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Improving the Efficiency of Rice Drying: Impact of Operational Variables on the Drying Rate and Quality of a South American Variety

Submitted: 29 May 2023 , Reviewed: 22 August 2023 , Published: 22 November 2023

DOI: 10.5772/intechopen.112970

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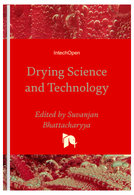
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Abstract

A key challenge for the rice industry during harvest is to improve the efficiency of the drying process, which involves increasing the drying rate and the head rice yield (HRY). In the present chapter, the main variables affecting the efficiency of rice drying were discussed. Then, the impact of the drying air conditions on the drying efficiency of a long-grain South American rice variety at different rice moisture contents (MC) was studied using a thin-layer lab-scale dryer. Drying at each air condition was modeled using Page's equation. The drying rate increased as the air conditions became more extreme (higher temperature or lower relative humidity). The effect on the HRY depended on the rice MC. Therefore, a two-stage drying program was proposed using different drying air temperatures depending on rice MC. These results were applied to create a drying program for a long-grain South American variety dried in a cross-flow commercial dryer. The two programs tested increased the drying rate and one of them also increased the HRY, compared to drying at the industry operational conditions. Implementing this program would improve the efficiency of the drying process, increasing the reception capacity and the profitability of the rice obtained.

Keywords

rice drying
drying rate
drying efficiency
rice quality
drying optimization

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Chapter sections

1. Introduction

Rice is a staple crop that feeds almost half of the world population [ ]. It is usually harvested at a moisture content (MC) of 16 to 22% and needs to be dried to a MC of 13% or lower for safe storage [ ]. Considering that rice must be dried immediately after harvest to prevent spoilage, drying becomes a critical process during the harvest season.

Increasing the drying rate is relevant because it allows a larger amount of rice to be dried in a given period of time, relieving the frequently occurring bottleneck generated when rows of producers' trucks are waiting to deliver their wet rice at the industrial plant.

During drying, moisture is removed from the surface of the rice grain. Initially, there is enough water available at the surface, making the drying rate rapid. After a short period of time, drying is limited by water diffusion from the interior to the surface of the kernel. This generates an increasing moisture gradient inside the kernel, with the center having a higher MC than the surface [ ]. MC gradients are present during the entire drying process, and they depend on the drying rate, which is determined by the rice grain MC and the drying air conditions (temperature, relative humidity, and flow rate) [ ]. The surface of the kernel tends to the equilibrium moisture content (EMC), which is given by the drying air temperature (T) and relative humidity (RH) [,]. A higher T or lower RH decreases the EMC, increasing the drying rate and the MC gradient.

The MC gradient generates tension at the surface of the grain, where the cells tend to shrink as moisture is lost, compressing the center [ ]. This is associated to the formation of fissures and cracking during drying. Fissured kernels are more prone to breaking during milling. Therefore, the head rice yield (HRY), defined as the mass percentage of rough rice that remains as head rice (kernels that are at least three-fourth of its original length) after milling, tends to decrease with the presence of fissured kernels. In addition, fissured kernels affect the functional properties of milled rice, and thus the sensory quality [ ].

Glass transition temperature (Tg) also plays an important role in fissures formation. Tg is the temperature range of transition of the amorphous regions of starch from a glassy into a rubbery state. Starch is the main component of rice and is formed by amylose and amylopectin chains. Glass transition occurs at the branching points of amylopectin [ ]. The glassy state has a low expansion coefficient, specific volume, specific heat, and diffusivity but high viscosity and modulus of elasticity. Contrarily, the rubbery state has higher expansion coefficient, specific heat, specific volume, and diffusivity [,]. The Tg increases as the grain MC decreases. During drying, the MC at the surface of the grain is lower than that at the center. This could cause the center of the grain to be in the rubbery state, while the surface is in the glassy state. The differences in the properties of the two states increase the tensions generated by the MC gradient and play an important role in terms of kernel fissuring potential [ ].

To prevent this, at least in part, a process called tempering is used between drying passes. During tempering, rice is held in bins for a certain period of time. The purpose is to allow the MC gradients generated during drying to subside, reducing the tensions inside the kernels and therefore preventing kernels' fissuring [,].

The drying rate is also affected by grain composition and geometry. Therefore, different varieties may respond differently to the same drying air conditions [,].

As a result of this, the need arises to find suitable drying programs for each variety, reducing the drying time while minimizing fissures formation. A compromise should be made between the drying rate and the MC gradient generated during drying, which could lead to fissures formation, especially when two states (glassy and rubbery) coexist within the same kernel.

Several authors studied the impact of the drying air conditions and Tg on the drying rate and HRY [, 5 ,]. Most of the studies were conducted using long-grain rice laid out in a thin layer, to ensure that all the rice is subjected to the same conditions.

As previously exposed, rice variety also plays an important role in relation to drying. Long-grain and medium-grain rice showed different behavior during drying [ ]. This was attributed to differences in the kernels' dimensions. Medium-grain kernels were thicker, so moisture had to travel a longer path in its migration to the surface (compared to long-grain kernels).

Different drying methods, including experiments in commercial dryers, were also studied by some researchers. In Ref. [ ], continuous drying of rough rice was compared with intermittent drying, while [ ] investigated rough rice drying in fixed and fluidized bed dryers. Natural drying (shade and sun drying) was compared with heated air drying in [ ] using different drying methods in a commercial and a lab scale.

The research published so far is mostly on varieties developed in the United States or Asia. There is very little literature on South American varieties, which have their own characteristics given by climatic conditions, cultivation practices, and genetics.

The present chapter introduces a review on the main variables affecting the drying efficiency, understanding the drying efficiency as the combination of drying rate and HRY. Then, the impact of the operating conditions on the efficiency of rice drying was studied for a South American variety using a thin-layer lab-scale dryer. Finally, an industrial application of the previous results is shown for a South American variety dried in a commercial cross-flow dryer.

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2. Variables affecting the efficiency of rice drying

This section presents a review of the main variables affecting the drying efficiency, understanding the drying efficiency as the combination of drying rate and HRY.

2.1 Drying air conditions

The drying air conditions have an impact on the drying rate and the HRY. Severe drying conditions (high drying air temperatures, flow rate, and/or low RH) increase the MC gradient, increasing the drying rate but decreasing the HRY.

In Ref. [ ], the authors study the HRY of rice dried at different drying conditions. At the milder condition (higher EMC), the HRY was not affected during the entire drying process. However, as the drying conditions became more severe (lower EMC), the HRY decreased during drying. The more severe the drying condition, the sooner the HRY begins to decrease once drying starts. This could probably be attributed to the formation of more pronounced MC gradients.

An increase in the drying air temperature increases the drying rate, even for the same EMC [ ]. The HRY is also susceptible to air temperature, even with equal EMC conditions. This is probably because higher drying rates cause more pronounced MC gradients inside the kernel, increasing tensions and favoring fissures formation. The HRY reduction is even more pronounced when drying above Tg, probably due to the coexistence of glassy and rubbery zones (surface and core, respectively) in the same rice kernel [ ].

Regarding the drying air RH, when reduced (at a given temperature), the drying duration is shortened [ ]. This could be related to an increase in the drying potential of the air.

2.2 Glass transition temperature

Tg is the temperature range corresponding to the transition of the amorphous regions of starch from a glassy to a rubbery state. It is a useful material descriptor due to its good correlation with structural and thermodynamic properties [ ]. Tg depends on the composition of the rice grains, particularly starch. The amylose/amylopectin ratio plays an important role in the Tg. The higher the amylose content, the higher the Tg, which is associated to chain-chain interactions of linear chains of amylose that induce partial crystallinity [ ]. On the contrary, high amylopectin starches show lower Tg. This was attributed to the formation of gel balls by the short-branched chains in amylopectin molecules. The gel balls require less energy to move than long linear chains, reducing the Tg. Water also reduces the Tg, acting as a plasticizer [,]. Therefore, the Tg of a rice kernel depends on its MC. This means that at a certain temperature, a kernel could be in the glassy or in the rubbery state, depending on its MC.

The abrupt change in several properties of the material in the glass transition range can be used for its determination [ ]. There are changes in two groups of properties: rheological and thermodynamic properties. Differential scanning calorimetry (DSC) is used to determine Tg based on changes in thermodynamical properties, such as heat capacity. Dynamic mechanical thermal analysis (DMTA) is another methodology used and is based on the change in rheological properties, such as the storage and loss moduli. Both methodologies showed good results and proved to be suitable for Tg determination [,].

shows the state diagram for three Uruguayan rice varieties (Uy1, Uy2, and Uy3), built using DSC [ ]. A significative difference between the Tg of Uy1 and Uy3 in the MC range of 12 to 16% was found, proving that different varieties could have differences in the Tg. This was attributed to differences in the starch composition and in the kernels' dimensions of both varieties.

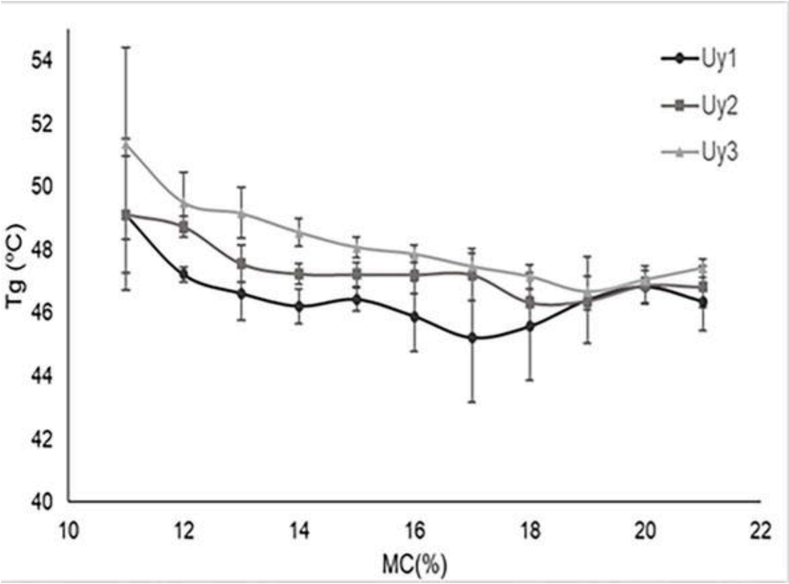

Figure 1.
State diagram for three Uruguayan varieties (reprinted, with permission, from [16]). Tg, glass transition temperature; MC, moisture content.

Tg plays an important role in the rice drying process. Drying at temperatures above the Tg increases the drying rate since thermal conductivity and mass diffusivity are higher in the rubbery state. However, the possible presence of glassy and rubbery regions within the same kernel (due to differences in the MC given by the MC gradient formed) could increase the tensions inside the grain, favoring fissures formation and reduction of the HRY [ ]. represents this situation in a state diagram [ ]. A rice kernel with initial MC of 19% is heated during drying to a temperature of 55°C, going from the glassy to the rubbery zone. As drying continues, the center (more humid) remains in the rubbery zone, while the surface tends to the EMC in the glassy zone. This increases the tensions that already exist inside the kernel due to the MC gradient. Increasing the air relative humidity (RH) increases the EMC, and consequently reduces the MC gradient. This enables a greater part of the kernel to remain in the rubbery state (when drying above the Tg), and therefore increases the HRY [ ].

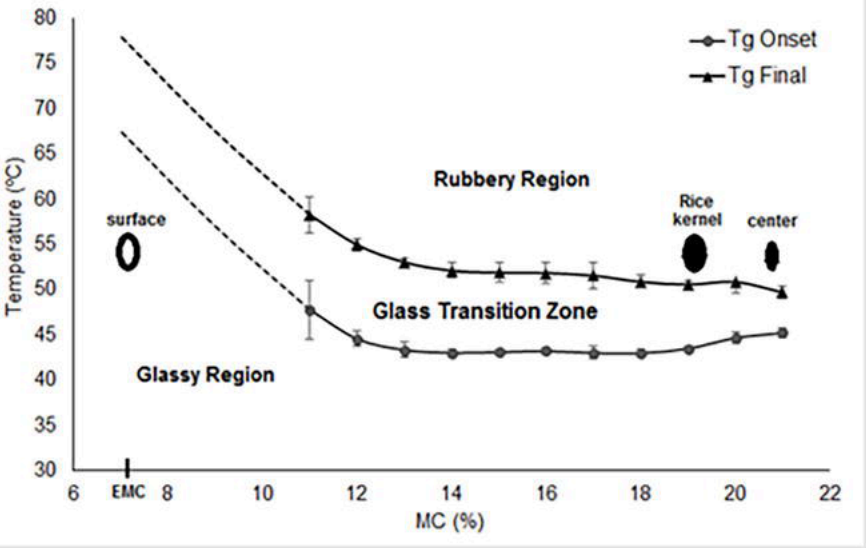

Figure 2.

Representation of a rice kernel (whole grain, center, and surface) in a state diagram. MC, moisture content, EMC = equilibrium MC, Tg = glass transition temperature (reprinted, with permission, from reference [11]).

In Ref. [ ], a glass transition mapping inside a rice kernel during drying was performed by modeling. It was found that when the drying air temperature is higher than the Tg, the outer layers of the kernel go from the glassy to the rubbery state due to a rapid temperature rise at the beginning of drying. Then, as MC decreases, a transition from the rubbery back to the glassy state could occur (as shown in). Simulation suggests that fissures initiate more easily from the tensile zones, where the transitions from a rubbery to a glassy state occur, probably because of the stress concentration in the interface between the regions of expansion and contraction caused by the change of state.

2.3 Kernels dimensions and composition

The dimensions and composition of the grain kernels affect their behavior during drying. As the kernel thickness increases, the fissured kernel percentage also increases [ ]. It was hypothesized that the thicker kernels experience a greater MC gradient than thinner kernels when exposed to the same drying condition. This leaves thicker kernels more susceptible to fissuring. Confirming these results, a study with Bengal (medium-grain), Cypress, and Kaybonnet (both long-grain) varieties dried under the same drying conditions shows that medium-grain Bengal has a faster and more pronounced HRY reduction compared to the other two varieties [ ].

The chemical composition (amylose and protein content) and physicochemical properties of rice also impact the HRY [ ]. Drying of both low and high amylose rice, at the same level of grain temperature, shows quality differences [ ].

The drying rate is also affected by the rice grain variety, influenced by the kernel dimensions and/or composition [ ].

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3. Impact of operating conditions on the efficiency of rice drying

As seen in the previous section, there are numerous variables that affect the drying rate and the HRY, among which are the operating (drying air) conditions. The operating conditions needed to increase the drying rate are usually opposite to those needed to improve the HRY.

The aim of the present section is to study the impact of the operating conditions on the milling quality and drying duration of a South American long-grain rice variety (Uy2) at different stages of the drying process. To this purpose, a thin-layer lab-scale dryer was used to dry rice under different controlled drying air conditions. The drying process at each condition was modeled using Page's equation.

3.1 Materials and methods

3.1.1 Rice sample

Rice of the Uruguayan variety Uy2 was collected from a single producer in the south-east region of Uruguay. The MC was determined by gravimetry [ ]. 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 two hours.

3.1.2 Experimental procedure

Drying runs of long-grain rice Uy2 at different MC levels and using different drying air conditions (temperature and relative humidity) were performed. 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.

shows the experimental design. Runs were carried out at different temperatures, below and above the Tg, and two RH were tested at each T. The RH was 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 (since 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 [ ]. 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). At the air T of 47°C, a greater variation of the milling quality was observed between the two EMC conditions (compared to other air temperatures). Therefore, two extra runs at two different RHs (corresponding to EMC of 8% and 12%) were added.

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

Table 1.
Experimental design.

T, Air temperature (°C); RH, Relative humidity (%); EMC, Equilibrium moisture content.

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 minutes of run in all cases. Therefore, the grain temperature was considered equivalent to the drying air temperature.

3.1.3 Drying system

Rice was dried in a laboratory drying equipment, especially 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. shows a schematic of the drying system used.

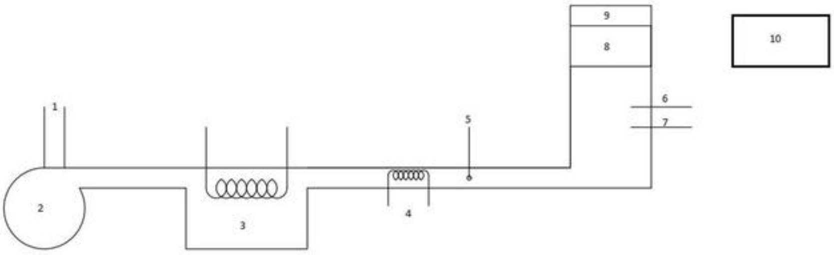

Figure 3.
Schematic of the drying equipment. 1-air entrance, 2-blower; 3-condenser, 4-resistors, 5-vapor injector, 6-velocity sensor, 7-air temperature and relative humidity sensor, 8-drying chamber, 9-load cell, and 10-PLC.

The ambient air entered the system with the aid of a blower, which controlled the air velocity. A 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).

The rice sample was disposed in a tray with a perforated bottom to allow the air circulation. A temperature sensor was introduced in 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:

$$MCt = 100 \times \left(1 - \frac{IW}{Wt} \times \left(1 - \frac{IMC}{100}\right)\right) \qquad \text{E1}$$

where MCt is the MC at a time t, IW is the initial weight of the sample, Wt is the weight of the sample at a time t, and IMC is the initial MC of the sample expressed on a wet basis.

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

3.1.4 Rice drying

Once the drying air reached the set condition, five hundred grams of paddy rice were put on the tray, arranged in a thin layer of one centimeter 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 ten consecutive measurements with grain MC differences among measurements lower than 0.5%). The drying curves were fitted to Page's :

$$\frac{MC-EMC}{IMC-EMC} = \exp\left(-k\ x\ t^{n}\right) \qquad \text{E2}$$

where MC is the moisture content at the drying duration t (h), EMC is the equilibrium moisture content, IMC is the initial moisture content, k is the drying rate constant (h^{-1}), and n is a dimensionless constant. MC, EMC, and IMC are 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 one-hour tempering at the correspondent drying air temperature. Based on preliminary experiments, this was the minimum tempering time needed to minimize kernels' breakage after drying [ ]. 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 the grain quality, allowing to study the drying process at the MC range of interest. All experiments were performed in triplicate.

3.1.5 Milling quality

After drying and tempering, the samples were kept at room temperature for at least 72 hours. Then, the head rice yield (HRY) was determined.

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:

$$\mathrm{HRYR} = \mathrm{HRY}_{\mathrm{final}} - \mathrm{HRY}_{\mathrm{initial}} \qquad \mathrm{E3}$$

where $\mathrm{HRY}_{\mathrm{final}}$ was the HRY after the drying/tempering process at each drying condition evaluated, and $\mathrm{HRY}_{\mathrm{initial}}$ represents the "maximum milling potential" of the rice lot. The HRYR is expressed in percentage points (pp), corresponding to the grams of milled head rice every 100 g of rough rice.

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 [,]. Therefore, the HRYR obtained represents the maximum milling quality that can be achieved for the rice lot used.

3.1.6 Statistical analysis

The drying curves were fitted to Page's equation using the software JMP 12.0.

The standard deviation was calculated for the Page's equation parameters and the HRYR. Analysis of variance (ANOVA) was used to compare the n constant of Page's equation at different drying conditions. In the case of significative difference ($p < 0.05$), the Tukey test was applied to determine which are the values that differ.

The mean squared error (MSE) was calculated for Page's equation at each drying condition.

3.2 Results and discussion

shows the EMC calculated using the modified Chung-Pfost equation, the parameters k, n, and EMC from the fitted Page's equations, the corresponding mean squared error (MSE), and the drying durations to reach a final MC of 13%, 15%, and 17% (calculated using the fitted Page's equations) for each drying air condition.

T (°C)	RH (%)	$\mathrm{EMC}_{\mathrm{C\text{-}Pfost}}$ (%)	$\mathrm{EMC}_{\mathrm{Page}}$ (%)	k (h^{-1})	n	MSE	t_{MC} = 13% (min)	t_{MC} = 15% (min)	t_{MC} = 17% (min)
35	25	7.4	7.3 ± 0.4	0.47 ± 0.04	$0.60 \pm 0.04^{A,B}$	0.0342	171	80	29
35	50	10.0	7.9 ± 0.4	0.35 ± 0.04	0.54 ± 0.04^{B}	0.1054	377	158	51
47	27	7.0	6.7 ± 0.4	0.69 ± 0.04	$0.59 \pm 0.02^{A,B}$	0.0396	80	37	13
47	42	8.5	8.2 ± 0.4	0.69 ± 0.04	$0.61 \pm 0.08^{A,B,C}$	0.0302	115	55	22
47	57	10.0	10.9 ± 0.2	0.54 ± 0.00	$0.74 \pm 0.06^{D,E}$	0.0204	244	110	44
47	70	12.0	12.3 ± 0.6	0.61 ± 0.02	$0.73 \pm 0.06^{D,E}$	0.0180	474	166	74
55	30	7.0	5.7 ± 2.0	0.76 ± 0.08	$0.60 \pm 0.08^{A,B}$	0.0356	67	35	15
55	60	10.0	9.3 ± 0.4	0.84 ± 0.1	$0.69 \pm 0.06^{C,D}$	0.0239	102	52	23
65	31	6.5	6.7 ± 0.2	1.16 ± 0.04	$0.65 \pm 0.08^{A,C}$	0.0598	35	17	7
65	45	8.6	8.5 ± 0.4	1.17 ± 0.06	0.80 ± 0.02^{E}	0.0552	51	28	13

Table 2.

EMC obtained from Chung-Pfost equation, Page's equation parameters (EMC, k, and n), MSE, and time needed to reach the final MC.

Error: ± 2σ. Different letters within a column indicate significative difference. T, temperature; RH, relative humidity; EMC, equilibrium moisture content using the Chung-Pfost eq. (C-Pfost) and Page's equation (Page), k, kinetic constant; n, Page's equation constant; MSE, mean squared error; t, duration to reach the indicated moisture content (MC). Each experimental value is an average of three replicates.

The modified Chung-Pfost equation has been extensively used to calculate the EMC of grains. In Ref. [ ], five different equations were compared and their suitability for describing the EMC of rough rice of different varieties (long and medium grain) was evaluated in a wide range of T and RH. The Chung-Pfost equation was the best model for describing equilibrium data.

Mathematical modeling of rough rice drying has also been studied by several researchers. A diffusion model assuming that liquid diffusion is the only moisture transfer inside the rice kernels has been used by some authors [,]. However, solving this type of modeling is quite complex. Therefore, researchers usually use empirical or semiempirical models to simulate rice drying [ ]. In Ref. [ ], ten different models for continuous and intermittent drying of thin-layer rough rice were compared. The authors found that the Midilli model showed the best results but another four of them, including Page's model, were also adequate in describing the experimental data.

In Ref. [ ], the suitability of twelve empirical and semiempirical models in defining thin-layer drying behavior of long-grain rough rice was studied. They also found that Midilli's model showed the best results, in part due to its high number of coefficients (four). The fact that it is a simplified version of the diffusion equation could also contribute, proving that liquid diffusion is the dominant transport mechanism in rough rice. Nevertheless, they found that Page's model was also suitable and was the most accurate among the two-parameter models. In agreement with these results, Pereira et al. [ ] found that Page's model was the best model, among the six models studied, for describing continuous and intermittent drying of rough rice. Based on these previous reports, Page's model could be considered a simple (only two parameters), suitable model for describing thin-layer rough rice drying.

In the present study, except for the air condition at T = 35°C and RH = 50%, the EMC calculated using the modified Chung-Pfost equation was in quite good agreement with those obtained from Page's equation. In addition, Page's equations presented low MSE values (see), confirming its suitability for representing thin-layer drying of the long-grain rice variety Uy2.

also shows that n values are significantly different among some of the runs ($p < 0.05$). The k values can only be compared among those runs with n not significantly different. In those cases, k increased as the drying air temperature increased. Consequently, at constant EMC, the time needed to reach a certain grain MC decreased as temperature increased, as shown in . In agreement with our results, Chen et al. [ ] found that higher temperatures may cause higher k values, even when the EMC was the same. This behavior could be expected since higher drying temperatures are associated with higher drying rates [ ]. This is probably due to higher moisture effective diffusivities at higher drying temperatures [,].

In Ref. [ ], the authors found that drying above the Tg significantly increased the drying rate compared to drying below the Tg. This was attributed to the higher diffusivity observed in the rubbery state (compared to the glassy state). As previously exposed, in our experiments the drying constant (k), when comparable, also increased as the drying air T increased. In fact, when the drying air T increased from 35°C (below Tg) to 47°C (above Tg) at a constant EMC of 7%, the value of k increased almost 50%. However, when the drying air T increased from 47 to 55°C (both above Tg), the value of k only increased 10%. Therefore, the sharper increase of k in the former situation could be attributed, at least in part, to the glass transition phenomenon.

presents the HRYR of the rice dried at different drying air conditions and to different final MC. For rice taken to 17% and 15% MC, drying was finished in the drying chamber under mild conditions (T = 20.5°C and 62% RH). It can be observed that rice could be dried to a MC of 15% using drying air at temperatures as high as 47°C and RH as low as 27% maintaining a low HRYR (under 5 pp). Drying air temperatures of 55°C or higher increased drastically the HRYR.

T (°C)	*RH (%)*	MC = 17%	MC = 15%	MC = 13%
35	25	3.1 ± 1.4	2.0 ± 0.5	3.7 ± 0.9
35	50	2.7 ± 1.3	2.1 ± 1.3	1.5 ± 1.2
47	27	2.2 ± 0.7	2.5 ± 0.7	34.4 ± 3.3
47	42	4.1 ± 0.3	4.2 ± 0.8	8.6 ± 4.6
47	57	6.9 ± 0.3	3.8 ± 1.4	2.6 ± 0.6
47	70	3.5 ± 1.6	4.9 ± 1.8	4.4 ± 0.4
55	30	7.6 ± 1.9	10.9 ± 0.3	40.4 ± 1.7
55	60	7.4 ± 1.2	8.9 ± 1.2	26.5 ± 0.5
65	31	5.3 ± 0.9	9.4 ± 3.9	47.4 ± 1.6
65	45	5.1 ± 1.0	18.4 ± 3.4	56.0 ± 1.5

Table 3.

Head rice yield reduction (HRYR) of rice dried to different moisture contents (MC: 17%, 15%, 13%) at different drying air conditions (T, RH). Rice with MC 17% and 15% was taken to a final MC of 13% under mild drying conditions (T = 20.5 °C/62% RH).

HRYR is expressed in percentage points. Errors of HRYR correspond to two standard deviations (±2σ).

During the last stage of the drying process (15–13% MC), milder drying air conditions should be applied to maintain a low HRYR. At 35°C, the HRYR was low at both RH tested. However, at 47°C the RH should be 57% or higher to keep the HRYR low.

This research brings important information on how the drying air conditions affect the drying rate and HRYR of a South American long-grain rice variety. The results could be used to implement a drying program that improves both aspects, using a more severe drying air condition until a MC of 15% to increase the drying rate, and then softening the drying air conditions at MC below 15%, to avoid an increase in the HRYR.

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4. Industrial application: a case study

In the first two sections, a review of the main concepts and research works regarding the variables affecting rice drying were presented. In the third section, the impact of the operation variables on thin-layer drying of a South American rice variety was studied. Based on these results, in the present section two drying programs are proposed and tested to dry a South American variety in a commercial cross-flow dryer, with the aim of increasing the HRY and the drying rate. The objective of this section is to provide a practical application to the results obtained on a laboratory scale.

4.1 Materials and methods

4.1.1 Commercial dryer

Runs were performed in a cross-flow commercial dryer. The dryer has two sections: a drying chamber and a tempering zone. Rice enters the dryer and recirculates, passing the drying chamber and tempering zone in each cycle, until it reaches the final MC (approximately 13%). Contrarily to what occurs in the lab-scale dryer (see Section 3), in the commercial dryer, rice temperature never reaches the drying air temperature (due to the absence of a thin layer of rice and the passage through the tempering zone between the drying cycles). Therefore, the drying programs were based on controlling the rice grain temperature (not the drying air temperature).

The drying air was taken from the environment and brought to the desired drying temperature in an industrial oven. Therefore, its RH depends on the environmental conditions. Since the drying air temperature was much higher than the ambient, the RH of the drying air was low.

4.1.2 Experimental design

From the experiments in the lab-scale dryer (see Section 3), it could be concluded that at low RH (which is the case in the commercial dryer) and a grain MC of 15% or higher, the air temperature (which equals the grain temperature) should be below 55°C and above 47°C. This allows a high drying rate with low HRYR (below 5 pp). Higher drying air temperatures not only increase the drying rate but also increase the HRYR.

At grain MC below 15% and low RH, the air temperature should be below 47°C, being the HRYR very low at an air temperature of 35°C (no data is available between 35 and 47°C).

During the experiments, it was also observed that the Tg plays an important role, being critical when a pronounced MC gradient is present within the kernel. Therefore, drying at temperatures above Tg should be avoided at low grain MC.

Based on these considerations, two programs were proposed and tested by triplicate:

Program A:

Grain MC > 18%: grain temperature = 48 ± 2°C

Grain MC < 18%: grain temperature = 42 ± 2°C

Program B:

Grain MC > 18%: grain temperature = 48 ± 2°C

15% < Grain MC < 18%: grain temperature = 42 ± 2°C

Grain MC < 15%: T grain temperature = 40 ± 2°C

4.1.3 Experimental procedure

The rice used was a long-grain Uruguayan variety, with similar dimensions and composition than Uy2 (see Section 3). All runs (at the ordinary operating conditions and the programs) were performed with the same rice variety.

A representative sample of the rice entering the dryer in each run was collected using an automatic sampler. It collected a sample of approximately half kilogram every 2 minutes during the loading of the equipment. Once the loading was completed, the samples were mixed and homogenized properly. The same procedure was followed during the unloading, to obtain a representative sample at the exit of the dryer (once the drying run was finished). The rice MC was determined by gravimetry [ ], and the HRYR was determined as described in Section 3.1.5, being HRY_{final} the HRY of the sample collected at the exit of the dryer and $HRY_{initial}$ the HRY of the sample collected at the entrance of the dryer and gently dried in the chamber until a final MC of 13 ± 0.5%.

The average drying rate of each run was defined as the average MC (on a dry basis) removed per hour and was calculated as:

$$Drying\ rate = \frac{MCfinal,d.b. - MCinicial,d.b.}{time} \qquad \text{E4}$$

where MCfinal,d.b. is the MC of rice at the end of the run on a dry basis (%MC), MCinitial,d.b. is the MC of rice at the beginning of the run on a dry basis (%MC), and time is the drying duration of the run (hours).

Thermal properties of all the rice samples were measured with a differential scanning calorimeter (TA instruments, DSC Q2000) as described in [ ]. The data obtained comprise the onset temperature, peak temperature, conclusion temperature, and crystal melting enthalpy (ΔH).

Pasting properties were measured with a rapid visco analyzer (Perten Instruments, RVA 4500) following AACCI Approved Method 61–02.01. The peak, trough, final, breakdown, and setback viscosities were measured.

The drying rate, HRYR, and thermal and pasting properties of programs A and B were compared with those from the ordinary drying runs (runs under the ordinary operating conditions of the industry), which maintained a constant grain temperature.

4.1.4 Statistical analysis

The standard deviation was calculated for the HRYR and the drying rates.

Analysis of variance (ANOVA) was used to compare variables. In case of significative difference among variables ($p < 0.05$), Tukey test was applied to determine which were the variables that differ.

4.2 Results and discussion

shows the average HRYR and drying rate of the runs dried with program A, program B, and ordinary operating conditions of the industry. Program A and B had significantly higher drying rates than the ordinary runs. In addition, program B had a significantly lower HRYR than the ordinary runs. Although the difference between program A and program B was not significant, it was observed that program B runs tend to have lower HRYR than program A.

	HRYR (pp)	Drying rate (%MC/h)
Program A	$2.0 \pm 1.0^{A,B}$	1.38 ± 0.2^{A}
Program B	0.8 ± 0.9^{B}	1.28 ± 0.2^{A}

	HRYR (pp)	Drying rate (%MC/h)
OOC	2.8 ± 0.4^{A}	1.06 ± 0.2^{B}

Table 4.
HRYR and drying rate of drying programs and ordinary commercial drying runs.

Different characters in the same column indicate significative difference among samples ($p < 0.05$). Errors correspond to two standard deviations ($\pm 2\sigma$). HRYR Head rice yield reduction and OOC = Ordinary operating conditions.

Based on these results, program B seems to be the most promising to improve the drying efficiency, increasing the drying rate and reducing the HRYR compared to the ordinary operating conditions. Implementing this program would reduce the drying duration of each run, increasing the reception capacity of the drying plant and, consequently, improving its productivity. At the same time, reducing the HRYR would increase the profitability of the rice obtained.

Drying conditions can affect the quality of rice, especially when high grain temperatures are reached during the drying process [, ,]. For this reason, thermal and pasting properties of the samples from program B and those from the runs under ordinary operating conditions were measured and compared. and show these results.

	T. Peak (°C)	T. Onset (°C)	T. Conclude (°C)	ΔH (J/g)
PROG B-IN	65.19	59.28	78.03	11.01
PROG B-OUT	65.52	59.74	76.19	11.56
OOC-IN	66.06	59.95	77.89	11.65
OOC-OUT	66.38	60.72	80.98	11.13

Table 5.
Thermal properties of rice samples collected during drying.

Results are the average of two runs in each condition (program B or ordinary operating conditions). PROG, Program; OOC, Ordinary operating conditions; IN, Representative sample of the loading; OUT, Representative sample of the unloading; T, Temperature; ΔH, Enthalpy.

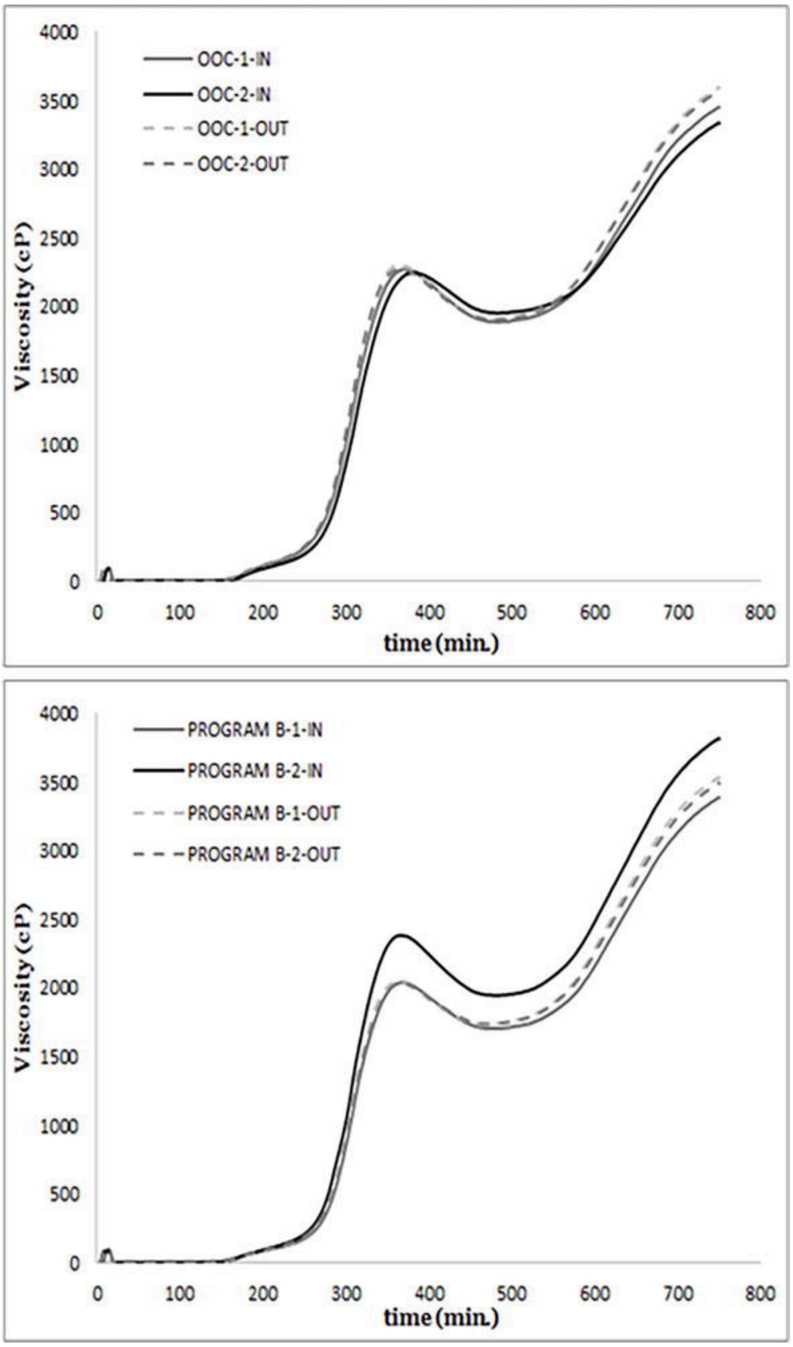

Figure 4.

Viscosity profiles of rice samples collected during drying. OOC, ordinary operating conditions; PROG, program; IN, representative sample of the loading; OUT, representative sample of the unloading.

Comparing the values and profiles of the samples collected during the loading (before drying) with those collected during the unloading (after drying), no significant differences were observed either for samples from Program B or for those from the ordinary operating conditions. The same behavior was observed with samples from program A (data not shown). Therefore, it could be concluded that the drying process had no effect on the cooking properties in any of the conditions tested, confirming that Program B is a suitable drying program to implement in the industry to improve the drying efficiency.

In Ref. ( ), the authors found that hardness and stickiness of an aromatic long-grain rice dried using different drying methods were not significantly different to the control sample (sample dried under very mild conditions) when the drying temperature was kept below 60°C. In agreement with this, Dillahunty et al. [ ] found that only drying above 55°C with exposure durations higher than 12 hours lowered the peak viscosity of a long-grain (Cypress) and a medium-grain (Bengal) rice. At temperatures below that, there were no significant differences with the control samples. In our experiments, temperature never exceeded 50°C, being below the temperature reported as critical by these researchers. Therefore, our results for a South American variety were in agreement with these findings reported for other long-grain varieties.

5. Conclusions

This chapter reviews the main variables affecting the drying efficiency, understanding the drying efficiency as the combination of drying rate and HRY.

Drying of a long-grain South American rice variety under controlled drying air conditions was studied using a thin-layer lab-scale dryer. It was found that the HRYR and drying rate were affected by the drying air temperature and RH. Tg also played an important role in the drying process.

During these experiments, it was concluded that drying at grain temperatures above 47°C without affecting the HRY was possible up to a grain MC of 15%. This allowed an increase in the drying rate (compared to drying at lower temperatures). For MC below 15%, the grain should be dried at milder conditions (lower grain temperatures) to avoid an increase of the HRYR.

Based on these results, a two-stage drying program was proposed to improve the drying efficiency (drying rate and HRYR). This program was tested in a commercial cross-flow dryer using a South American rice variety with promising results. The HRYR was reduced and the drying rate increased, compared to the runs performed at the ordinary operating conditions of the industry. Additionally, the cooking properties were not affected.

Implementing this drying program would allow to increase the reception capacity of the rice industries and reduce the percentage of rice kernels with lower added value (broken kernels), improving the productivity of the industrial sector.

Acknowledgments

We thank LATU (Technological Laboratory of Uruguay) for the financial support.

Nomenclature

EMC	Equilibrium moisture content
HRY	head rice yield (pp)
HRYR	head rice yield reduction (pp)
k	drying rate constant (h^{-1})
MC	moisture content, dry basis
RH	relative humidity (%)

T	temperature (°C)
Tg	glass transition temperature (°C)
W	weight (g)
I	initial

Subscript:

t	variable at a time t

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Submitted: 29 May 2023 , Reviewed: 22 August 2023 , Published: 22 November 2023

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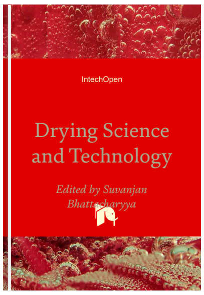

Drying Science and Technology

Edited by Suvanjan Bhattacharyya

PUBLISHED: 28 FEBRUARY 2024

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