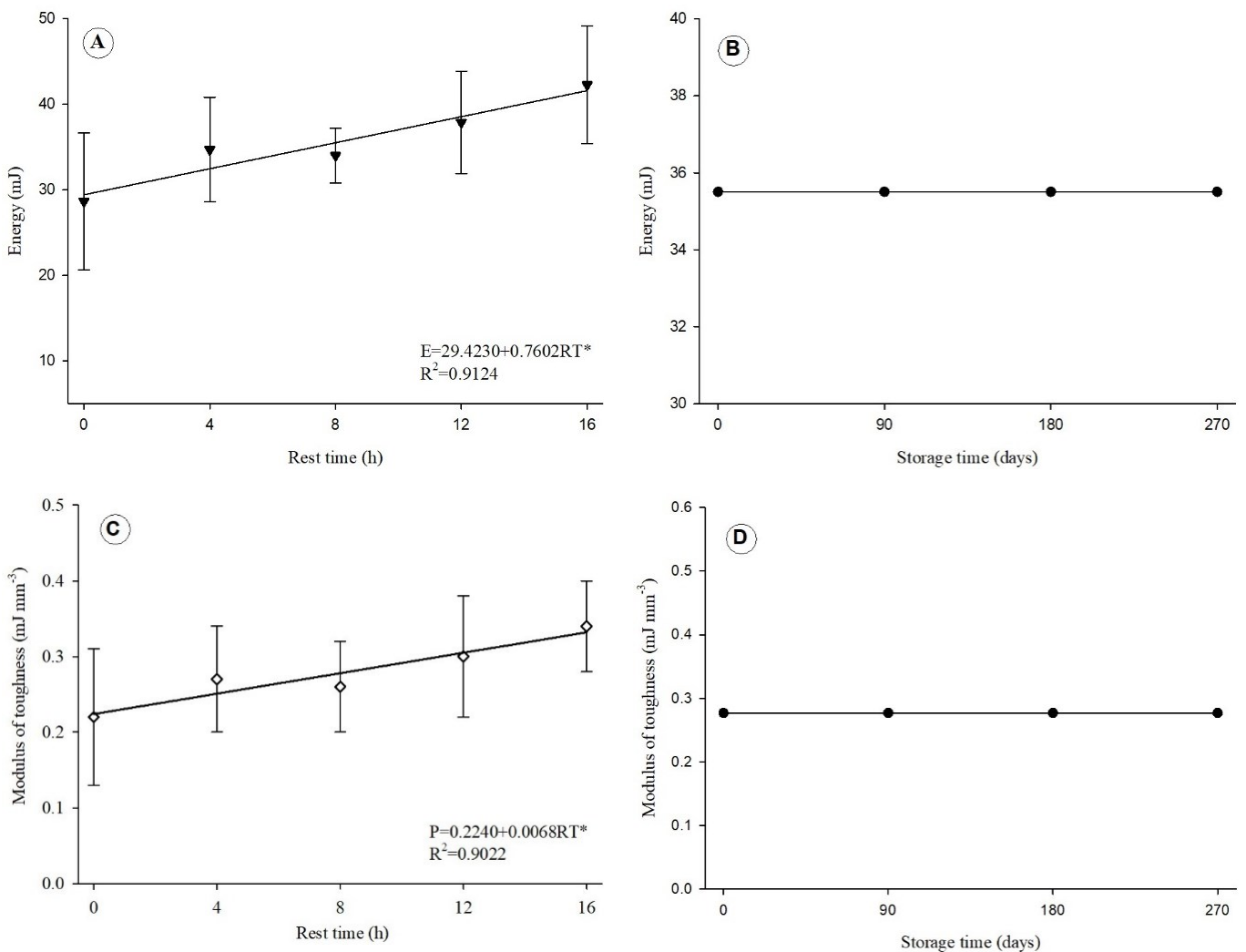
Figure 3A demonstrates the effect of rest time in intermittent drying on rupture force; however, this technique did not affect grain storage (Figure 2B) because there was a significant interaction between rest and storage times. Moreover, the rupture force of grains declined during storage, regardless of the drying system adopted, with a more marked decrease already apparent at 90 days.

According to Rodrigues et al. (2019), the force required for grain rupture is linked with its physical structure, moisture content, and resistance. The tendency for moisture content to decline in corn grains during storage may have affected their resistance and, consequently, rupture force.

Although rupture force is expected to be greater at low moisture contents, as observed in the drying of sorghum grains (Rodrigues et al., 2019), quinoa seeds (Jan et al., 2019), and crambe grains (Resende et al., 2018), the corn grain drying conditions associated with storage produce the opposite behavior, with longer rest times resulting in harder grains.

However, the grains lost this characteristic during storage, possibly due to the behavior of their cell structure, evident in the electrical conductivity analysis (Figure 1). Grain deformation until rupture was not influenced by rest or storage times, with an average deformation of 0.27 mm.

Longer rest times had a positive effect on grain hardness, with a variation rate of 12.22 N mm⁻¹ for every hour of rest at 10%



*Significant at $p < 0.05$.

Figure 3. Effect of (A) rest and (B) storage times on energy at rupture point; effect of (C) rest and (D) storage times on modulus of toughness.

Table 2. Results of analysis of Pearson's correlation between rupture force, deformation, hardness, modulus of toughness (M. of toughness), and energy of corn grains storage after drying with different rest times.

	Deformation	Hardness	M. of toughness	Energy
Rupture force	0.82**	0.32 ^{NS}	0.96**	0.94**
Deformation		-0.26 ^{NS}	0.92**	0.95**
Hardness			0.09 ^{NS}	0.01 ^{NS}
M. of toughness				0.99**

**Significant at Pearson's correlation $p < 0.01$; NS: not significant.

probability (Figure 2C). Storage time did not influence hardness (Figure 2D), corroborating the behavior observed for deformation.

Hardness tends to behave similarly to rupture force, whereby the greater the rupture force, the tougher the grain. This was also reported by Mabasso et al. (2020), who observed an increasing trend for both variables at longer rest time, immediately after drying. The average values recorded for both variables were equally low, indicating that storage potential declined at shorter rest times, which was also observed for increased electrical conductivity, due to greater cell disorganization and membrane damage.

The energy required for grain rupture was greater for longer rest times but unaffected by storage time (Figures 3A and 3B), with an average value of 35.51 mJ during storage.

The behavior of the modulus of toughness was similar to that of the previous variables (Figures 3C and 3D). Similarly, except for rupture force, storage time had no significant effect. The average modulus of toughness recorded during storage was 0.28 mJ mm⁻³. This behavior is similar to that of the energy required for rupture, since the unit volume of the grains was not affected by storage time.

Based on the Pearson's correlation data presented in Table 2, rupture force showed a positive correlation with deformation, modulus of toughness, and the energy required for grain rupture. However, this behavior was not observed for grain hardness, which, in turn, exhibited no correlation with any of the variables related to grain resistance.

Considering the existing relationship between rupture force and deformation for the remaining variables, rupture force had a greater effect. This may be because deformation did not vary for cases in which there was a direct relationship between the variables studied and deformation.

4 CONCLUSION

Grain integrity is better maintained when dried at longer rest times and stored for short periods. Rupture force increased linearly at longer rest times and declined exponentially as storage time increased. The increase in rest time produced a linear increase in hardness, energy required for grain rupture, and modulus of toughness, which, in turn, were not influenced by storage time. Grain deformation was not affected by rest or storage times.

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