Original Article
Food Science and Technology

ISSN 0101-2061 (Print)
ISSN 1678-457X (Online)

DOI: https://doi.org/10.5327/fst.00422

Influence of drying temperature on the mechanical properties of popcorn kernels

Yuri de Brito PAIVA[1], Ana Claudia Sátiro de ARAUJO[2*], Pedro Rogério GIONGO[1], Dienifer de Araújo LIMA[1], Wellysson Rafael Costa SANTOS[1], José Henrique da Silva TAVEIRA[1]

Abstract

High drying rates render desiccation protection mechanisms inefficient in grains, potentially resulting in increased susceptibility to cracks and breaks. Thus, the present study aimed to evaluate the impact of drying temperature and moisture content on the mechanical properties of popcorn kernels, determining the proportional deformity modulus, rupture force, and maximum compression force. Popcorn kernels with different moisture contents were used, dried at temperatures of 40°C, 60°C, and 40/60°C. The kernels were subjected to individual uniaxial compression, in their natural resting position, at 0.001 m s^{-1}. The results indicate that the compression force required to deform the popcorn kernels and the proportional deformity modulus increased with a decrease in the moisture content, regardless of the drying temperature. The rupture point or "bioyield point" increased as the moisture content decreased, with temperature being an influential factor in determining the point. The temperature of 60°C had the worst average for moisture content below 0.198 dry basis for the rupture force parameter, while the temperature of 40/60°C stood out from the others due to the longer induction time for the membrane desiccation protection mechanism.

Keywords: compression; mixed temperature; burst strength.

Practical Application: Optimal drying conditions to preserve popcorn quality and strength.

1 INTRODUCTION

Popcorn (*Zea mays L.*) is a food exclusively for human consumption, typical of the American continent, with its first appearance in Mexico between 7,000 and 10,000 years ago. Due to its popularization and significant increase in consumption, Brazil has become a major producer of this commodity, being the second-largest producer in the world, second only to the United States (García-Lara & Serna-Saldivar, 2019).

To achieve maximum quality along with high productivity, some stages become crucial in the production process up to the commercialization of corn seeds, which include post-harvest processing. The main objective of this stage is to maintain the physical and physiological qualities of the seeds, allowing for long-term storage and subsequent commercialization.

The drying of agricultural products is the most important process for ensuring the maintenance of grain quality, as it aims to reduce metabolic activities, thus minimizing the rate of deterioration due to biological activity and enabling long-term storage without significant losses in physiological quality. However, drying, besides causing contraction in the seeds, directly influences their other physical and mechanical properties. If performed inadequately, it can become a highly destructive process for the product (Coradi et al., 2015).

When seeds are subjected to drying, they rely on certain cellular membrane protection mechanisms that ensure they can undergo desiccation while preserving much of their structure. In most cereals, this mechanism is only efficient with slow drying and an initial moisture content of 30% (Silva et al., 2007).

However, when exposed to high drying rates with elevated temperatures aimed at reducing operation time, these mechanisms become inefficient due to the reduced time available for the induction of membrane protection. This leads to membrane rupture, causing internal and external fissures, which contribute to increased physical and mechanical damage (Menezes et al., 2012). In the case of popcorn, variables related to the drying process, such as temperature and airspeed, have a significant effect on the reduction of popping yield, expansion time, and β-carotene content (Pohndorf et al., 2019).

In this regard, several studies have observed the association of drying temperature with the decrease in mechanical resistance at different moisture contents, as is the case with forage radish seeds (Sousa et al., 2018); grain sorghum (Rodrigues et al., 2019); and wheat (Fernandes et al., 2014). However, information correlating drying and mechanical properties in popcorn crops is scarce in the literature.

Received:10/30/2024.
Accepted: 12/10/2024.
[1]*Universidade Estadual de Goiás, Santa Helena de Goiás, Goiás, Brazil.*
[2]*Universidade de São Paulo, Escola Superior de Agricultura Luiz de Queiroz, Piracicaba, São Paulo, Brazil.*
*Corresponding author: satiroagro@usp.br
Conflict of interest: nothing to declare.
Funding: The authors acknowledge the research support provided through the funding resources from the Water Security Research Call Nº 20/2023.

Therefore, given the influence of the drying method on the structural properties of the seed, seeking a better understanding of the subject becomes essential for optimizing various stages of agricultural production. This motivates the present study, which aimed to evaluate the influence of drying temperature and moisture content on the mechanical properties of popcorn.

1.1 Relevance of the work

This study presents essential insights into the relationship between drying processes and the structural integrity of popcorn kernels, a critical factor influencing the quality and marketability of the product. By evaluating the effects of temperature and moisture content on the mechanical properties of the kernels, the research contributes to the establishment of optimal drying conditions aimed at minimizing physical damage and preserving structural resilience. The findings of this study offer a significant contribution to the agricultural industry, supporting the optimization of processing and storage practices, thereby ensuring a superior final product and reducing economic losses.

2 MATERIALS AND METHODS

The experiment was conducted at the State University of Goiás (UEG) in Santa Helena de Goiás. Drying took place at the Post-Harvest Laboratory of Plant Products at the Federal Institute of Education, Science and Technology of Goiás – Rio Verde Campus (IF Goiano – Rio Verde Campus), and the mechanical properties were analyzed at the UEG in Anápolis, Goiás.

The seeds, donated by the Santa Cecilia farm, were harvested and manually shelled. To determine the initial moisture content, the gravimetric method was used, which involves drying the grain in an oven with forced ventilation, maintained at a temperature of 105 ± 1°C for approximately 24 h, in three repetitions.

The grains had a moisture content of 27% wet basis (w.b.), after which drying began in an oven at temperatures of 40°C, 60°C, and 40/60°C. Following this process, mechanical property analyses were conducted at moisture contents of 0.37, 0.307, 0.250, 0.198, and 0.149 dry basis (d.b.). The reduction in the moisture content was monitored by weighing three trays with 500 g of grains, kept under the same drying conditions.

The parameters for determining the mechanical properties were obtained through compression testing of the seeds using a "TA.HDi Texture Analyzer" universal testing machine, with a 500 N load cell. The seeds were subjected to individual uniaxial compression, applied in their natural resting position (Figure 1), at a force application rate of 0.001 m s^{-1}, on 20 popcorn kernels.

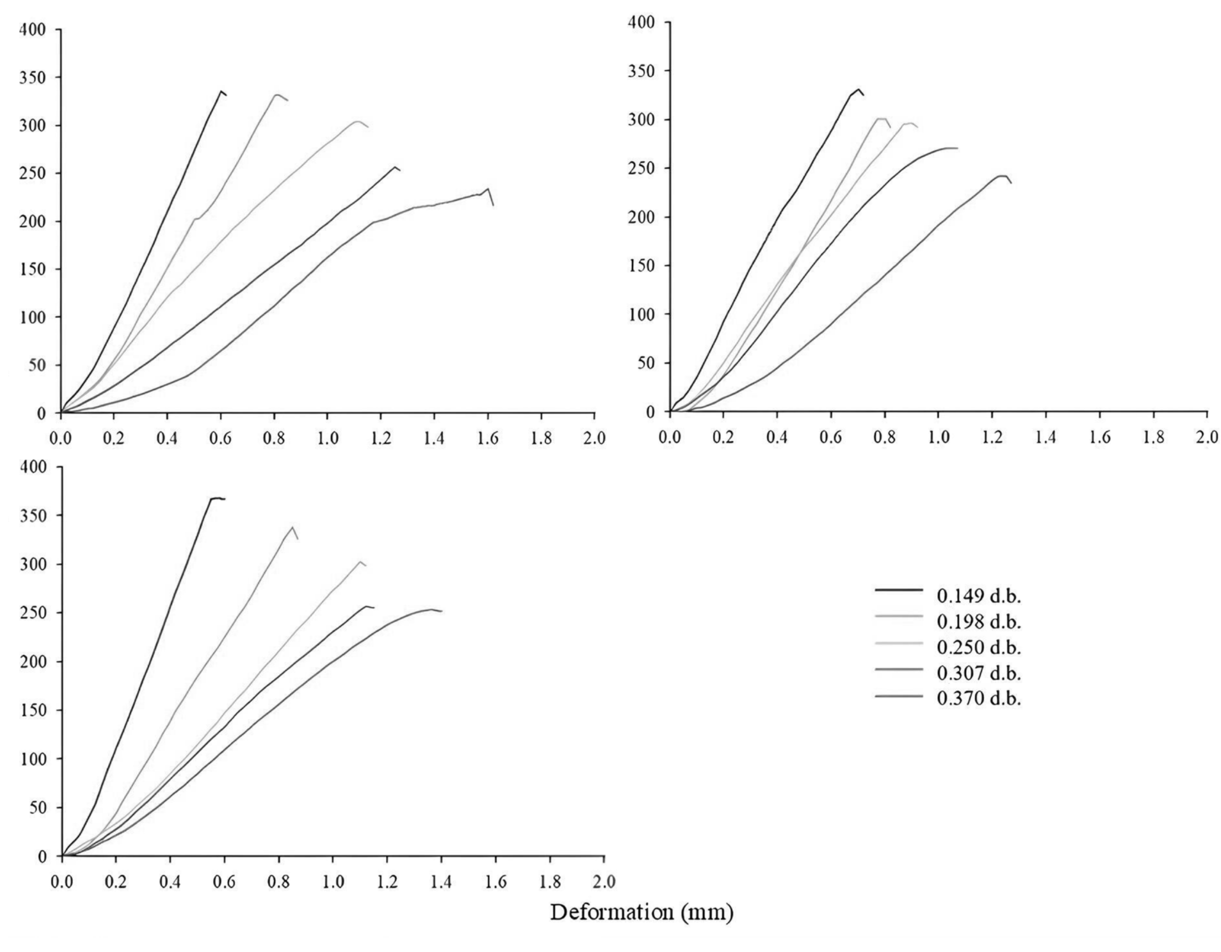


Figure 1. Mean compression force values (N) as a function of deformations (mm) for drying temperatures of A (40°C), B (60°C), and C (40/60°C) of popcorn kernels.

Initially, by obtaining the applied force versus deformation curves, the "bioyield point" was extracted. This point is defined as the position on the curve where increased deformation of the product is associated with the onset of a decrease in compression force (Figure 2). This phenomenon characteristically indicates the beginning of the product's structural rupture (Rodrigues, 2018).

To represent the behavior of the grain during the compression test, compression curves were generated as a function of moisture content and deformation for the three drying temperatures. The deformity modulus delineates the total deformation when a product undergoes compression, allowing for the comparison of resistance between various materials (Resende et al., 2007). It can be determined according to Equation 1, for deformations of 0.05, 0.10, 0.15, 0.2, 0.25, 0.30, 0.35, 0.4, 0.45, and 0.50 mm.

$$Ep=\frac{E}{1-\mu^2}=\frac{0.531\times F}{D^{\frac{3}{2}}}\cdot\left[2.\left(\frac{1}{r}+\frac{1}{R}\right)^{\frac{1}{3}}\right]^{\frac{3}{2}} \quad (1)$$

Where

Ep: proportional deformity modulus, Pa;

E: modulus of elasticity, Pa;

F: compression force, N;

μ: Poisson's ratio, varying from 0.2 to 0.5 for agricultural products;

D: total deformation (sum of elastic and plastic), m;

r and R: radius of curvature of the body at the points of contact, m.

The values of the radius of curvature (*r* and *R*) of the seeds at the points of contact were obtained by fitting a circumference to the body's curvature, according to the coordinate planes relevant to the compression position as per Couto et al. (2002).

The experimental design used was completely randomized, with the experiment set up in a 3 × 5 factorial scheme (three drying temperatures and five moisture contents). The data were

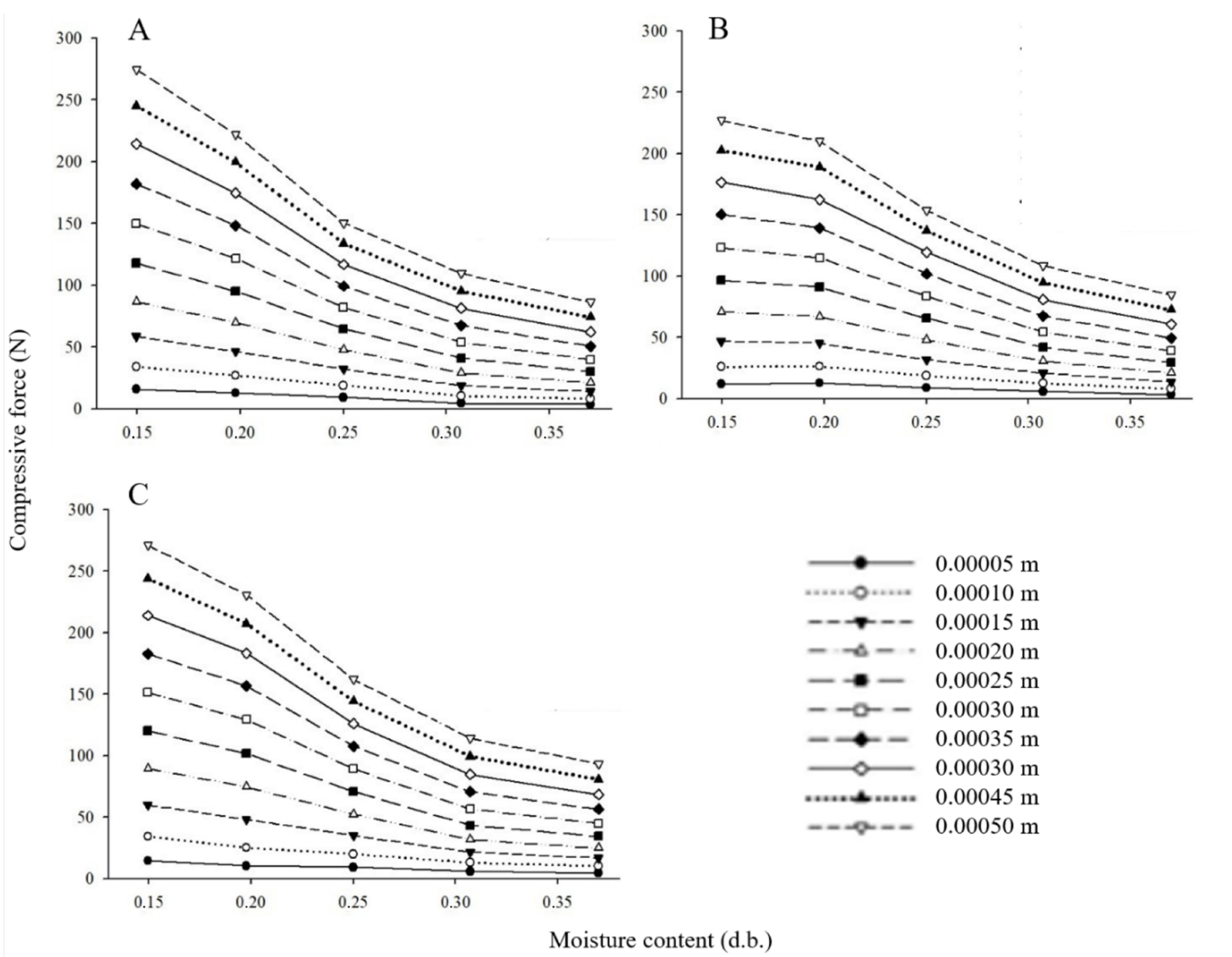


Figure 2. Average maximum compression force values (N) for drying temperatures of **A** (40°C), **B** (60°C), and **C** (40/60°C), as a function of the moisture content (dry basis) of popcorn kernels.

subjected to regression analysis at a 5% significance level to verify the effects of drying temperatures on the mechanical properties of popcorn kernels, using the SigmaPlot software.

3 RESULTS AND DISCUSSION

The average compressive force values as a function of deformation in the popcorn kernels are presented in Figure 1. It was observed that, at all three drying temperatures, the compression forces are proportional to the increase in deformations.

However, the product tends to offer greater resistance to compression as the moisture content decreases. This phenomenon is closely related to the aggregation of the cellular matrix with the reduction in the moisture content (Rodrigues et al., 2019).

The “bioyield point” or rupture point was extracted at the end of the inflection of each deformation curve. It was observed that the reduction in the moisture content resulted in “bioyield points” with progressively smaller deformations and increasingly higher compression forces. In other words, the force required to break the structure of the product increased as the moisture content decreased. This is due to the stiffening of the structural wall caused by the removal of water from the grain (Gupta & Das, 2000), as well as the cells becoming smaller and less turgid.

Abasi and Minaei (2014) concluded in their study that an increase in the drying temperature from 40 to 70°C, on average, decreased the rupture stresses by 38% (from 60.898 to 45.192 MPa), and that the rupture stress data versus drying temperatures can be well represented by a linear relationship.

In Figure 2, the average compression force values are plotted against the moisture content for selected deformities. It was observed that reducing the moisture content for the same deformation led to an increase in compression force.

These findings corroborate those from Figure 1, showing that lower moisture content requires greater force for material deformation, thereby directly increasing the material’s resistance to mechanical damage.

This result aligns with Zhu et al. (2023), who studied different corn varieties with varying moisture contents and observed that decreasing the moisture content increases the compression resistance of grains. Similar results were also found by Resende et al. (2007) in their evaluation of beans and by Sousa et al. (2018) in their assessment of forage turnip seeds.

The compression forces for the selected deformations ranged from 3.70 to 274.75 N, 3.43 to 227.16 N, and 4.72 to 271.22 N for temperatures of 40°C, 60°C, and 40/60°C, respectively (Figure 2). It was noted that the temperature of 60°C resulted in the lowest compression force. This is attributed to the high rate of water removal from the grain, which contributes to the inefficiency of the membrane desiccation protection mechanism, making the structural wall of the product less tight and more susceptible to cracks and breakage.

According to Pohndorf et al. (2019), in the case of popcorn kernels, the reduction in popping yield and expansion capacity may be associated with the formation of cracks in grains subjected to high drying temperatures, with the best results observed at drying temperatures between 40 and 50°C. To evaluate the effect of drying temperature on grain deformation, the accuracy of the results depends on the physical properties of the grains used (Abasi & Minaei, 2014).

The average values of curvature radii for popcorn kernels at each temperature, used to determine the proportional modulus of deformation, are described in Table 1. It was observed that these radii varied with moisture content and temperature, yet a clear trend of contraction was not discernible. This variability can be attributed to the high heterogeneity of the biological materials under analysis. According to Abasi and Minaei (2014), ideally, these values should be identical or very close, which is challenging to achieve in reality. Similar results were found by Rodrigues et al. (2019) in their evaluation of grain sorghum and by Fernandes et al. (2014) in their study of wheat grains.

Table 2 presents the equations adjusted to the experimental values of the proportional modulus of deformation (Ep) of popcorn kernels as a function of moisture content (X) and deformation (D) for the evaluated drying temperatures.

It was noted that the coefficient of determination (R^2) exceeded 80%, indicating a good fit of the model to the analyzed data.

Table 2. Equations adjusted to the experimental values of the proportional modulus of deformation (Ep) of popcorn kernels as a function of moisture content (X) and deformation (D), for the drying temperatures evaluated.

Temperature (°C)	Model	R^2 (%)
40	Ep = 134,179−282,287X−47,135,069D	0.893**
60	Ep = 116,467−224,223X−45,561,221D	0.875**
40/60	Ep = 135,829−277,773X−47,046,301D	0.926**

**Significant at 1% by the F-test.

Table 1. Average curvature radius values for popcorn kernels (m) at each temperature (°C), for each moisture content (% dry basis).

Moisture content (% dry basis)	Temperature					
	40°C		60°		40/60°C	
	R	r	R	r	R	r
0.15	0.00897	0.00474	0.00853	0.00488	0.00833	0.00449
0.20	0.00850	0.00491	0.00785	0.00449	0.00829	0.00457
0.25	0.00822	0.00480	0.00779	0.00455	0.00829	0.00466
0.31	0.00786	0.00444	0.00738	0.00451	0.00858	0.00467
0.37	0.00803	0.00460	0.00786	0.00443	0.00787	0.00465

Figure 3 presents the average values of the proportional modulus of deformation of popcorn kernels as a function of moisture content and deformation, for drying temperatures of A (40°C), B (60°C), and C (40/60°C), where the response surface illustrates the adjusted equations obtained from Table 2.

It was observed that for all drying temperatures, there was an increase in the proportional modulus of deformation as the moisture content and deformation decreased. This result exhibits the same behavior found in compression force as a function of moisture content.

Similar findings were reported by Ribeiro et al. (2007) in their evaluation of the mechanical properties of soybeans and by Santos (2016) assessing the mechanical properties of safflower grains. However, contrasting results were found by Oliveira et al. (2017) in their study of baru fruits, where there was an increase in the proportional modulus with increasing deformation.

The values of the proportional modulus of deformation for the selected moisture contents varied from 21.46×10^{-7} to 120.90×10^{-7} (N m^{-2}); 21.38×10^{-7} to 92.14×10^{-7} (N m^{-2}); and 23.17×10^{-7} to 114.99×10^{-7} (N m^{-2}) for temperatures of 40°C,

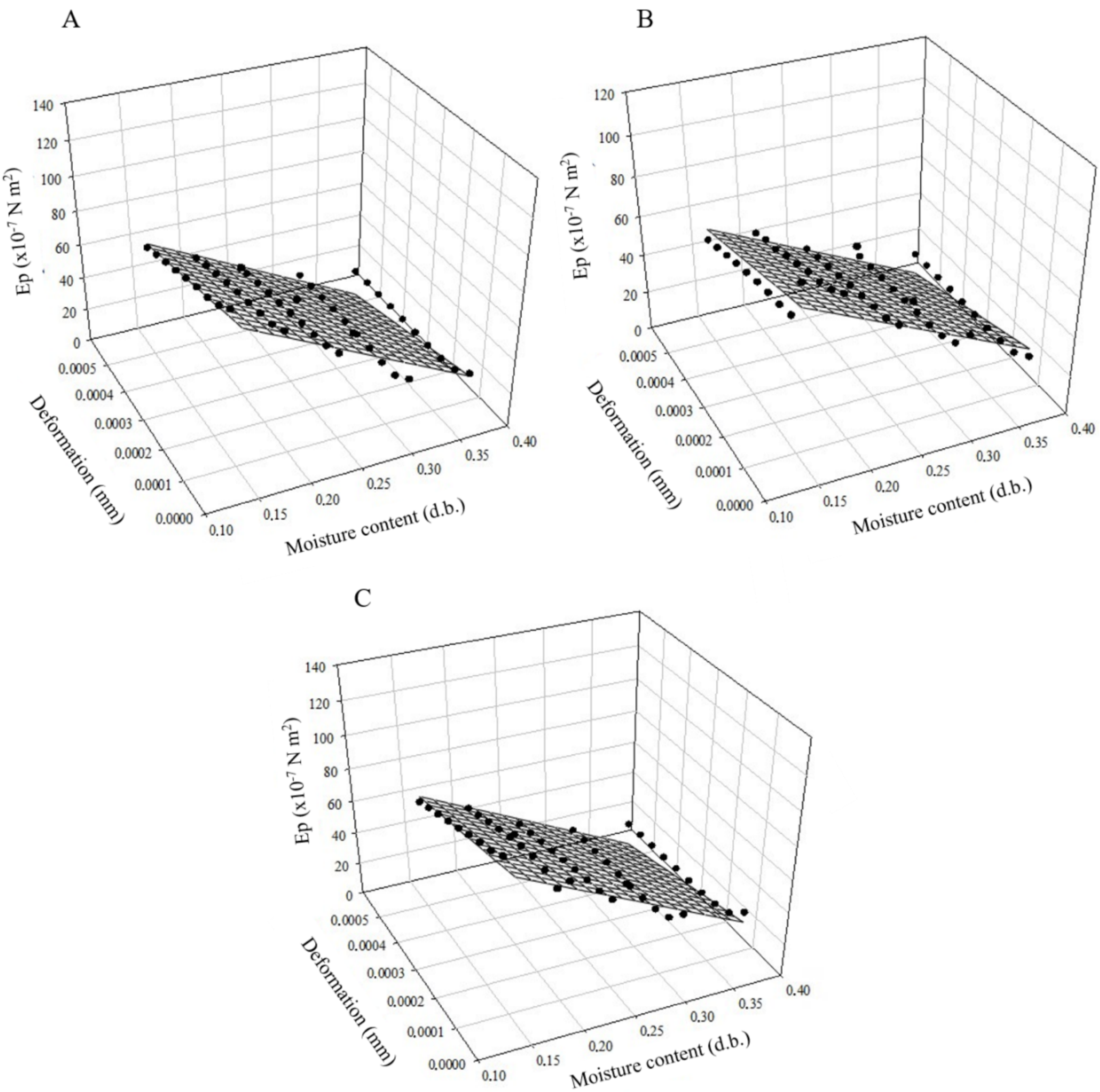


Figure 3. Average values of the proportional modulus of deformation (N m^{-2}) of popcorn kernels as a function of moisture content (dry basis) and deformation (m), for drying temperatures of **A** (40°C), **B** (60°C), and **C** (40/60°C).

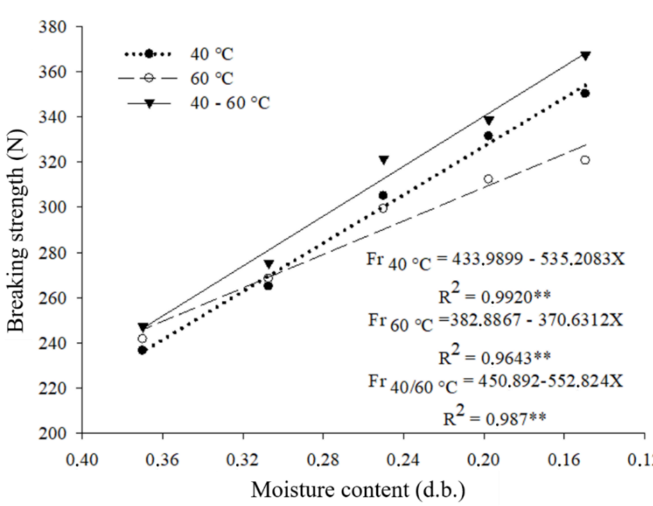
60°C, and 40/60°C, respectively. Ribeiro et al. (2007) studied the proportional modulus under natural compression resting conditions of soybean grains at 35°C, with moisture content ranging from 0.58 to 0.093 (d.b.), obtaining values of the proportional modulus of deformation ranging from 23.1×10^{-7} to 106.9×10^{-7} (N m^{-2}). In another study, Rodrigues et al. (2019) investigated the proportional modulus of deformation for sweet sorghum grains, obtaining values between 87×10^{-7} and 354.99×10^{-7} (N m^{-2}), 132.63×10^{-7} and 465.98×10^{-7} (N m^{-2}), and $80.18 \times 1\ 0^{-7}$ and 429.85×10^{-7} (N m^{-2}) for moisture content ranging from 0.260 to 0.014 (d.b.), dried at 60°C, 80°C, and 100°C, respectively.

The average rupture forces of popcorn kernels, as a function of moisture content and drying temperature, are represented in Figure 4.

It was observed that for all temperatures, there was a linear increase in rupture force with decreasing moisture content. This phenomenon is closely linked to the densification of the cellular matrix caused by desiccation, which promotes greater rigidity and consequently greater physical protection (Goneli, 2008).

The average forces to reach the "bioyield point" of popcorn kernels ranged from 236.49 to 350.22 N; 241.58 to 320.70 N; and 247.20 to 367.41 N for temperatures of 40°C, 60°C, and 40/60°C, respectively. It was observed that in addition to moisture content, temperature also influenced the rupture force. The highest temperature (60°C) showed the lowest average rupture force, whereas the mixed temperature (40/60°C) outperformed others, especially for moisture contents below 0.198 (d.b.).

These findings are consistent with Rodrigues et al., 2019, who analyzed the mechanical properties of grain sorghum with moisture contents ranging from 0.515 to 0.099 (d.b.) at drying temperatures of 60°C, 80°C, and 100°C. They found that lower temperatures and moisture contents below 0.162 (d.b.) yielded the best average rupture forces.



**Significant at 1% by F-test.

Figure 4. Average values of the maximum rupture force (N) of popcorn kernels as a function of moisture content (dry basis) for drying temperatures (40°C, 60°C, and 40/60°C).

4 CONCLUSION

The compression force required to deform popcorn kernels increases as the moisture content decreases, regardless of the drying temperature.

The proportional modulus of deformation increases as both moisture content and deformation are reduced, independent of the drying temperature.

The rupture point or "bioyield point," resulting from the rupture force, increases as the moisture content decreases, with temperature being a significant factor in determining this point.

The temperature of 60°C showed the lowest average rupture force for moisture contents below 0.198 (d.b.), whereas the temperature of 40/60°C outperformed others, attributed to a longer induction time for membrane protection against desiccation.

Drying at 40/60°C can be recommended for the safe and effective preservation of the internal structures of popcorn kernels.

REFERENCES

Abasi, S., & Minaei, S. (2014). Effect of drying temperature on mechanical properties of dried corn. *Drying Technology*, *32*(7), 774–780. https://doi.org/10.1080/07373937.2013.845203

Coradi, P. C., Lacerda Filho, A. F., Chaves, J. B. P., & Melo, E. C. (2015). Quantification of physical losses products in a plant of feed. *Revista Engenharia na Agricultura*, *23*(2), 105–118. https://doi.org/10.13083/reveng.v23i2.421

Couto, S. M., Batista, C. S., Peixoto, A. B., & Devilla, I. A. (2002). Comportamento mecânico de frutos de café: módulo de deformidade. *Revista Brasileira de Engenharia Agrícola e Ambiental*, *6*(2), 285–294. https://doi.org/10.1590/S1415-43662002000200018

Fernandes, L. S., Corrêa, P. C., Diniz, M. D. M. S., Leite, D. M., & Vasconcellos, D. S. L. (2014). Influência do teor de água nas propriedades mecânicas dos grãos de trigo submetidos à compressão. *Bioscience Journal*, *30*(1), 219–223. https://seer.ufu.br/index.php/biosciencejournal/article/view/18008

García-Lara, S., & Serna-Saldivar, S. O. (2019). Corn history and culture. In S. O. Serna-Saldivar (Ed.), *Corn - Chemistry and Technology*, (3rd ed., pp. 1–18). AACC International. https://doi.org/10.1016/B978-0-12-811971-6.00001-2

Goneli, A. L. D. (2008). *Variação das propriedades físico-mecânicas e da qualidade de mamona (Ricinus communis L.) durante a secagem e o armazenamento*. [Tese de doutorado, Universidade Federal de Viçosa]. https://locus.ufv.br/items/e8700caf-5ba2-49f1-a51c-c3a1099f9b59

Gupta, R. K., & Das, S. K. (2000). Fracture resistance of sunflower seed and kernel to compressive loading. *Journal of Food Engineering*, *46*(1), 1–8. https://doi.org/10.1016/S0260-8774(00)00061-3

Menezes, N. L., Pasqualli, L. L., Barbieri, A. P. P., Vidal, M. D., & Conceição, G. M. (2012). Temperaturas de secagem na integridade física, qualidade fisiológica e composição química de sementes de arroz. *Pesquisa Agropecuária Tropical*, *42*(4), 430–436. https://doi.org/10.1590/S1983-40632012000400011

Oliveira, D. E. C., Resende, O., & Devilla, I. A. (2017). Mechanical properties of baru fruit (Dipteryx alata Vogel). *Semina: Ciências Agrárias*, *38*(1), 185–196, 2017. http://doi.org/10.5433/1679-0359.2017v38n1p185

Pohndorf, R. S., Lang, G. H., Ferreira, C. D., Ziegler, V., Goebel, J. T., & Oliveira, M. (2019). Kinetic evaluation and optimization of red popcorn grain drying: Influence of the temperature and air velocity on the expansion properties and β-carotene content. *Journal of Food Process Engineering*, *42*(6), Article e13204. https://doi.org/10.1111/jfpe.13204

Resende, O., Corrêa, P. C., Ribeiro, D. M., & Figueiredo Neto, A. (2007). Comportamento mecânico dos grãos de feijão submetidos a compressão. *Revista Brasileira de Engenharia Agrícola e Ambiental*, *11*(4), 404–409. https://doi.org/10.1590/S1415-43662007000400010

Ribeiro, D. M., Corrêa, P. C., Furtado, B. F., Goneli, A. L. D., & Resende, O. (2007). Propriedades mecânicas dos grãos de soja em função do teor de água. *Engenharia Agrícola*, *27*(2), 493–500. https://doi.org/10.1590/S0100-69162007000300019

Rodrigues, G. B. (2018). *Propriedades físicas e mecânicas das sementes de sorgo granífero (sorghum bicolor l. moench) durante a secagem e qualidade fisiológica durante o armazenamento*. [Dissertação de mestrado, Instituto Federal de Educação, Ciência e Tecnologia Goiano]. https://sistemas.ifgoiano.edu.br/sgcursos/uploads/anexos_5/2019-07-31-10-57-1808-%20Gabrielly.pdf

Rodrigues, G. B., Resende, O., Oliveira, D. E. C., Silva, L. C. M., & Ferreira Junior, W. N. (2019). Mechanical properties of grains sorghum subjected to compression at different moisture contents. *Journal of Agricultural Science*, *11*(4), Article 279. https://doi.org/10.5539/jas.v11n4p279

Santos, C. C. (2016). *Propriedades mecânicas de grãos de cártamo submetidos à secagem*. [Trabalho de Conclusão de Curso, Universidade Federal da Grande Dourados]. https://repositorio.ufgd.edu.br/jspui/handle/prefix/3407

Silva, P. A., Diniz, K. A., Oliveira, J. A., & Von Pinho, É. V. R. (2007). Análise fisiológica e ultra-estrutural durante o desenvolvimento e a secagem de sementes de soja. *Revista Brasileira de Sementes*, *29*(2), 15–22. https://doi.org/10.1590/S0101-31222007000200003

Sousa, K. A., Resende, O., Ullmann, R., & Smaniotto, T. A. S. (2018). Propriedades mecânicas das sementes de Raphanus sativus L. *Revista Ciência Agronômica*, *49*(3), 437–442. https://doi.org/10.5935/1806-6690.20180049

Zhu, X., Chi, R., & Ma, Y. (2023). Effects of corn varieties and moisture content on mechanical properties of corn. *Agronomy*, *13*(2), Arcticle 545. https://doi.org/10.3390/agronomy13020545