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Impact of the drying air conditions on the milling quality of a long-grain rice variety at different moisture content ranges using a lab-scale dryer

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Abstract

During the harvest season, rice needs to be dried immediately to prevent deterioration. Therefore, the rice industry must have the capacity to dry fast while minimizing the milling quality loss. The aim of this study was to assess the impact of drying processing variables on milling quality and drying duration, at different stages of drying. To this purpose, a thin-layer lab-scale dryer was used at different drying air temperatures, relative humidities (RH), and grain moisture content (MC) ranges. At MC up to 15%, it was possible to dry at a temperature of 47°C and 27% RH maintaining a low milling quality loss. At lower MC, the drying air temperature should decrease to 35°C and 50% RH to maintain the milling quality loss low. This condition increases the drying duration (compared with drying at 47°C). Therefore, a two-stage drying program was proposed, using more severe drying conditions during the first stage (MC up to 15%) and softening the conditions during the final stage (MC from 15 to 13%). This drying program allows decreasing the drying duration, maintaining a low milling quality loss. The implementation of step-wise drying programs is expected to increase the efficiency of the commercial process.

Keywords: rice drying; drying conditions; glass transition temperature; stepwise drying program.

Practical Application: Obtaining a drying program to reduce the drying duration without decreasing the milling quality is critical for the rice industry. In this study, a stepwise drying program was obtained using lab-scale equipment. The knowledge acquired, assessing the impact of the interaction between drying operation variables and rice moisture content on milling quality, allows taking these findings to a commercial scale.

1 INTRODUCTION

Rice is a staple food for many people all around the world. The grain harvest moisture content (MC) is usually between 25 and 17%, and it is dried to an MC of 13% or lower for safe storage. Commercial drying generally takes place by exposing the rice kernels to a stream of heated air. The drying process causes the outer cells of a kernel to shrink as they lose moisture, while the interior remains more humid, producing tension at the surface and compression at the center of the grain (Kunze & Choudhury, 1972). The stress generated could be enough to produce kernel fissuring and eventually breakage (Cnossen et al., 2002). The magnitude of this stress is given by the magnitude of the MC gradient generated between the center (more humid) and the surface of the rice kernel, which depends on the rice grain MC and the drying air conditions (i.e., temperature, relative humidity (RH) and flow rate) (Buggenhout et al., 2013). Therefore, the combination of rice grain MC and drying air conditions will define the MC gradient, meaning that the same drying air conditions will have different impacts on fissures' formation depending on the stage of the drying process (as the grain MC varies along the process).

Rice kernel material properties could also play an important role in fissures' formation. Starch, the main component of rice, is a polymer of glucose formed by crystalline and amorphous zones (Perdon et al., 2000). The crystalline zones are composed of highly branched amylopectin molecules, while the amorphous zones are composed by the branching points of amylopectin (Zeleznak & Hoseney, 1987). At the grain MC and temperatures usually observed during drying, changes occur in the amorphous region (Perdon et al., 2000). The glass transition temperature (Tg) is the temperature range of transition of the amorphous regions of starch from a glassy into a rubbery state (Liu et al., 2010). Below Tg, the amorphous regions are in a glassy state, with low expansion coefficient, specific volume, specific heat, and diffusivity, but high viscosity and modulus of elasticity. Above the Tg, the material is in a rubbery state, with a higher expansion coefficient, specific heat, specific volume, and diffusivity (Cnossen & Siebenmorgen, 2000; Perdon et al., 2000). Garcia-Llobodanin et al. (2020) built the Tg diagram of a Uruguayan variety (Uy2). In agreement with previous studies (Perdon et al., 2000; Sablani et al., 2009; Siebenmorgen et al., 2004), it was observed that the Tg increased as the grain MC decreased.

It is generally accepted that the surface of the kernels tends to the equilibrium moisture content (EMC) shortly after drying begins (Cnossen et al., 2002). The EMC is defined as the MC of the kernels after exposing them to certain air conditions for an infinitely long period of time (Brooker et al., 1992). The EMC depends on the drying air conditions (temperature and RH),

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the rice variety, and the maturity of the grain. Considering that Tg increases as the grain MC decreases, during a hypothetical drying process, the surface of the kernel (at the EMC) may be in the glassy state, while the center (more humid) could be in the rubbery state. When the glassy and the rubbery states coexist within the same kernel, extra tensions are generated due to differences in the properties of the two states. Therefore, the tensions generated by MC gradients inside the rice kernels are increased by the coexistence of glassy and rubbery zones within the same grain. Odek et al. (2018) found that the fissured kernels percentage of two long-grain rice varieties dried using the same drying conditions and time was higher for the lots with higher MC. They attributed this behavior to the transition of the high MC kernels from a glassy to a rubbery state during drying.

The stresses present in a kernel may exist as residual stresses during and for some period after moisture is lost (Kunze & Choudhury, 1972). If a kernel is subjected to tension under this condition, less force will cause a tensile failure compared with the kernel in a neutral-stress condition. Therefore, grain fissuring or breakage may occur not only during drying but also later during the milling process, leading to a decrease in the milling quality in both cases.

Tempering is a commonly used practice aiming to reduce kernels' fissuring and breakage. It consists of holding the rice without blowing drying air for a certain period, allowing moisture gradients within a kernel to subside (Cnossen & Siebenmorgen, 2000). This prevents both the tensions generated by these gradients and the coexistence of starch in different states (glassy and rubbery). Drying above Tg without fissures generation is possible under certain drying air conditions if sufficient tempering is allowed at the drying temperature (Cnossen & Siebenmorgen, 2000; Schluterman & Siebenmorgen, 2007). Mukhopadhyay and Siebenmorgen (2018) found that the milling quality of rice dried above Tg significantly decreased compared with that dried below Tg. However, if these samples were subjected to tempering, the kernels' damage was reduced significantly.

Franco et al. (2020) modeled rough rice drying at different T followed by a tempering period. They found that tempering rice for 3 h could almost eliminate the MC gradient generated inside the kernels during drying at T as high as 70°C. In agreement with these results, Assar et al. (2016) found that a 3-h tempering can reduce more than 80% the MC gradient when drying a long-grain variety at temperatures of 40–60°C.

It is a major challenge for the rice industry to dry all the rice received during the harvest season fast enough to avoid rice deterioration and, at the same time, maintain the milling quality. Therefore, optimizing the drying conditions to achieve the best results is one of the main goals of the rice sector.

Numerous efforts and research work have been made in this regard over the recent years. Schluterman and Siebenmorgen (2007) studied the maximum MC reduction that could be achieved during one drying pass without reducing the milling quality. Xing-jun et al. (2016) determined the drying time of three different varieties (long and medium grain) at temperatures of 50–70°C to maintain the kernel damage below 10%. However, there is scarce information about how the drying air conditions impact the milling quality of a long-grain rice variety at different stages of the drying process (different grain MC).

Therefore, the objective of this work was to study the impact of the drying air conditions on the milling quality and drying duration of a long-grain rice variety (Uy2) at different MC ranges using a lab-scale thin-layer dryer. To this purpose, drying runs of rice at different MC levels and using different drying air conditions (temperature and RH) were performed. The milling qualities and drying durations of each run were determined and compared.

2 MATERIALS AND METHODS

2.1 Rice sample

Rice of the Uruguayan variety Uy2 was collected from a single producer in the southeast region of Uruguay. The harvest MC of the paddy lot was 20.5 ± 1.0%.

The sample was homogenized and stored in a refrigerating chamber at 4.3 ± 1.8°C until use. Before each experiment, the amount needed was removed from the chamber and left in sealed bags at room temperature for at least 2 h.

2.2 Determination of MC

The MC was determined by gravimetry (AACC, 1999). Briefly, the samples were ground in an ultracentrifugal ZM200 mill (Retsch, Germany). Then, approximately 3 g was exactly weighed in an aluminum capsule and dried in a forced convection oven (Memmert, Germany) at 130°C for 1 h. The water content of the samples was calculated based on the weight difference and expressed as percentage on a wet basis.

For samples with MC greater than 16%, a two-stage method was used (AACC, 1999). Approximately 20 g of paddy rice was weighed, allowed to dry on the surface of the stove for 24 h, and weighed again (to determine the water loss). Then, approximately 3 g of the sample was milled, and the same procedure used for samples with MC lower than 16% was followed.

2.3 Experimental design

The drying air velocity was set at 0.4 m/s for all runs, and the air T and RH were constant during each run. Based on the Tg diagram for the variety Uy2 (Garcia-Llobodanin et al., 2020), the drying air T of each run was chosen, including temperatures below, above, and in the glass transition range. Two RHs were tested at each drying T. Table 1 shows the experimental design for this study. As can be seen, the RHs were chosen to have the same EMC values (7 and 10%) at all the air T levels, meaning that the grain surface MC was also the same (as the grain surface MC equals the EMC soon after the drying begins). The RHs for each combination of EMC and air T were calculated using the modified Chung-Pfost equation for long grains (Ondier et al., 2011). For some runs, the air conditions set could not be reached (due to limitations of the drying system). In those cases, the runs were set at the closest condition possible (see Table 1). At the air T of 47°C, a greater variation of the milling quality was observed between the two EMC conditions (compared with other air temperatures). Therefore, two extra runs at two different RHs (corresponding to EMC of 8.5% and 12%) were added.

For each drying condition, rice was dried to a final MC of 17 ± 0.7%, 15 ± 0.7%, and 13 ± 0.7%. This allowed the study of the impact of the drying conditions on the milling quality at each MC range.

The rice samples reached the drying air temperature within the first 2-3 min of run, in all cases. Therefore, the grain temperature was considered equivalent to the drying air temperature.

2.4 Drying system

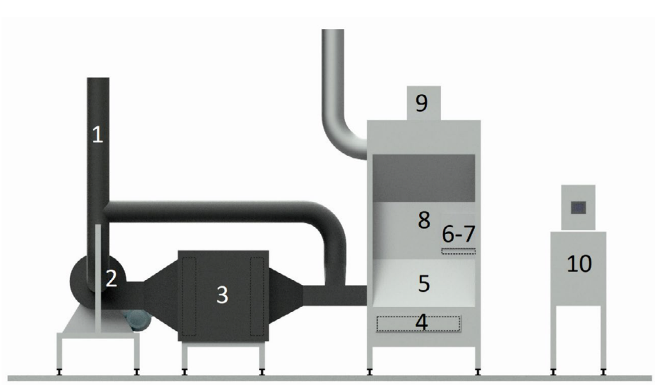
Rice was dried in a laboratory drying equipment specially designed and built for this purpose (Urumáquinas, Uruguay). It allowed controlling the drying air conditions including T, RH, and velocity with a precision of ± 0.6°C, ± 2.6%, and ± 0.02 m/s, respectively. The equipment also monitored the weight loss and grain temperature of the sample during drying. Figure 1 shows a schematic of the drying system used.

The ambient air entered the system with the aid of a blower, which controlled the air velocity. A water condenser and a vapor injector regulated the air humidity, and resistors regulated the air temperature. A sensor of T and RH together with a sensor of velocity was installed just before the drying chamber. Air conditions were set and controlled with the aid of a PLC (Secoin, Uruguay).

Table 1. Experimental design.

T (°C)	RH (%)	EMC (%)
35	25	7.4
35	50	10.0
47	27	7.0
47	42	8.5
47	57	10.0
47	70	12.0
55	30	7.0
55	60	10.0
65	31	6.5
65	45	8.6

T: air temperature (°C); RH: relative humidity (%); EMC: equilibrium moisture content.



1: air entrance; 2: blower; 3: water condenser; 4: resistors; 5: vapor injector; 6: velocity sensor; 7: air temperature and relative humidity sensor; 8: drying chamber; 9: load cell; 10: PLC.

Figure 1. Schematic of the drying equipment.

The rice sample was disposed of in a tray with a perforated bottom, to allow air circulation. A temperature sensor was introduced into the rice sample to monitor the grain temperature. The sample weight was measured with the aid of a load cell, and the grain MC was calculated at different times using the initial MC and the weight loss (Equation 1):

$$MCt = 100 \times \left(1 - \frac{IW}{Wt} \times \left(1 - \frac{IMC}{100}\right)\right) \quad (1)$$

Where:

MCt: the MC at a time *t*;

IW: the initial weight of the sample;

Wt: the weight of the sample at a time *t*;

IMC: the initial MC of the sample expressed on a wet basis.

All parameters (namely, drying air T, RH, velocity, sample temperature, and weight) were registered every 5 min along each drying run.

2.5 Rice drying

Once the drying air reached the set condition, 500 g of paddy rice was put on the tray, arranged in a thin layer of 1 cm high, and introduced into the drying chamber.

A drying curve was built for each condition, leaving the rice to dry until no MC change was detected (at least 10 consecutive measurements with grain MC differences among measurements lower than 0.5%). The drying curves were fitted to Page's equation (Equation 2) (Chen et al., 1997):

$$\frac{MC - EMC}{IMC - EMC} = \exp(-k\ x\ t^n) \quad (2)$$

Where:

MC: the moisture content at the drying duration t (h);

EMC: the equilibrium moisture content;

IMC: the initial moisture content;

k: the drying rate constant (h^{-1});

n: a dimensionless constant;

MC, *EMC*, and *IMC*: expressed in a decimal dry basis.

Then, for each drying condition, rice was dried to a final MC of 17 ± 0.7%, 15 ± 0.7%, and 13 ± 0.7%. The time needed to reach each final MC at each drying air condition was calculated using the fitted Page's equation.

After drying, samples were submitted to 1-h tempering at the corresponding drying air temperature. Based on preliminary experiments, this was the minimum tempering time needed to minimize kernels' breakage after drying (data not shown). After tempering, samples with a final MC of 17% and 15% were dried in a chamber (Alfa-Laval Gruppe, Germany) at 20.5°C and 60% RH until a final MC of 13 ± 0.5%. This gentle drying has a minimum impact on grain quality, allowing us to study the impact of the drying process at the MC range of interest. All experiments were performed in triplicate.

2.6 Drying duration

The drying duration was calculated as the sum of the drying durations of each MC range (from harvest MC to 13%) (Equation 3):

$$Drying\ duration = \sum (MC\ range\ drying\ duration) \quad (3)$$

When rice was dried from harvest MC to a final MC of 13% using the same drying conditions, the drying duration was the duration of that single stage. In case rice was dried in the lab-scale dryer only to an MC of 15 or 17%, the drying duration was calculated as the sum of the drying duration of this period plus the drying duration of the final drying range (from 15 or 17 to 13%) dried at the milder drying condition (T=35°C/50% RH). This condition was chosen due to being the one with a lower impact on the milling quality.

2.7 Milling quality

After drying and tempering, the samples were kept at room temperature for at least 72 h. Then, the head rice yield (HRY) was determined. The HRY is defined as the mass percentage of rough rice that remains as head rice after milling. Head rice are kernels that are at least three-fourths of the original kernel length after complete milling.

Before milling, each sample was cleaned with a grain cleaner (Grainman, USA). Then, 100 g of clean paddy rice was hulled using a paddy husker (THU35B, Satake, Japan). The dehulled rice samples were milled with a laboratory rice polisher (TM05C, Satake, Japan) to a degree of milling (DOM) of 100 ± 3, measured with a milling meter (MM1D, Satake, Japan). After milling, the broken kernels were separated using a trieur (Satake, Japan) and quantified using an Image Analyzer (Image 5, Selgron, Brazil). The results were expressed as grams of head rice obtained from 100 g of rough rice.

The head rice yield reduction (HRYR) during drying was defined as follows (Equation 4):

$$HRYR = HRY_{final} - HRY_{initial} \quad (4)$$

Where:

HRY_{final}: the HRY after the drying/tempering process at each drying condition;

$HRY_{initial}$: the "maximum milling potential" of the rice lot.

To determine the "maximum milling potential," four samples were gently dried in a chamber (Alfa-Laval Gruppe, Germany) at 20.5°C and 60% RH until a final MC of 13 ± 0.5%. This air condition produces minimum fissuring and, thus, minimal quality loss (Fan et al., 2000; Schluterman & Siebenmorgen, 2007). Therefore, the $HRY_{initial}$ represents the maximum milling quality that can be achieved for the rice lot used.

The HRYR is expressed in percentage points (pp), corresponding to the grams of milled head rice for every 100 g of rough rice.

2.8 Statistical analyses

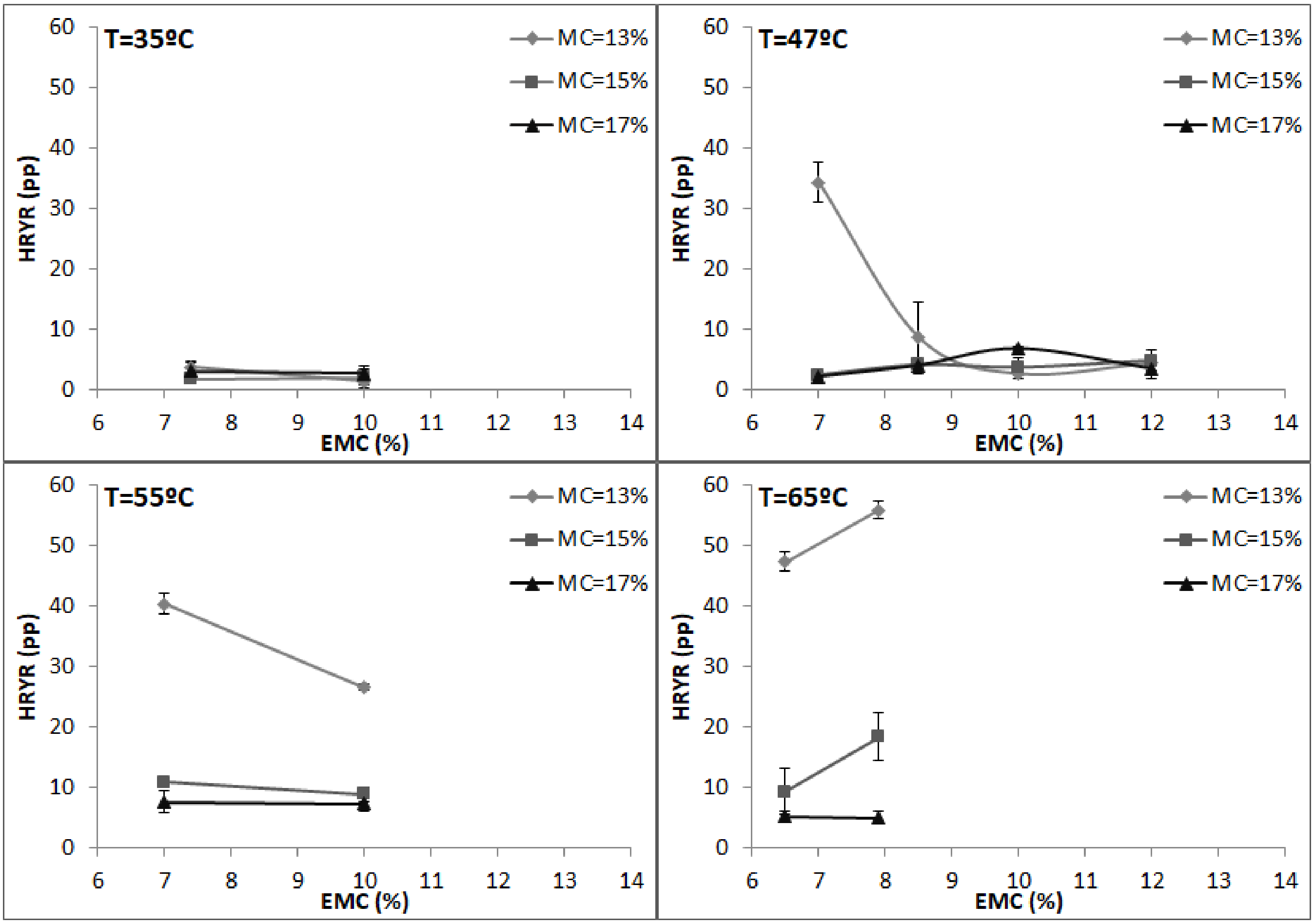
Non-linear regression using least squares was used to fit the drying curves to Page's equation. All statistical analyses were performed using the software JMP 12.0 (SAS Institute Inc., USA).

3 RESULTS AND DISCUSSION

Figure 2 shows the HRYR at different stages of the drying process (grain dried to an MC of 17, 15, and 13%), for the different drying air conditions. It is worth noting that, despite applying a 60-min tempering after every drying process, there existed a considerable HRYR in many of the drying conditions tested, especially when drying to a grain MC of 13%. This was possibly because irreversible grain damage occurred during drying, so subsequent tempering could not prevent breakage. In agreement with our results, Ondier et al. (2012) found that the HRYR increased when drying rice at high T and low RH, even after 120-min tempering. This was attributed to the intra-kernel stress created during drying. Maldaner et al. (2021) showed that intermittent drying improved the whole rice yield compared with continuous drying under the same conditions but did not prevent rice breakage completely.

Figure 2 also shows that, for all the runs at drying air temperatures of 35 and 47°C, it was possible to dry to a grain MC of 15% keeping the HRYR low (lower than 5 pp in all cases). However, at a drying air temperature of 55°C or higher, the HRYR increased even during the first stages of drying (HRYR higher than 9 pp at a grain MC of 15%). Going along with our results, Chayjan et al. (2019) found that the stress cracking index of rough rice increased as the drying air temperature increased, probably due to the greater internal MC gradient generated during drying. Yang et al. (2003) modeled the MC gradient inside rice kernels during drying runs at different air conditions. When comparing drying at 54 and 58°C (with an EMC of around 5.5% in both cases), they found that, for a given drying duration, a greater MC gradient was formed at the highest temperature. This was observed even at the early stages of the drying process. A greater MC gradient increases the tensions inside the kernel, favoring fissure formation and breakage. This could explain the higher HRYR observed in our experiments (even from early stages) when the drying air T was 55°C or higher.

At each drying air condition, the HRYR increased with drying duration, except for the milder conditions (low T and high RH), where it remained constant. In addition, the greatest increase always occurred during the last stage of the drying process



T: air temperature (°C); Error bars correspond to two standard deviations (± 2σ).

Figure 2. Head rice yield reduction (HRYR) versus equilibrium moisture content (EMC) of rice dried to different moisture contents (MC: 17, 15, and 13%) at the lab-scale dryer and taken to 13% MC at the drying chamber (T = 20.5°C/62% RH).

(grain MC decreasing from 15 to 13%). Going along with these results, Chen et al. (1997) found that there was less difference in the HRYR of different drying air conditions at the shortest drying durations compared with the longer ones. Fan et al. (2000) noticed that there existed a period during the early drying stages where the MC of the kernels decreased without affecting the HRYR. In our study, this period depended on the drying air conditions, which were longer at the milder conditions.

Yang et al. (2002) found that MC gradients inside rice kernels increased with drying duration until they reached a peak, after which they decreased very slowly. In addition, Yang et al. (2003) found that the maximal MC gradient time depended on the drying air conditions and the kernel dimensions, but, in all cases, it coincided with the time at which the HRYR started to increase dramatically. Chayjan et al. (2019) also estimated, by modeling, that MC gradients inside rice kernels increased dramatically, and then, if drying continued, they slowly decreased. Based on these results, it could be assumed that, in our experiments, the maximal MC gradient was probably formed at grain MC lower than 15%. During this period, a dramatic increase in the HRYR was observed. In addition, the low HRYR observed at mild drying conditions (low air T combined with high RH) was probably because, under these conditions, the MC gradient was not severe enough to drastically increase the HRYR. In agreement with our results, Yang et al. (2003) found that the HRYR of a long grain rice variety during drying at a T of 43°C or lower (with RH increasing from 31% to 47%) increased very little during the entire drying process.

In addition to MC gradients, the Tg could play an important role in the HRYR. Several researchers studied glass transition in different long- and medium-grain rice varieties (Perdon et al., 2000; Sablani et al., 2009; Siebenmorgen et al., 2004). Yang and Jia (2004) used numerical simulation to map the glass transition inside a rice kernel. As expected, during the early stages of drying, the glass transition zone was close to the surface of the kernel. As drying progressed, this zone moved toward the center of the kernel. Another interesting finding was that fissures initiated more easily from the tensile between the glass transition zones and the surface of the kernel. This means that when two different states coexisted within the same kernel, it was more susceptible to breakage. In our experiments, it was observed that drying below the Tg (T = 35°C), with the whole grain in the glassy state, resulted in low HRYR (HRYR < 4 pp). At 47°C, the HRYR depended much on the drying air RH. At high RH

(57 and 70%), corresponding to high EMC (10 and 12%, respectively), the HRYR was very low, showing similar values to those obtained when drying at 35°C. These conditions involved drying with the kernel in the transition region, without having part of the kernel in the glassy state. However, at lower drying air RH (27 and 42%), corresponding to lower EMC (7 and 8.5%, respectively), part of the kernel (the outside) was in the glassy state, while the rest was in the transition zone. The existence of an MC gradient combined with two different states within the same kernel significantly increased the HRYR. Drying at higher T (55 and 65°C) also involved the coexistence of different states within the same kernel, increasing the HRYR. These results agreed with previous studies which reported that a dramatic increase was observed in the HRYR when drying above the Tg without proper tempering immediately after drying (Cnossen & Siebenmorgen, 2000; Ondier et al., 2012; Yang et al., 2003). Mukhopadhyay and Siebenmorgen (2018) found that tempering significantly reduced the HRYR when drying above Tg.

In our experiments, 1-h tempering was performed after drying. However, tempering did not completely prevent the HRYR. In addition, preliminary experiments showed that longer tempering periods did not improve the HRYR. As previously exposed, this was probably because irreversible kernel damage occurred during drying, so a longer tempering did not prevent some kernels from breaking. Therefore, a 1-h tempering should follow the drying process in all cases.

The lowest HRYR was obtained when drying at 35°C and 10% EMC (HRYR = 2 pp). However, the drying duration at this condition was one of the highest (377 min). Therefore, a compromise should be made between drying duration and HRYR to optimize the drying process.

Considering our results, a two-stage drying could be proposed, starting with a more severe drying condition until a grain MC of 15%. Then, when the MC decreases (lower than 15%), a lower T and/or higher RH should be applied to avoid an increase in the HRYR.

Figure 3 shows the drying duration at different T and EMC. For the samples with final MCs of 15 and 17% (dried at the lab-scale dryer), the drying duration was the sum of the drying time needed to reach this condition plus the time needed to dry from that MC to the final MC of 13% at the mildest condition (see Section 2.6).

At a certain temperature, the drying duration increased as the EMC (and RH) increased. This is probably associated with a decrease in the water adsorption capacity of the drying air,

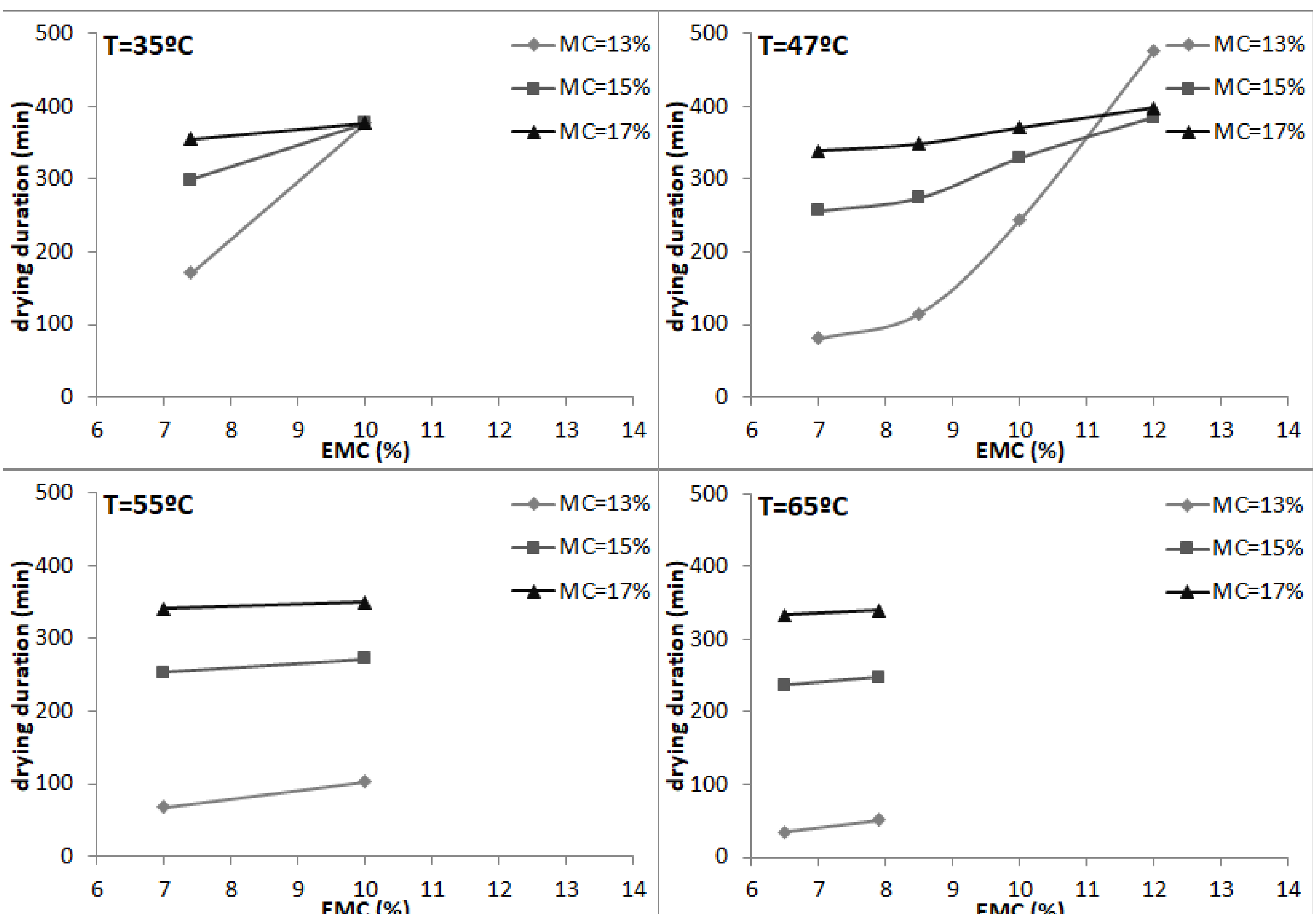


Figure 3. Drying duration versus equilibrium moisture content (EMC) of rice dried to different moisture contents (MC: 17, 15, and 13%) at the lab-scale dryer and taken to 13% MC at the drying chamber (T = 20.5°C/62% RH).

given by its higher RH. Going along with our results, Luthra and Sadaka (2021) found that the drying rate increased when the drying air was dehumidified, which they related to an increase in the drying air capacity. They also found an increase in the drying rate with increasing drying temperature, which coincides with the findings of Xing-jun et al. (2016) for six paddy samples of japonica and indica varieties. This behavior also seems to occur in our experiments, where the drying duration decreased as the drying temperature increased, at a constant EMC.

Based on our results, during the first stage of drying (until a grain MC of 15%), the air (grain) temperature could be up to 47°C with EMC as low as 7% (27% RH) without significantly increasing the HRYR (lower than 5 pp). Then, during the second stage of drying (grain MC from 15 to 13%), the air (grain) temperature should be 35°C or lower (with RH of 25% or higher) to minimize grain damage. Considering this two-stage drying process, with air conditions of 47°C and 27% RH (EMC = 7%) until an MC of 15% and 35°C and 50% RH (EMC = 10%) for MC from 15 to 13%, the total drying duration would be reduced to 256 min. This implies that drying runs were 32% faster (compared with drying at one single condition of 35°C and 50% RH), without increasing the HRYR.

All rice received by the industries must be dried within hours of reception to be stored at a safe MC. Therefore, implementing this two-stage drying process would be of great benefit, as it would increase the receiving capacity while achieving high milling quality. At present, according to the authors' knowledge, the rice industry applies drying programs that maintain constant grain T throughout the entire drying process, regardless of grain MC. Thus, the authors believe that the proposed novel drying operational approach - adjusting grain T based on rice MC throughout the process - may be key to improve the efficiency of drying. This would improve industry logistics and profitability, supported on the promising results obtained in this study.

4 CONCLUSION

Page's equation proved to be suitable for model thin-layer drying of a long-grain rice variety at different drying air conditions. The combination of drying air temperature and RH had a notorious influence on drying duration and HRYR. It was observed that, during the first step of the drying process (grain MC higher than 15%), the rice kernels were less susceptible to breakage than during the final stage (grain MC decreasing from 15 to 13%). Therefore, for all the combinations of drying air T and RH studied, the final stage was the most critical.

Based on these results, it was possible to propose a two-stage drying process with more severe drying conditions during the first stage and softening the conditions during the final stage. This result is of extreme interest to the rice sector and the rice industry as it would allow minimizing the drying time without increasing the HRYR.

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