WHEAT GRAINS HYDRATION: CHANGES IN THE PHYSICAL PROPERTIES WITH INCREASING MOISTURE CONTENT

HIDRATAÇÃO DOS GRÃOS DE TRIGO: ALTERAÇÕES NAS PROPRIEDADES FÍSICAS COM O AUMENTO DO TEOR DE UMIDADE

HIDRATACIÓN DE LOS GRANOS DE TRIGO: CAMBIOS EN LAS PROPIEDADES FÍSICAS CON EL AUMENTO DEL CONTENIDO DE HUMEDAD

https://doi.org/10.56238/edimpacto2025.085-003

Bianca Guimarães[1]

ABSTRACT
Wheat is a grass-type plant that is grown almost everywhere in the world. It is widely used in the production of many food products, with growing interests by the the brewing industry. In this context, the way by how grains' physical properties change over the hydration has become essential to design processes and equipments involved in the malting steps. Thus, the objective of this work was to evaluate the influence of moisture content (14.40–90.90% dry basis) on the physical properties (dimensions, porosity, surface area and density) of wheat grains. Moreover, different mathematical models were tested to fit the experimental values. It was found that most of the physical properties varied significantly ($p < 0.05$) with increasing moisture content and were well correlated by means of a second order polynomial model. In this way, because wheat is one of the main grains produced in the world, these results are important for to design safer and more efficient equipment and to improve processes that involve this type of grain.

Keywords: Malt. Influence. Mathematical Models. Design.

RESUMO
O trigo é uma planta do tipo gramínea cultivada em quase todo o mundo. É amplamente utilizado na produção de diversos produtos alimentícios, com crescente interesse pela indústria cervejeira. Nesse contexto, a forma como as propriedades físicas dos grãos mudam ao longo da hidratação tornou-se essencial para o projeto de processos e equipamentos envolvidos nas etapas de maltagem. Assim, o objetivo deste trabalho foi avaliar a influência do teor de umidade (14,40–90,90% base seca) nas propriedades físicas (dimensões, porosidade, área superficial e densidade) dos grãos de trigo. Além disso, diferentes modelos matemáticos foram testados para ajustar os valores experimentais. Verificou-se que a maioria das propriedades físicas variou significativamente ($p < 0,05$) com o aumento do teor de umidade e foram bem correlacionadas por meio de um modelo polinomial de segunda ordem. Dessa forma, por ser o trigo um dos principais grãos produzidos no mundo, esses

[1] Dr. in Food Engineering and Science. Universidade Estadual Paulista "Júlio de Mesquita Filho" (UNESP). São Paulo, Brazil. E-mail: biancaguimaraeseng@gmail.com Orcid: 0000-0001-7076-0070
Lattes: 5758189501582163

resultados são importantes para o projeto de equipamentos mais seguros e eficientes e para o aprimoramento de processos que envolvem esse tipo de grão.

Palavras-chave: Malte. Influência. Modelos Matemáticos. Design.

RESUMEN

El trigo es una planta herbácea que se cultiva en casi todo el mundo. Se utiliza ampliamente en la producción de numerosos productos alimenticios, con un creciente interés en la industria cervecera. En este contexto, la forma en que las propiedades físicas de los granos cambian durante la hidratación se ha vuelto esencial para diseñar procesos y equipos involucrados en las etapas de malteado. Por lo tanto, el objetivo de este trabajo fue evaluar la influencia del contenido de humedad (14,40–90,90% en base seca) en las propiedades físicas (dimensiones, porosidad, área superficial y densidad) de los granos de trigo. Además, se probaron diferentes modelos matemáticos para ajustar los valores experimentales. Se encontró que la mayoría de las propiedades físicas variaron significativamente ($p < 0,05$) con el aumento del contenido de humedad y estaban bien correlacionadas mediante un modelo polinomial de segundo orden. De esta manera, dado que el trigo es uno de los principales granos producidos en el mundo, estos resultados son importantes para diseñar equipos más seguros y eficientes y para mejorar los procesos que involucran este tipo de grano.

Palabras clave: Malta. Influencia. Modelos Matemáticos. Diseño.

1 INTRODUCTION

Wheat (Triticum spp.) is undoubtedly one of the oldest agricultural crops in the world and is an important cereal not only due to its productive potential but also to its chemical composition, technological properties and nutritional value (Noello et al., 2012). It has been considered as one of the most produced grains around the world, losing place only to corn and rice (Faostat, 2019). Currently, wheat has been increasingly used for beer production in replacement or together with barley as a malted cereal.

Malting is an industrial process which consists of an initial hydration, followed by germination and drying operations. In this process, the carbohydrate-rich grains are stimulated to germinate at high moisture content, thus modifying their composition and developingenzymes such as α- and β-amylase (Pyler & Thomas, 2000). The moisture content reduction by drying methods are, then, used to stop germination and maintain the desired level of enzymatic activity.

The adequate malting is dependent on many parameters such as the initial quality of the grain, chemical composition, characteristics of the endosperm (Chandra et al., 1999) and the design of the own malting conditions

The grains hydration step is complex and can be governed by different mechanism as capilatity and diffusion. Studying how the physical properties of the grains are affected during water uptake provides important information for the correct design of heat and mass transfer operations. Grains dimension, surface area, bulk density and porosity may be altered, making unsuitable equipment and conditions previously designed to process dried grains instead moisty ones. Therefore, the experimental determination of the physical properties with varying moisture content becomes essential for the calculation of the necessary parameters involved in the malting procedure (Al-Mahasneh & Rababah, 2007). In additional to the experimental measurements, their mathematical modeling provides ready-to-use information for process control as well as to predict data trend with increasing moisture content

Although the physical properties of wheat grains have been studied (Belcar et al., 2020; Kandel et al.,2022), there is a lack of information in the literature on these properties over a wide range of moisture content, mainly the ones used in the malting process. Considering the necessity for this information, this work aimed at evaluating the influence of the moisture content (from 14.40 up to 90.90% b.s.) on the physical properties of the grains.

2 MATERIAL AND METHODS

Wheat grains (Triticum aestivum) of Toruk variety, with initial water content of 14.40% d.b. supplied by Malteria Blumenau (Blumenau-SC, Brazil), were used. Samples were stored for 60 days in 10 kg polypropylene containers in an environment with relative humidity (<40%) and temperature of 273.15 K (± 2 K). The wheat grains were previously subjected to a cleaning and selection process so that only the grains in perfect condition were used.

The initial moisture content of the wheatwere determined by the oven method with forced air circulation at 378.15 K (± 1 K), in triplicate, until reaching constant mass (AOAC, 2010).

For the study of the physical properties of the grains, it was necessary to artificially humidify the product to obtain the different levels of desired water content, varying from 14.40 to 90.90% d.b.. The determination of the water uptakeby the sample was performed by mass difference from the initial water content according to Eq. 1.

$$M_a = \frac{M_i (X_f - X_i)}{X_i + 100} \qquad (1)$$

Where:

Ma - the mass of water added in the sample, kg;

Mi - the initial mass of the sample, kg;

Xf - the final moisture of the wheat, % b.s.;

Xi - the initial moisture of the wheat, % b.s..

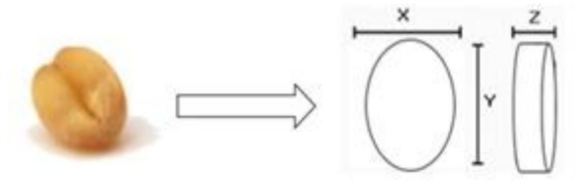
Once the desired moisture content was obtained, the product was homogenized for one week and had the physical properties determined. The following physical properties were determined: grain size, arithmetic mean diameter, geometric mean diameter, sphere diameter, sphericity, mass of a thousand grains, surface area, bulk density, real density and porosity of the granular mass.

2.1 DIMENSIONS OF THE GRAIN

The dimensions of the wheat grain, length (x), width (y) and thickness (z) were obtained from the measurement of the three orthogonal axes (Figure 1) along the wetting process using a digital caliper with an accuracy of 5 10-5 m (Sologubik et al., 2013).

Figure 1

Schematic drawing of wheat grain with its characteristic dimensions



2.2 DIAMETERS OF THE GRAIN

The arithmetic mean diameter (Da) and the geometric mean diameter (Dg) of the grainswere calculated using Eqs. 2 and 3 (Mohsenin, 1986).

$$D_a = \frac{x+y+z}{3} \qquad (2)$$

$$D_g = (xyz)^{\frac{1}{3}} \qquad (3)$$

Where:
Da - the arithmetic mean diameter, m;
Dg - the geometric mean diameter, m;
X - length, m;
y - width, m;
z - thickness, m.

The equivalent diameter of a sphere (Desf) was obtained by equalizing the volume of the wheat grain to the volume of a sphere. Thus, it was possible to calculate the diameter of this volume according to Eq. 4.

$$D_{esf} = \frac{(6V)^{\frac{1}{3}}}{\pi} \qquad (4)$$

Where:
Desf - equivalent diameter of a sphere, m;
V- volume of a grain, m³.
Sphericity ( ), mass of 1000 grains (M1000) and surface area (S)

The sphericity ( ) of the wheat grains was calculated using Eq. 5 (Mohsenin, 1986).

$$\phi = \left[\frac{(xyz)^{\frac{1}{3}}}{x} \right] 100 \qquad (5)$$

Where:

- sphericity, %;

X - length, m;

y - width, m;

z - thickness, m.

The mass of 1000 grains (M1000) was determined following the counting method described by Brasil (2009), selecting randomly 100 grains of wheat with mass determined in an analytical balance. The results are multiplied by 10 to obtain the mass of 1000 grains .

The surface area of the wheat grains (S), expressed in m², was obtained by the geometric mean diameter analogous to a sphere (Eq. 6):

$$S = \pi D_g^{\ 2} \qquad (6)$$

Where:

S - surface area, m²;

Dg - the geometric mean diameter, m;

Bulk density (apparent) (ρb), real density (ρt) and porosity (ε)

The bulk density (ρb) was determined from the mass of grains occupying a total volume of 8 10-5 m³ (Vilche et al., 2003).

$$\rho_b = \frac{m_{grains}}{V_{recipient}} \qquad (7)$$

Where:

- bulk density, kg m-³;

mgrains - the mass of grains occupying a volume of 8 10-5 m³, kg;

Vrecipient - 8 10-5 m³.

The actual density (ρt), defined as the ratio of grain mass to total volume, was determined by the toluene displacement.

The porosity (ε) of the grain layer was defined by the fraction not occupied by the grains:

$$\varepsilon = \left(1 - \frac{\rho_b}{\rho_t}\right)100 \qquad (8)$$

Where:

ε - porosity, %;

 - bulk density, kg m-³;

 - actual density, kg m-3;

Statistical analyses and mathematical modeling

The experimental data were submitted to Analysis of Variance (ANOVA) and comparison of means by the Duncan test, at a level of 5% of significance, was performed usingthe Statistica 12 software (Statsoft Inc., Tulsa, USA).

Different empirical models were used to fit the mean experimental values of the physical properties. All of the models represented a given property as a function of the moisture content. The accuracy of fit was evaluated by the determination coefficient. For this, the Microsoft Excel software was used to fit the experimental data.

3 RESULTS AND DISCUSSIONS

Physical properties were experimentally determined and the mean values and standard deviation calculated. Table 1 presents these data for the physical properties of wheat grains as a function of moisture content (d.b.). It was possible to observe that all of the physical properties varied significantly ($p < 0.05$) with increasing moisture content from 14.40 to 90.90% d.b.., except for the thickness (z) and the porosity ( ) ($p > 0.05$).

Table 1

Physical properties of wheat grain for different moisture contents (means ± standard deviation)

	Moisture content (% - g of water per 100 g of dry matter)										
Physical properties	**14.40**	**22.05**	**29.70**	**37.35**	**45.00**	**52.65**	**60.30**	**67.95**	**75.60**	**83.25**	**90.90**
x (10^3)	6.46± 0.04^{b}	6.42± 0.05^{bc}	6.39± 0.01^{bcd}	6.34± 0.01^{de}	6.25± 0.01^{fg}	6.19± 0.02^{g}	6.28± 0.05^{ef}	6.36± 0.04^{cd}	6.41± 0.08^{bcd}	6.45± 0.04^{b}	6.55± 0.05^{a}
y (10^3)	3.29± 0.04^{c}	3.36± 0.16^{bc}	3.41± 0.01^{abc}	3.49± 0.04^{ab}	3.51± 0.01^{ab}	3.54± 0.12^{a}	3.51± 0.01^{ab}	3.52± 0.10^{a}	3.53± 0.15^{a}	3.53± 0.06^{a}	3.50± 0.02^{ab}
z (10^3)	2.62± 0.02^{a}	2.63± 0.06^{a}	2.64± 0.03^{a}	2.65± 0.08^{a}	2.63± 0.04^{a}	2.65± 0.09^{a}	2.66± 0.05^{a}	2.67± 0.12^{a}	2.68± 0.05^{a}	2.71± 0.05^{a}	2.73± 0.07^{a}
D_a (10^3)	4.13± 0.02^{c}	4.13± 0.07^{c}	4.15± 0.01^{bc}	4.18± 0.03^{bc}	4.13± 0.02^{c}	4.11± 0.04^{c}	4.16± 0.01^{bc}	4.17± 0.06^{bc}	4.22± 0.07^{ab}	4.22± 0.04^{ab}	4.27± 0.03^{a}
D_g (10^3)	3.82± 0.01^{e}	3.84± 0.08^{de}	3.86± 0.01^{cde}	3.88± 0.05^{bcde}	3.87± 0.03^{cde}	3.87± 0.01^{cde}	3.89± 0.02^{bcde}	3.91± 0.06^{abcd}	3.93± 0.05^{abc}	3.95± 0.05^{ab}	3.97± 0.04^{a}
D_{esf} (10^3)	3.55± 0.03^{e}	3.67± 0.01^{e}	4.11± 0.08^{cd}	4.05± 0.02^{d}	4.19± 0.15^{c}	4.33± 0.12^{b}	4.33± 0.8^{b}	4.40± 0.04^{ab}	4.417± 0.07^{ab}	4.44± 0.06^{ab}	4.48± 0.04^{a}
ϕ	59.18± 0.16^{f}	59.82± 0.89^{ef}	60.39± 0.08^{de}	61.26± 0.65^{bcd}	61.85± 0.42^{ab}	62.52± 0.39^{a}	61.95± 0.81^{ab}	61.50± 0.71^{abc}	61.32± 0.72^{bcd}	61.24± 0.52^{bcd}	60.63± 0.11^{cde}
M_{1000} (10^2)	3.86± 0.01^{f}	4.28± 0.06^{e}	4.56± 0.05^{d}	4.87± 0.04^{c}	4.87± 0.04^{c}	5.42± 0.32^{b}	5.36± 0.22^{b}	5.69± 0.29^{a}	5.80± 0.07^{a}	5.75± 0.03^{a}	5.96± 0.16^{a}
S (10^5)	4.59± 0.03^{e}	4.64± 0.19^{de}	4.68± 0.02^{cde}	4.74± 0.11^{bcde}	4.70± 0.06^{cde}	4.71± 0.03^{cde}	4.75± 0.04^{bcde}	4.81± 0.15^{abcd}	4.86± 0.13^{abc}	4.91± 0.13^{ab}	4.85± 0.09^{a}
ρ_b	815,13± 7,80^{a}	807,25± 8,17^{a}	761,42± 5,78^{b}	754,54± 4,25^{b}	708,46± 17,52^{c}	668,791± 15,10^{d}	681,54± 6,38^{d}	668,17± 13,56^{d}	681,50± 6,81^{d}	682,38± 14,51^{d}	678,13± 5,93^{d}
ρ_t	1600,11± 33,13^{a}	1496,83± 34,11^{b}	1372,41± 45,22^{c}	1404,55± 19,22^{c}	1235,00± 69,80^{d}	1272,59± 85,14^{d}	1260,51± 22,43^{d}	1278,45± 26,83^{d}	1285,75± 68,72^{d}	1257,50± 38,44^{d}	1267,70± 0,50^{d}
ε	49,04± 1.46^{a}	46,05± 1.63^{a}	44,48± 1.80^{a}	46,27± 0.99^{a}	42,51± 3.64^{a}	47,31± 3.30^{a}	45,92± 1.42^{a}	47,71± 1.90^{a}	48,88± 3.33^{a}	45,72± 0.86^{a}	46,51± 0.45^{a}

Means followed by different letters on the same line differ significantly among themselves at a level of 5% ($p \leq 0.05$) by the Duncan test

x- length, m; y- width, m; z- thickness, m; Da- the arithmetic mean diameter, m; Dg- the geometric mean diameter, m; Desf- the equivalent diameter of a sphere, m; - sphericity, %; M1000- mass of 1000 grains, kg; S- surface área, m²; ρb- bulk density, kg m-3; ρt- actual density, kg m-3; - porosity, %.

Grains dimension

By means of the results, it is shown a decrease in the length with increasing moisture content up to the moisture content of 52.65% d.b. Then, it begins to increase above this value. On the other hand, the width exhibits an inverse behavior, Where: there is an increase up to the moisture content of 52.65% and, then, it remains basically constant. It is in agreement with most of the porous biological products. During hydration or drying, irregularly contraction in the longitudinal, tangential and radial directions were found by Fortes & Okos (1980) in maize drying and by Resende et al. (2005) on bean grains.

Corrêa et al. (2006), in the study of physical properties of wheat grains during drying from 31 to 11% d.b.., found that the the all three dimensions of the wheat grains reduced proportionally with the decrease in the content of water. This difference in behavior can be justified due to the small range of moisture content analyzed and as well as by the wheat cultivar.

The thickness undergoes a lower influence with changes inmoisture content, varying from an initial value of 0.0026 to a final value of 0.0027 m, without significant difference ($p>0.05$). It is possible due to internal stresses of the own grain.

Table 2 shows the fitted models for grain length, width and thickness as a function of moisture content and their respective determination coefficients (R^2).

Table 2

Relationship between the dimensions (x, y e z) and the diameters with the moisture content (X)

Equations	R^2
$x = 2\times10^{-7}X^2 - 2\times10^{-5}X + 0.0067$	0.8661
$y = -9\times10^{-3}X^2 + 1\times10^{-5}X + 0.0031$	0.9606
$z = 2\times10^{-8}X^2 - 8\times10^{-7}X + 0.0026$	0.9716

x- length, m; y- width, m; z- thickness, m; X- moisture contente, % b.s.

It is observed that the experimental values of the length, width and thickness dimensions of the wheat grain can be satisfactorily represented by a second order polynomial model as shown bythe high value of R^2.

Diameters of the grain

According to Table 1, all of the diameters increased with increasing moisture content, a fact that was also observed by Araujo et al. (2014) in peanut grain at higher moisture content. Hhowever, it was found the arithmetic mean diameter increased up to 37.35% and then suffered a decrease in the two subsequent moisture contents, increasing again above 60.17%.

In addition, the equivalent diameter of a sphere was more unstable over the range of moisture content studied with a variation of 9.4×10-4 m. While the geometric and arithmetic mean diameter varied by 1.5×10-4 and 1.4×10-4 m, respectively (Table 1).

It is assumed that above 60.17% of moisture content, both dimensions and diameters begin to assume a constant value, showing that wheat grains have a maximum capacity of expansion.

The dependence of these parameters on the moisture content could be described by the mathematical models in Table 3.

Table 3

Relationship between the diameters (Da, Dg, Desf) with the moisture content (X)

Equations	R²
$D_a = 4\times10^{-3}X^2 - 2\times10^{-6}X + 0.0042$	0.8131
$D_g = 1\times10^{-3}X^2 + 5\times10^{-7}X + 0.0038$	0.9488
$D_{esf} = -2\times10^{-7}X^2 + 3\times10^{-5}X + 0.0031$	0.9509

Da- the arithmetic mean diameter, m; Dg- the geometric mean diameter, m; Desf- the equivalent diameter of a sphere, m; X- the moisture contente, % b.s.

The high determination coefficients (R^2) observed indicated a good accuracy of the predictive equations in fitting to the experimental data. Thus, there was an increase in the dimensions, arithmetic, geometric and spherical diameters, which can be attributed to the grain expansion as a result of the absorption of moisture in the intracellular spaces inside the grains (Sologubik et al., 2013). Moreover, the diameter that best describes the wheat grain is the spherical diameter thanks to the better fitting accuracy.

Sphericity ( ), mass of 1000 grains (M1000) and surface area (S)

The sphericity of wheat grain ranged from 59.18% to 60.63%, representing an an increase up to 52.65% of moisture content.. From this point, it started to decrease. It is in accordance to Araujo et al. (2014), who also found higher sphericity for peanut grains at similar moisture contents (3% up to 56% d.b..).

This slight increase in sphericity can be attributed to the greater increase in grain width and thickness compared to the length, a fact that can be observed in the previous results.

The M1000 ranged from 0.0386 to 0.0595 kg and as a consequence of the increase in the moisture content. It is common for many agricultural products, because during the drying process removes part of the water bound to the agricultural products, causing their mass to decrease (Martins et al. 2017). However, this increase was not linear as found for most agricultural products (Araujo et al., 2014; Bande et al., 2012; Goneli et al., 2008) which can be attributed to the fact that grains reach an equilibrium of water absorption and do not suffer any further changes in their size.

The surface area varied from 4.59×10-5 to 4.95×10-5 m². These values are in close agreement with the grain size, which which increased with increasing moisture content. Thus, increasing the grain size also leads to an increased surface area as observed by Bande et al. (2012) for melon seeds.

to the equations described in Table 4 represents the mathematical relationship between the sphericity, the mass of a thousand grains and the surface area with the moisture content.

Table 4

Relationship between sphericity ( ), mass of 1000 grains (M1000) and surface area (S) with moisture content (X)

Equations	R²
$\phi = -0.0015\,X^2 + 0.1747X + 56.811$	0.9210
$M_{1000} = -3\times10^{-6}X^2 + 0.0005X + 0.0319$	0.9808
$S = 1x10^{-11}X^3 - 2\times10^{-9}X^2 + 1\times10^{-7}X + 4\times10^{-5}$	0.9655

- sphericity, %; M1000- mass of 1000 grains, kg; S- surface área, m²; X- moisture contente, % b.s.

A third-order polynomial was able to fit the surface area data with higher accuracy ((high R^2), differing from Araujo et al. (2014); Bande et al. (2012) and Kibar & Ozturk (2008) who found a linear fit for the surface area. This difference can be attributed to the difficulty in determining the surface area of agricultural products, since most of these products do not present a uniformity and homogeneity.

Bulk density (apparent) (ρb), actual density (ρt) and porosity (ε)

The apparent and actual density reduced significantly ($p < 0.05$) up to the moisture content of 52.65% with a deviation of 15.10 kg m^{-3} for the apparent density and 85.14 kg m^{-3} for the actual density. The reduction in the density values can be attributed to decreased mass per volume ratio of the grains asthe water was added to the grains. This reduction of apparent density with increasing water content in wheat grains has also been described by Corrêa et al. (2006) and is observed for most agricultural products.

The porosity of the grains varied significantly ($p < 0.05$), but did not exhibit a well-defined correlation with moisture content. It presented a value of 49.04 ± 1.46% for the initial moisture content and 46.51 ± 0.45% for the final moisture content, but reached a minimum of 42.51 ± 3.64% for the humidity of 45%. This reduction of porosity with increasing water content was also found for three coffee bean varieties as described by Couto et al. (1999). The expansion of grains matrix may have caused the capilars to contract, thus reducing the porosity. Table 5 shows the dependence of the actual and apparent grain densities on moisture content and their corresponding determination coefficients (R^2).

Table 5

Adjustment of the actual and apparent densities in relation to the moisture content

Equations	R²
$\rho_b = 0.043X^2 - 6.4611X + 914.55$	0.9448
$\rho_t = -0.1116X^2 - 15.442X + 1777.6$	0.8998

ρb- apparent density, kg m-3; ρt- actual density, kg m-³; X- moisture contente, % b.s.

A high determination coefficient (R^2) was observed for density when fitting a second-order polynomial model to the experimental data.. A similar trend was also found by Couto et al. (1999) for coffee beans. Porosity data could not be described by mathematical models as it did not present a clear trend with changes in the moisture content.

4 CONCLUSION

The physical properties of wheat grains varied in studied moisture content range (14.40 - 90.90% d.b.). In general, the increase in moisture caused an increase in the physical properties. On the other hand, the actual and apparent densities decreased with increasing moisture content

All physical properties were well-correlated with moisture by means of a polynomial fit. It shows that physical properties, in some ranges of moisture, are dependent on the moisture content. Thefore, the results obtained by this study provide important information for the correct design of the unit operations involved in the malting industry and processes which deals with grains with different moisture content.

ACKNOWLEDGMENTS

The authors thank CNPq (Proc. N°. 308567/2017) for the financial support.

REFERENCES

Al-Mahasneh, M. A., & Rababah, T. M. (2007). Effect of moisture content on some physical properties of green wheat. Journal of Food Engineering, 79(4), 1467–1473.

AOAC - Association of Official Analytical Chemists. (2010). Official methods of analysis of the association of official analytical chemists (18th ed., 3rd rev.). AOAC.

Araujo, W. D., Goneli, A. L., Souza, C., Gonçalves, A. A., & Vilhasanti, H. C. (2014). Physical properties of peanut kernels during drying. Revista Brasileira de Engenharia Agrícola e Ambiental, 18(3), 279–286.

Bande, Y. M., Adam, N. M., Azmi, Y., Jamarei, O. (2012). Moisture-dependent physical and compression properties of bitter melon (Citrullus colocynthis Lanatus) seeds. International Journal of Agricultural Research, 7 established(5), 243–254.

Belcar, J., Sobczyk, A., Sobolewska, M., Stankowski, S., & Gorzelany, J. (2020). Characteristics of technological properties of grain and flour from ancient varieties of wheat (einkorn, emmer and spelt). Acta Universitatis Cibiniensis, Series E: Food Technology, 24(2).

Brasil. Ministério da Agricultura e Reforma Agrária. (2009). Regras para análise de sementes. MAPA.

Carneiro, L. M. T. A., Biagi, J. D., Freitas, J. G. D., Carneiro, M. C., & Felício, J. C. (2005). Diferentes épocas de colheita, secagem e armazenamento na qualidade de grãos de trigo comum e duro. Bragantia, 64(1), 127–137.

Chandra, G. S., Proudlove, M. O., & Baxter, E. D. (1999). The structure of barley endosperm–an important determinant of malt modification. Journal of the Science of Food and Agriculture, 79(1), 37–46.

Corrêa, P. C., Ribeiro, D. M., Resende, O., & Botelho, F. M. (2006). Determinação e modelagem das propriedades físicas e da contração volumétrica do trigo, durante a secagem. Revista Brasileira de Engenharia Agrícola e Ambiental, 10(3), 665–670.

Couto, S. M., Magalhães, A. C., Queiroz, D. M. D., & Bastos, I. T. (1999). Massa específica aparente e real e porosidade de grãos de café em função do teor de umidade. Revista Brasileira de Engenharia Agrícola e Ambiental, 3(1), 61–68.

FAOSTAT. (2019). Crops/2019. Food and Agriculture Organization of the United Nations. http://faostat3.fao.org/browse/Q/QC/S

Fortes, M., & Okos, M. R. (1980). Changes physical properties of corn during drying. Transactions of the ASAE, 23(4), 1004–1008.

Goneli, A. L. D., Corrêa, P. C., Botelho, F. M., Oliveira, G. D., & Santos, E. D. S. (2008). Propriedades físicas dos frutos de mamona durante a secagem. Revista Brasileira de Armazenamento, 33(2), 148–155.

Kandel, T. I., Abd El Maksoud, M. A. F., & Eissa, A. H. A. (2022). Physical and mechanical properties of wheat grain affected by different storage methods. Menoufia Journal of Agricultural Engineering, 5(3), 39–55.

Kibar, H., & Öztürk, T. (2008). Physical and mechanical properties of soybean. International Agrophysics, 22(3), 239–244.

Martins, E. A., Goneli, A. L., Hartmann Filho, C. P., Mauad, M., Siqueira, V. C., & Gonçalves, A. A. (2017). Physical properties of safflower grains. Part I: Geometric and gravimetric characteristics. Revista Brasileira de Engenharia Agrícola e Ambiental, 21(5), 344–349.

Mohsenin, N. N. (1986). Physical properties of plant and animal materials. Gordon and Breach Publishers.

Noello, C., Biduski, B., Caregnatto, G., Elias, M. C., & Gutkoski, L. C. (2012). Avaliação da atividade enzimática de malte de trigo. Acta Iguazu, 1(4), 78–82.

Pyler, R. E., & Thomas, D. A. (2000). Malted cereals: Their production and use. Food Science and Technology-New York-Marcel Dekker, 685–696.

Resende, O., Corrêa, P. C., Goneli, A. L. D., & Cecon, P. R. (2005). Forma, tamanho e contração volumétrica do feijão (Phaseolus vulgaris L.) durante a secagem. Revista Brasileira de Produtos Agroindustriais, 7(1), 15–24.

Santos, I. J., Couto, S. M., & de Andrade, E. T. (2001). Cinética de secagem em camada fina do malte verde de cevada. Revista Brasileira de Produtos Agroindustriais, 3(1), 53–59.

Silva, F., Nogueira, L. C., Goncalves, C., Ferreira, A. A., Ferreira, I. M., & Teixeira, N. (2008). Electrophoretic and HPLC methods for comparative study of the protein fractions of malts, worts and beers produced from Scarlett and Prestige barley (Hordeum vulgare L.) varieties. Food Chemistry, 106(2), 820–829.

Sologubik, C. A., Campañone, L. A., Pagano, A. M., & Gely, M. C. (2013). Effect of moisture content on some physical properties of barley. Industrial Crops and Products, 43, 762–767.

Vilche, C., Gely, M., & Santalla, E. (2003). Physical properties of quinoa seeds. Biosystems Engineering, 86(1), 59–65.