ISSN 1807-1929
Revista Brasileira de Engenharia Agrícola e Ambiental
Brazilian Journal of Agricultural and Environmental Engineering
v.25, n.10, p.710-716, 2021
Campina Grande, PB – http://www.agriambi.com.br – http://www.scielo.br/rbeaa

DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v25n10p710-716

Energy efficiency and physical integrity of maize grains subjected to continuous and intermittent drying[1]

Eficiência energética e integridade física dos grãos de milho submetidos à secagem contínua e intermitente

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HIGHLIGHTS:
Tempering time promotes higher drying rate and reduces electrical conductivity.
Intermittent drying reduced the negative effects of continuous drying.
Longer tempering times promoted better energy efficiency and less membrane damage.

ABSTRACT: Grain drying is a common process, due to its need for the maintenance of quality, but it is the activity with the highest energy demand among the postharvest stages. Thus, this study aimed to evaluate the effect of different tempering times on the energy efficiency of drying process and maintenance of cell membrane integrity of maize grains harvested with moisture content at 0.34 ± 0.01 d.b. The grains were dried in an experimental fixed-bed dryer with control of temperature and air flow conditions. The experiment was conducted in a completely randomized design with five tempering times (0, 4, 8, 12 and 16 hours) and four repetitions, where zero corresponds to continuous drying, while the remaining times correspond to the intermittent dryings. The grains were dried at the temperature of 100 °C and air flow of 15.4 m^3 min^{-1} t^{-1} until reaching moisture content of 0.16 ± 0.03 d.b. For intermittent drying, the process was interrupted with 0.22 ± 0.02 d.b. and restarted after the tempering time. The increase of tempering time led to reductions in effective drying time, specific energy consumption, electrical conductivity and damage and increase in the drying rate and overall energy efficiency. Intermittent drying reduced the drying time, being 30.25% more efficient than continuous drying.

Key words: *Zea mays* L., drying rate, tempering time, electrical conductivity, iodine reaction

RESUMO: O processo de secagem de grãos é uma prática comum e necessária à manutenção da qualidade, porém é uma das atividades de maior demanda energética dentre as fases pós-colheita. Neste contexto, realizou-se este estudo com objetivo de avaliar os efeitos de diferentes períodos de repouso na eficiência energética do processo de secagem e manutenção da integridade das membranas dos grãos colhidos com teor de água de 0,34 ± 0,01 b.s. Os grãos foram secos em um secador experimental de camada fixa com controle de temperatura e fluxo de ar. O experimento foi montado em delineamento inteiramente casualizado, com cinco períodos de repouso (0, 4, 8, 12 e 16 horas) e quatro repetições, em que zero corresponde à secagem contínua e os demais à secagem intermitente. Os grãos foram secos a 100 °C de temperatura e fluxo de ar de 15,4 m^3 min^{-1} t^{-1} até atingir 0,16 ± 0,02 b.s. Para a secagem intermitente, o processo foi interrompido com 0,22 ± 0,03 b.s. e retomado após o período de repouso. O aumento do período de repouso diminuiu o tempo efetivo de secagem, consumo específico de energia, condutividade elétrica, danos da reação do iodo e aumentou a taxa de secagem e eficiência energética global. A secagem intermitente foi 30,25% mais eficiente que contínua.

Palavras-chave: *Zea mays* L., taxa de secagem, tempo de repouso, condutividade elétrica, reação do iodo

• Ref. 245635 – Received 16 Nov, 2020
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• Accepted 06 Apr, 2021 • Published 09 May, 2021
Edited by: Carlos Alberto Vieira de Azevedo

Introduction

Generally, air temperature and relative air humidity conditions that generate high drying rates tend to negatively affect product quality and stability (Ju et al., 2016). In the industry, drying represents a significant fraction of the use of energy in the whole process of grain production. The high energy demand is associated with the heat required for water removal, inefficiency in the process of heat transfer, and the loss factors associated with most dryers (Kudra, 2004; Brito et al., 2018).

Dryers whose technology allows the optimization of energy consumption or changes in the process can improve drying efficiency. Considering the high investment in new dryers, intermittent drying becomes an affordable alternative for meeting the investment required, also resulting in the improvement of product quality (Brito et al., 2018).

Intermittence could minimize the cost of drying without compromising the product quality (Vergara et al., 2018). Different intermittency strategies have the potential to increase energy efficiency and maintain product quality (Allaf et al., 2014; Kumar et al., 2014).

Adequate tempering times could optimize the process through the flexibilization of drying by the reduction in the effective time of drying and relieve trucks with additional grain bin (Barbosa de Lima et al., 2016a). Tempering is a common practice at some grain processing units, mainly of coffee, especially at peak harvest, aiming at relieve larger volumes of products; however, its use lacks research works that aim to potentiate the resulting gains in terms of energy efficiency and grain quality (Isquierdo et al., 2009).

In view of the above, the objective was to evaluate the drying rate and energy efficiency in continuous and intermittent drying of maize grains, as well as their integrity as a function of the different tempering times during drying, in terms of efficiency magnitude.

Material and Methods

This study was carried out in the Laboratory of Post-Harvest Processes (LPPC) of the Faculdade de Ciências Agrárias (FCA), Universidade Federal da Grande Dourados (UFGD), in the city of Dourados, Mato Grosso do Sul state, Brazil (22º 13’ 16” S; 54º 48’ 20” W and average altitude of 452 m).

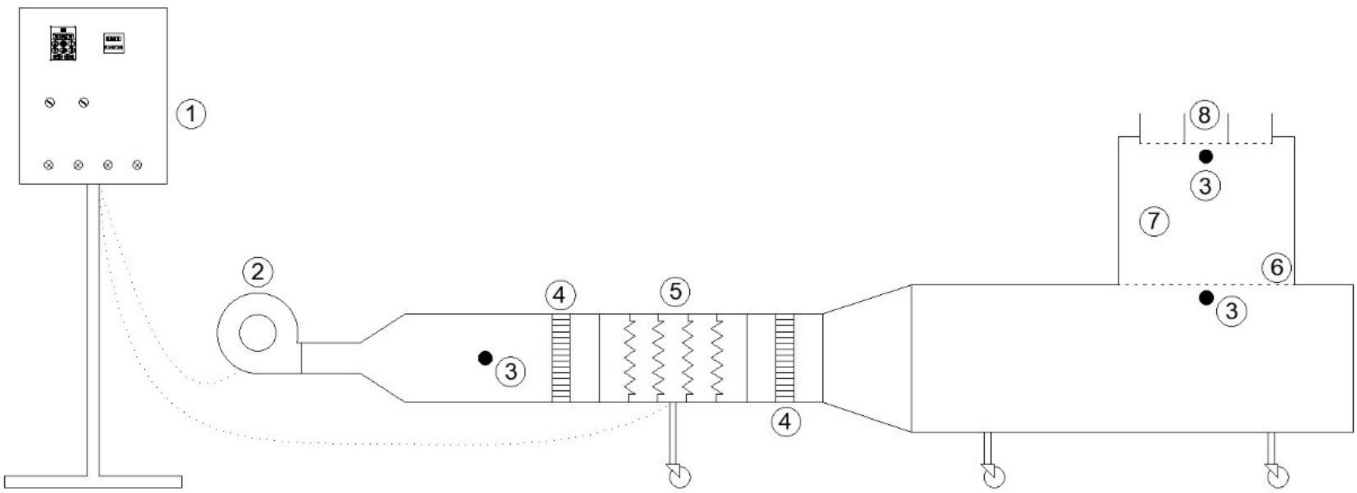
Maize grains of Cargo TL cultivar were harvested and threshed manually at the FCA’s experimental farm, with moisture content of 0.34 ± 0.01 (dry basis - d.b.). Their initial moisture content was determined by the gravimetric method in a forced circulation oven, using three replicates of 15 g, at temperature of 103 ± 1 ºC according to ASABE (2009).

The grains were subjected to drying at temperature of 100 ºC and air flow of 15.4 m^3 min^{-1} t^{-1} in an experimental fixed-layer dryer (Figure 1), equipped with a system that accurately controls the drying air flow and temperature. Air flow was controlled by drying air speed, using digital anemometer (Instrutherm - AM-100) after passing the heating system. The experiment was conducted in a completely randomized design using five tempering times: 0, 4, 8, 12 and 16 hours, where zero corresponds to continuous drying and the remaining times correspond to the intermittent drying, with four replicates.

The temperature of 100 °C is close to the real working temperature in the storage units, within the limits of the experimental dryer. The tempering times are within range of some works on intermittent drying for maize grain and seed (Devilla et al., 1999; Vergara et al., 2018; Mabasso et al., 2019; Mabasso et al., 2020). The air flow is in accordance with Queiroz & Valente (2018).

In each drying, a grain volume of 0.04 m^3 was placed in a drying chamber with 0.28 m^2 of base area, fully perforated, and a 0.12-m-thick layer of grains.

Throughout the drying, the mass of grains was turned to avoid the formation of temperature and moisture content gradients, at 10-min intervals, agreeing with moisture content control. Drying was monitored with the aid of three fully perforated polyethylene packages, containing 100 g of product and randomly placed in the middle of the grain mass. The continuous drying process was finished with moisture content of 0.16 ± 0.03 (d.b.), whereas in the treatments with tempering the process was interrupted with 0.22 ± 0.02 (d.b.) and resumed after the tempering, until the grains reached a moisture content of 0.16 ± 0.03 (d.b.).



1 - Temperature and air flow control panel; 2 - Centrifugal fan; 3 - Temperature measurement point; 4 - Air homogenizers; 5 - Set of electrical resistances; 6 - Perforated screen for thick-layer drying; 7 - Thick-layer drying bed; 8 - Set of trays for thin-layer drying

Figure 1. Experimental fixed-layer dryer used in the drying of maize grains

During the tempering, inside an expanded polystyrene box, fully closed in order to simulate the grain bin conditions, air temperature and relative air humidity conditions were measured in the grain mass with an ICEL HT-4010 digital data logger, assisted by HT Communication software, made in ICEL Manaus-Brazil.

The expanded polystyrene box with capacity of 100 L was resized to have the following dimensions: 0.51, 0.30 and 0.16 m for length, width and height, respectively, reducing the volume to 24.48 L (24.48 x 10^{-3} m^3) (Figure 2). With this adjustment, a 0.15 m thickness was adopted on all sides, including the upper and lower parts, equivalent to a thickness of 1.011 m in the mass of grains, considering the thermal conductivities of the material (0.02 W m^{-1} °C^{-1}) and of the product at the temperature and moisture content during the tempering (0.16 W m^{-1} °C^{-1}) (Suleiman & Rosentrater, 2016; Leila et al., 2019).

The drying rate was numerically determined based on the ratio between the difference in moisture contents and the drying time, using Eq. 1, considering the initial and final moisture contents at the various intervals along the drying.

$$DR = \frac{X_0 - X_i}{t_i - t_0} \tag{1}$$

where:

DR - drying rate (kg kg^{-1} h^{-1});
X_0 - previous moisture content (decimal, d.b.);
X_i - current moisture content (decimal, d.b.);
t_i - current total drying time (h); and,
t_0 - previous total drying time (h).

The specific energy consumption is the amount of energy required to evaporate a unit of water mass present in the product during drying. It is determined by reading the power consumed during the effective drying time.

A Landis+Gyr device, model E650 8602-B, made in Brazil by Landis+Gyr AG with instantaneous power records, was installed. The device was installed in such a way that the electric current passed through it before feeding the control panel, thus measuring the power required to make the fan run and heat the electrical resistances and other electrical circuits.

The values of power and time were integrated into the unit of energy (W s^{-1} or J). After determining the value of the total energy consumed, the specific consumption was determined according to Eq. 2 (Melo et al., 2013).

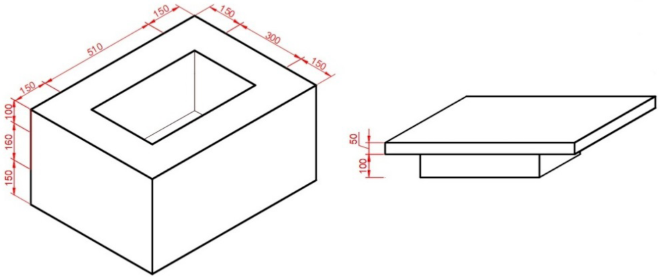


Figure 2. Characteristics and dimensions (mm) of the expanded polystyrene box used to hold maize grains during the tempering time

$$SEC = \frac{EC\left(100 - X_f\right)}{M_i\left(X_i - X_f\right)} \tag{2}$$

where:

SEC - specific energy consumption (kJ kg^{-1});
EC - energy consumed during drying (kJ);
X_i - initial moisture content of the grains (%, w.b.);
X_f - final moisture content of the grains (%, w.b.); and,
M_i - initial mass of grains (kg).

Energy efficiency (η) was determined as the ratio between the amount of energy required to remove water from the grain and the total energy used or supplied to the dryer, according to Eq. 3. The energy supplied to the system includes energy for air heating, fan actuation and the energy effectively used for water evaporation (Kudra, 2004; Barbosa de Lima et al., 2016b).

$$\eta = \frac{\text{Energy required}}{\text{Energy used or consumed}} \tag{3}$$

The energy required was determined based on the simplified equation of the drying balance, described by Brooker et al. (1992), which corresponds to the product between the latent heat of vaporization of the maize grain and the amount of water removed, according to Eq. 4.

$$\text{Energy required} = L\,dm\left(X_i - X_f\right) \tag{4}$$

where:

L - latent heat of vaporization of maize (kJ kg^{-1} evaporated water);
dm - total dry matter placed in the drying chamber (kg);
X_i - initial moisture content of the grains (decimal, d.b.); and,
X_f - final moisture content of the grains (decimal, d.b.).

The latent heat of vaporization of maize was estimated based on the average values of temperature and moisture content during the drying process, according to the methodology proposed by Brooker et al. (1992), and estimated by the computer program EtaGRÃO 3.0, developed by CENTREINAR, which relates the latent heat of vaporization of the product and of water as a function of the moisture content.

Electrical conductivity of grains was determined using the mass method (Vieira & Krzyzanowski, 1999). Four 50-grain replicates were used in each treatment, and their masses were measured on a digital scale with resolution of 0.01 g. Maize grains were placed in 100-mL disposable cups, and 75 mL of deionized water were added.

Then, the cups were placed inside a BOD chamber for 24 hours at temperature of 25 °C. After this period, the electrical conductivity was measured with a digital conductivity meter, model CG 1800, made by Gehaka-Brazil. The values obtained were converted to μS cm^{-1} g^{-1}, by dividing the result given in μS cm^{-1} by the mass obtained in each weighing procedure.

The test was adapted according to the methodology described by Cícero & Silva (2003), by establishing a 25-min soaking time for the maize grains, obtained in trials aimed at revealing damage caused by the drying process through the imbibition of 4% iodine solution. Four replicates of 100 grains, in duplicate, were used for each treatment. The samples were placed in 100 mL disposable polyethylene cups, where a soaking solution was added until fully covering the grains. After soaking, the grains were washed in running water, dried on paper towel and those with purple color, because of the starch reaction with the solution, and visible cracks were counted. The results were expressed in percentage.

Analysis of variance and Scott-Knott test were carried out at $p \leq 0.01$, using Sisvar 5.7® software.

Results and Discussion

The effective drying lasted 1.67 hours for the tempering times of 8, 12 and 16 hours, 2 hours for the tempering time of 4 and 2.17 hours for the continuous drying (Figure 3A). Proportionally, the intermittent drying represented a gain of about 23% in the effective drying time when maize was subjected to tempering with moisture content of 0.22 ± 0.02 (d.b.) for 8, 12 and 16 hours.

Thus, the adoption of intermittent drying contributes to the reduction in the effective time, compared to continuous drying, but in general terms it leads to a longer total time considering the tempering time. In heat-sensitive products, such as grains, the resistance to water removal for lower moisture content is an intrinsic characteristic, so caution should be taken not to expose the product to high heat supply rates that result in over-drying on the superficial layer of the grain and reduction of grain quality (Barbosa de Lima et al., 2016a; Kumar & Karim, 2017). In this context, it is expected to have a higher level of quality losses for continuous drying and low tempering time for intermittent drying.

Figure 3B shows that, with the adoption of the tempering, the drying rate reached a peak and remained above the values observed in the continuous drying until the end of the process. This reflects the equilibrium established during the tempering with the redistribution of water in the grain. Water tends to exit more easily, thus improving the relationship between the energy supplied and the amount of water removed; energy efficiency is substantially improved with the intermittency, while energy consumption is reduced.

During drying, a moisture content gradient is generated between the interior and the surface of the grain, and the superficial part in direct contact with the drying air tends to have lower moisture content than the inside. During the tempering time, the water starts moving from the center to the outer layers of the grain. The higher the tempering time the more uniform would be the moisture content inside the grain (Barbosa de Lima et al., 2016b).

During the tempering time, the variations in temperature and relative humidity of the intergranular air were not higher than 5 °C and 2%, respectively (Figure 4), after reaching the equilibrium, resulting in better insulation of the expanded polystyrene box, whose thermal conductivity is about seven times higher than that of maize grains (Suleiman & Rosentrater, 2016; Leila et al., 2019).

Such small variation of grain conditions along the tempering time allowed the energy stored in the form of heat

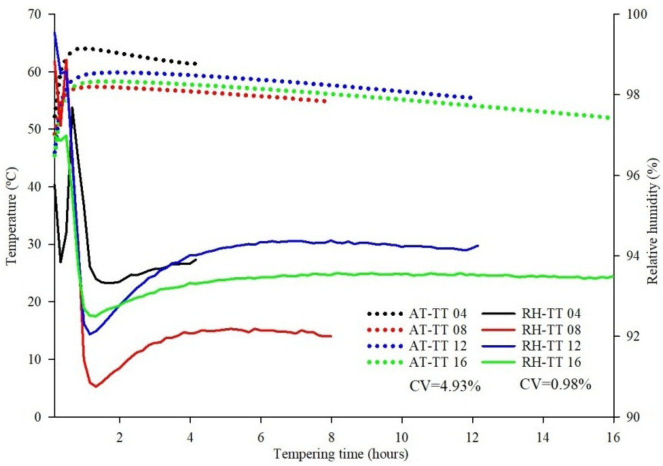


Figure 4. Variation of air temperature (AT) and relative air humidity (RH) inside the maize grain mass during the tempering times (TT) evaluated

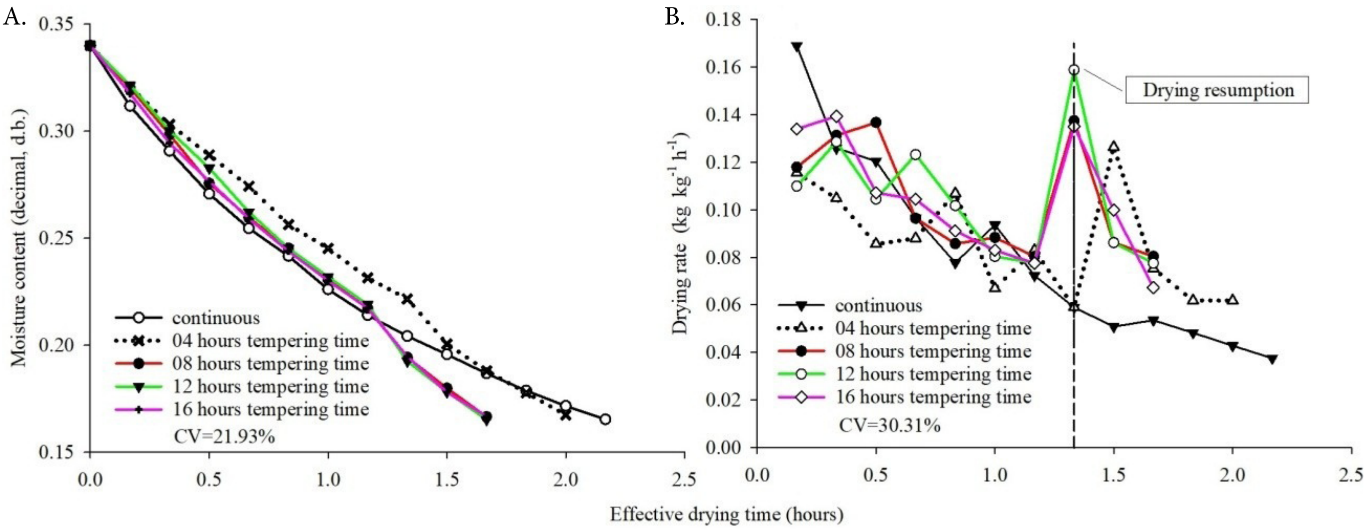
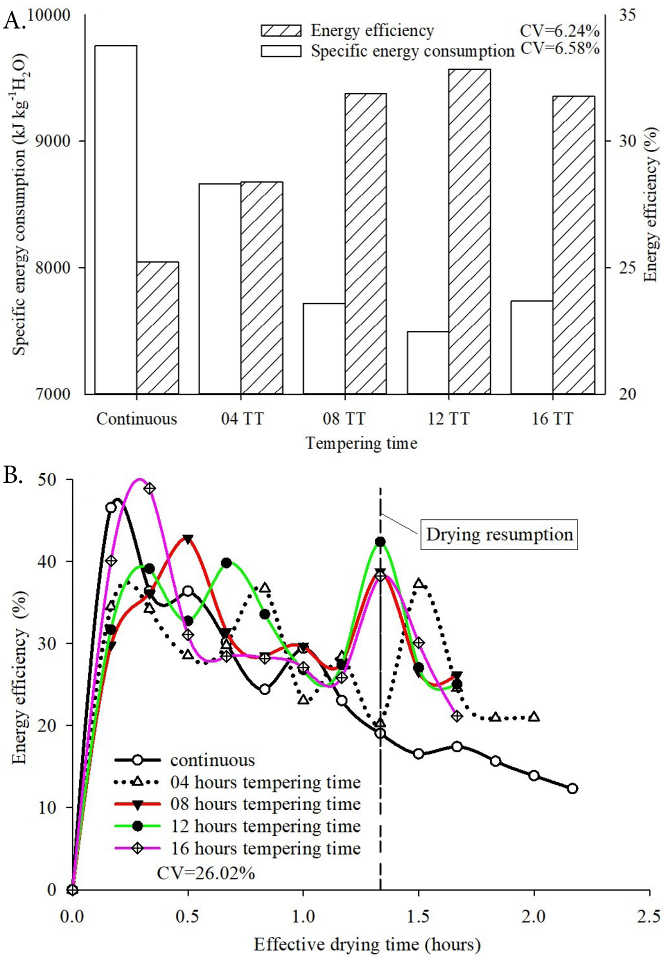


Figure 3. Curves of moisture content reduction (dry basis) during continuous and intermittent drying of maize grains with different tempering times (A) and behavior of drying rate during drying with different tempering times as a function of the effective drying time (B)

to be used after the tempering to continue the drying process, making it more efficient. Also, during the tempering time there is water redistribution inside each grain and it makes the drying process more efficient after the tempering time. There was also a difference between the initial values of air temperature and relative humidity inside the grain mass, caused by experimental procedures in the period between the interruption of drying and the beginning of the tempering.

The specific energy consumption during drying varied from 7492.55 to 9760.08 kJ kg^{-1} of evaporated water, with lowest value found in the drying with tempering time of 12 hours and highest values found in the continuous drying (Figure 5A). The variation of energy consumption reduces for the longest interval of tempering times, from 08 to 16 hours.

Thus, the reduction of specific energy consumption reached 23.23% in the intermittent drying, compared to the continuous drying. Such reduction results from the increase in the drying rate (Figure 3B) and from the shorter effective drying time (Figure 3) and is within the range mentioned by Kumar et al. (2014), from 19 to 37%, with the greatest reduction associated with the longest tempering time. Similar results were observed by Zhang & Litchfield (1991), who conducted an intermittent drying process in a thin-layer dryer under laboratory conditions and also concluded that the use of the tempering time, in addition to reducing energy consumption, also reduces the effective drying time and improves energy efficiency.



TT - Tempering time: 04, 08, 12 and 16 hours

Figure 5. Specific energy consumption (A) and average energy efficiency after drying with different tempering times (B)

As shown in Figure 5A, the longest tempering times led to the greatest reduction in the specific energy consumption, hence representing higher energy efficiency. These data also reflect the easy removal of water after the tempering time, and gains in energy efficiency also promote better product quality (Ullmann et al., 2015; Barbosa de Lima et al., 2016a).

Energy efficiency ranged from 25.22% to values between 28.40 and 32.85% for continuous drying and intermittent drying with different tempering times, which is equivalent to a 30.25% increase in the efficiency with the use of intermittency. The variation in energy efficiency throughout the drying process was decreasing and followed the behavior of the moisture reduction rate, varying from 46.55 to 12.31% for continuous drying and from 48.91 to 21.15% for intermittent drying with tempering time of 16 hours (Figure 5B).

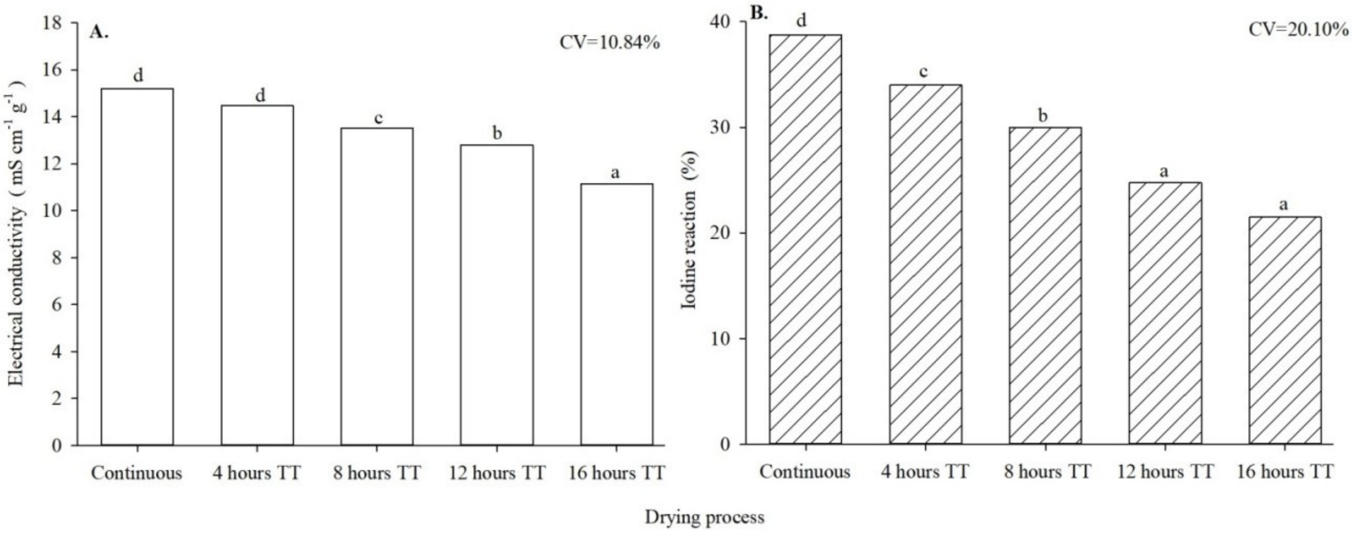
The magnitude of variation between continuous and intermittent drying reflects the difficulty with which the water was removed from the product and, consequently, the amount of energy spent in continuous drying was proportionally lower than in the intermittent drying (Kumar et al., 2014). Low efficiency not only increases costs, but also conditions the quality of the product, due to its limited capacity of volumetric expansion with the reduction of moisture content (Kudra, 2004).

The electrical conductivity of maize grains after drying decreased as longer tempering times were adopted (Figure 6A). Continuous drying led to the highest value of electrical conductivity, which did not differ from the value observed with tempering time of four hours. This situation demonstrates that drying had a negative effect on membrane integrity, consequently leading to greater damage and leakage of cell contents into the soaking solution (Ullmann et al., 2015).

The damage caused by drying process is in essence permanent, and the electrical conductivity test is considered the most adequate and efficient test to detect damage at cell membrane level (Zhang & Litchfield, 1991). According to Kumar et al. (2014), establishing the same conditions of drying air temperature results in quality losses at the end, due to the reduction in the drying rate with the decrease in moisture content, since the availability of water to be removed is lower, hindering the diffusion movement of water from the center to the periphery of the product.

Considering that the grains have limited elastic and plastic capacity to withstand very high mechanical stresses, the continuous drying may cause thermal and physical stresses, resulting in damage to their structure and leading to greater leakage of cellular content into the soaking solution for shorter tempering time (Barbosa de Lima et al., 2016a). According to Wei et al. (2020), due to the disproportion recorded during drying with the reduction of moisture content, the gradient generated between the moisture content inside the grain and its surface increases the level of damage.

Adopting the tempering time improves the integrity of cell membranes, a very important factor because it is directly associated with the overall quality of the product and its storage potential, as mentioned in the studies conducted by Borém et al. (2014), in which the reduction in the electrical conductivity of coffee grains was associated with the use of intermittent



Means with different letters are significantly different at p ≤ 0.01 by Scott-Knott test; TT - Tempering time

Figure 6. Electrical conductivity of maize grains (A) and iodine reaction on maize grains (B), subjected to continuous and intermittent drying

drying. According to Kumar et al. (2014), the choice of the best intermittency system or drying conditions in terms of energy efficiency should consider the quality of the product, considering the alternative that maximizes the drying rate and preserves product quality.

Grain damage was also observed by the iodine reaction with starch, and the longest tempering times led to lower intensity of damage, with no difference between the tempering times of 16 and 12 hours (Figure 6B). Such damage is consistent with the integrity of cell membranes, evidencing that the effect of the tension forces exerted by water in the shorter tempering times and in the continuous drying was determinant for the occurrence of damage. Since water is more strongly bound as the moisture content decreases, its diffusion to the periphery becomes more difficult and the likelihood of damage, which may be fractures and superficial cracks, increases (Abasi & Minaei, 2014; Nerling et al., 2014).

A joint analysis of the data allows observing that, from the energy standpoint, the tempering times of 8, 12 and 16 hours are the ones which led to the most efficient results, with little discrepancy between them. However, by associating this behavior with the damage or physical integrity at cellular level of the product, it is possible to observe that, despite promoting values of drying rate, specific energy consumption and energy efficiency similar to those obtained with tempering times of 8, 12 and 16 hours, the tempering times of 16 hours led to the best results. It is important to emphasize that this period represents the longest total drying time.

Despite the positive results of intermittent drying in terms of energy efficiency and maintenance of the integrity of the grain membranes, its use still has a certain operational limitation, requiring the additional existence of at least one grain bin, framed in the grain reception and processing system in the storage unit. When properly implemented, it can make it possible to relieve larger volumes of load at harvest time, reducing the tempering time for load in trucks.

According to Vergara et al. (2018), intermittent drying with different tempering times can mean cost savings, since the tempering time coincides with the peak energy cost, where energy is more expensive, and it can reduce costs by 25%, providing greater returns. For the producer, it is important to ensure correct harvest planning and, when drying is properly adjusted to the load flow, it allows, in addition to gains in qualitative and quantitative terms, the release of the area for the next harvest.

Conclusions

1. Drying rate and energy efficiency decreased along the drying time as a result of the reduction of moisture content in the grain, with slight increment in the resumption of drying after the tempering time.

2. The average energy efficiency was higher when tempering was adopted during drying.

3. Increasing the tempering time in intermittent drying positively contributed to the physical integrity of maize grains, with best results for the longest tempering time.

Acknowledgments

To Instituto de Bolsas de Estudo de Moçambique (IBE) for granting the scholarship to the first author, UFGD and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for providing conditions for the study to be conducted.

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