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Thick layer drying and storage of rice grain cultivars in silo-dryer-aerator: Quality evaluation at low drying temperature

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A B S T R A C T

Drying rice in a single layer in a silo-dryer-aerator allows uniform drying. The objective of this study was to evaluate the physical, physicochemical, and morphological quality of rice grain cultivars (IRGA 424, BRS Pampeira, and Guri INTA) in the lower (initial time) and upper (final time) layers in a silo-dryer-aerator, employing single-layer loading at low temperatures, using the methods of near-infrared spectroscopy, X-ray diffraction analysis, scanning electron microscopy, and multivariate statistical analysis. Drying rice in silo-dryer-aerator attenuated the moisture diffusivity in the grains, minimizing its effects on the physical, physicochemical, and morphological properties of the grains. However, the physicochemical constituents and morphology of starch were preserved by the low drying temperatures, mainly in the lower layers throughout the 2-month drying. The rice grains of the Guri INTA and BRS Pampeira cultivars were the most resistant to drying and showed greater uniformity on the final quality.

1. Introduction

Rice is one of the main components of the diet in many places around the world [1]. The cereal is composed of approximately 10% protein and 80% starch, in addition to other nutrients such as lipids, fiber, minerals, vitamins, and phenolic compounds [1]. Currently, there are several types of rice cultivars that have adapted to different climates and regions of the world, influencing production management and the final grain yield. The characteristics of cultivars associated with good post-harvest parameters can influence the quality of processed rice [2]. Thus, to ensure the nutritional quality of the grains in the post-harvest stages, it is necessary to reduce the moisture content of rice for safe storage [3].

In the drying process, the rice moisture content is reduced for safe storage and conservation. Rice drying is usually carried out in intermittent or continuous dryers [4]. In intermittent drying, the rice passes through a drying chamber and then through a resting chamber (intermittent) to equalize the rice moisture [5]. Under these conditions, the pile of grains passes through the drying chamber

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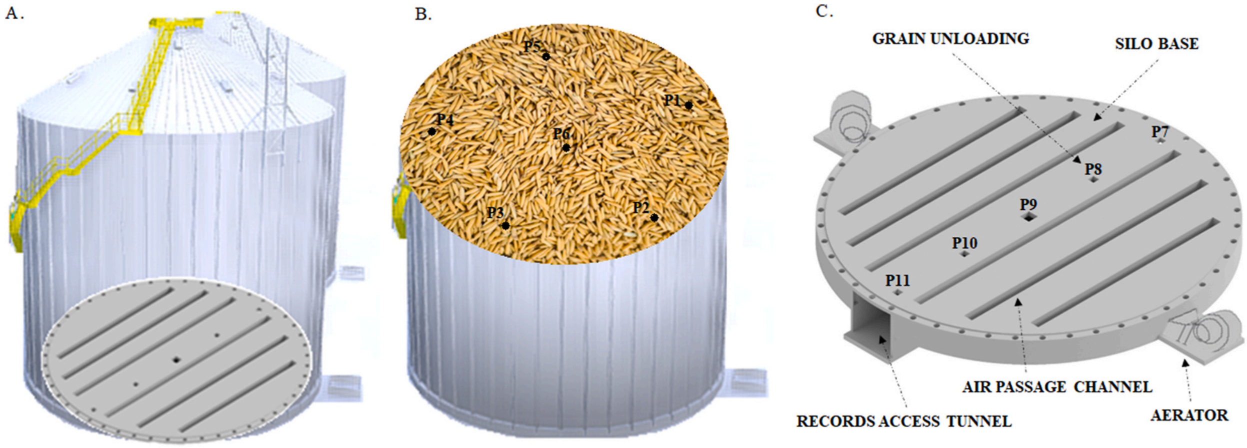


Fig. 1. (A) Structure of the silos dryer-aerator, (B) sampling points in the upper layers (position of the thermometric cables), (C) base structure of the silos-dryers-aerators, exhausters, ducts for air passage, discharge points, and sampling points of grains in the lower layers.

several times for complete moisture removal until the grains are safely stored, resulting in a long drying time and excessive movement of the mass that can cause physical and mechanical damage to the grains [6].

In continuous drying, priority is given to speed and capacity. Continuous drying allows for greater operational dynamics and more uniform drying than intermittent drying. The continuous drying equipment consists of loading, drying, and cooling chambers, with heating and air movement systems. In addition, continuous dryers can operate in whole columns, resulting in an increased drying capacity. In this process, drying air temperatures above 70 °C are used, accelerating the removal of moisture and reducing the drying time, which can be decisive factors for the quality of the rice. The increase in drying air temperature can influence in the reduction of the lipid content [7], in the physical quality [8] and in the rice starch [9]. The drying parameters (air temperature, air flow, and grain mass temperature) must be monitored [10]. High drying temperatures offer high diffusivity and low resistance to moisture removal from the grain, thus reducing the drying time [11]. Elevated temperatures can affect the properties of rice starch and protein [11].

When drying rice in a silo-dryer, low temperatures are used to mitigate the effects on grain quality [12]. The silo-dryer technology has the main advantage of carrying out both drying and storage processes in the same structure, reducing costs with initial investments in equipment. In this process, the grain mass remains static, while the drying air flows upward through the pore spaces between the grain mass [13]. As the rice is harvested, the grain lots are loaded into the silo-dryer and subjected to drying through the activation of exhaust fans for the passage of natural air under favorable temperature and relative humidity [14].

Differences in moisture content of the rice lots harvested can lead to the formation of layers with different moisture content ranges along the silo-dryer filling, making uniform drying difficult. In the silo-dryer, the prolonged exposure of drying can contribute for loss grain quality [15]. On the other hand, delayed drying of grains with high moisture content [16] combined with high temperature in a certain storage environment can cause overheating and affect rice quality [17].

Some studies verified effects of resting grains at ambient (23 °C), intermediate (40–60 °C), and high (above 60 °C) temperatures. Scariot et al. [18] found that resting at high temperatures resulted in increased moisture removal and reduction in the drying time by up to 40%, but a high resting temperature had a notable effect on the starch structure of rice. In addition, the authors verified that the effects of drying reduced lipid and protein in the grains, where the non-soluble lipids were redistributed on the surface of the grain. To minimize the formation of grain layers of different moisture contents that could influence the uniformity of drying and transfer of moisture between the layers, it is preferable to load the silo-dryer-aerator in a single thick layer of the same cultivar harvested from crops with similar characteristics. Therefore, the aim of this study was to evaluate the quality of rice grain cultivars in the lower (initial time) and upper (final time) layers of drying at low temperatures in a silo-dryer-aerator, utilizing the near-infrared spectroscopy, X-ray diffraction analysis, scanning electron microscopy, and multivariate statistical analysis.

2. Material and methods

2.1. Description of rice silos-dryers-aerators

The experiment was conducted in three metallic silos-dryers-aerators with capacity of 40,000 bags (50 kg each) of rice each silo (Fig. 1A–C), with aeration system controlled (Widitec, Panambi, Rio Grande do Sul, Brazil). Forced air aeration is designed with two centrifugal fans (Dryeration Industry and Commerce and Projects Ltda, Cachoeirinha, Brazil) motor de 40.0 H P, flow of 26,000 $m^3 h^{-1}$ and static pressure of 284 mmca. The air velocities were monitored in the silos dryers using a thermo-anemometer, model PCE-423 (PCE Instruments UK Ltd., Southampton, Hampshire, England). The grain mass temperature was monitored with digital sensors, positioned equidistantly.

Table 1
Multivariate analysis.

Cultivars	Position of the grain column	Clusters
IRGA 424	Upper	R1
IRGA 424	Upper	R2
IRGA 424	Upper	R3
IRGA 424	Upper	R4
IRGA 424	Upper	R5
IRGA 424	Upper	R6
IRGA 424	Lower	R7
IRGA 424	Lower	R8
IRGA 424	Lower	R9
IRGA 424	Lower	R10
IRGA 424	Lower	R11
BRS Pampeira	Upper	R12
BRS Pampeira	Upper	R13
BRS Pampeira	Upper	R14
BRS Pampeira	Upper	R15
BRS Pampeira	Upper	R16
BRS Pampeira	Upper	R17
BRS Pampeira	Lower	R18
BRS Pampeira	Lower	R19
BRS Pampeira	Lower	R20
BRS Pampeira	Lower	R21
BRS Pampeira	Lower	R22
Guri INTA	Upper	R23
Guri INTA	Upper	R24
Guri INTA	Upper	R25
Guri INTA	Upper	R26
Guri INTA	Upper	R27
Guri INTA	Upper	R28
Guri INTA	Lower	R29
Guri INTA	Lower	R30
Guri INTA	Lower	R31
Guri INTA	Lower	R32
Guri INTA	Lower	R33

2.2. Experimental conditions of drying

The quality of paddy was evaluated in a metallic silo-dryer-aerator during drying in a thick layer. Two layers of rice grain dough (lower and upper) were considered for an experimental design (3×2), being three cultivars in silo-dryer-aerator (SDA1 – IRGA 424, SDA2 – BRS Pampeira, SDA3 – Guri INTA), and two positions in the grains column in the silo-dryer-aerator (upper and lower) on the initial and final time of drying. Six points were sampled (three hundred grams each) in the upper part of the dryer, and the other five points were sampled in the bottoms of the dryer to represent a position average of the grains column (upper and lower).

2.3. Milling process and rice physical quality

The grains were milled using a rice taster (Zaccaria, Paz-1/DTA, Limeira, Brazil) [19]. After milling, the samples were submitted for evaluation of income, whole grain yield and broken grains, physical classification, and physicochemical quality. The collected rice samples were classified according to the moisture content (MC, % w. b.) and apparent specific mass (ASM, kg m^{-3}) [19]. A 5.5-mm alveolar separator cylinder (Zaccaria, Paz-1/DTA, Limeira, Brazil) was used to classify whole grains for subsequent rice classification manual [19].

2.4. Determination of proximate composition of rice

To determine the contents of starch (ST), crude protein (CP), fat (FT), ashes (AS), and crude fiber (CF) in the rice grains was utilized near-infrared spectroscopy (Metrohm, DS2500 spectrometer, Herisau, Switzerland) with 400–2500 nm diffuse reflectance detector (triplicate). The near-infrared spectroscopy was calibrated with a mathematical model of prediction the proximate composition of rice.

2.5. X-ray diffraction analysis (XRD)

In the samples with the lowest, medium, and highest starch contents, diffractograms were obtained using a Rigaku X-ray powder diffractometer (Mini Flex 300). The crystallinity index (C) was calculated using Eq. (1):

$$C = \frac{H_c}{(H_a + H_c)}, \tag{1}$$

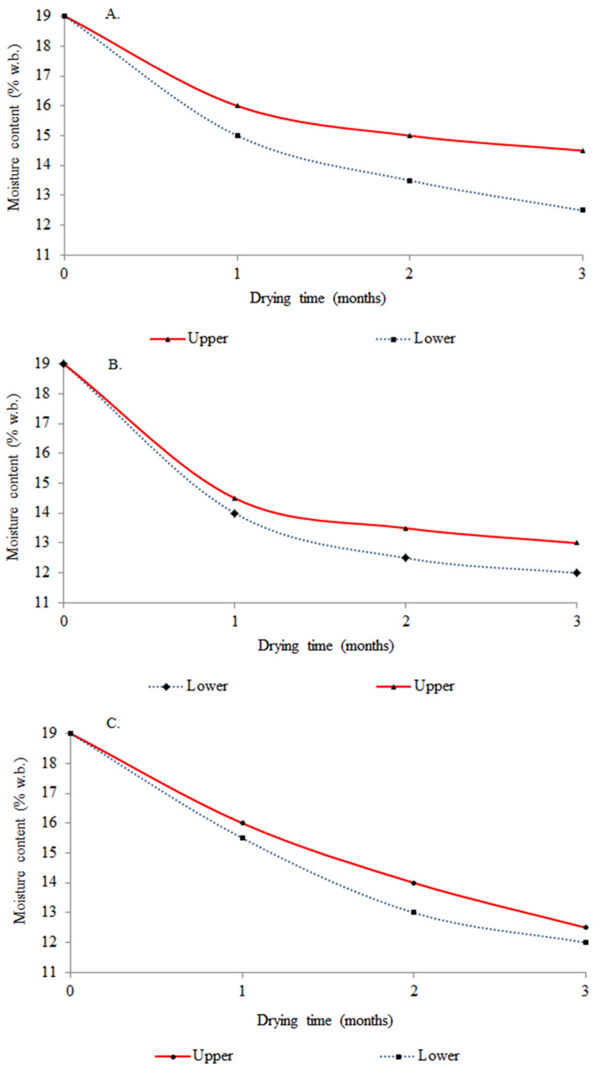


Fig. 2. Drying curves of rice grains (A) IRGA 424, (B) BRS Pampeira, (C) Guri INTA, evaluated in the lower and upper layers of the grain column in the silo-dryer-aerator, over 3 months of storage.

where,

H_c: crystalline peak height.

H_a: height of the peak.

2.6. Scanning electron microscopy (SEM)

Microscopy analyses were performed using a scanning electron microscope (Carl Zeiss, Sigma 300 V P, Jena, Germany). The images (lower and upper positions of the stationary dryer were analyzed) were obtained using the secondary detector (SE2) in the high-vacuum mode (1×10^{-9} bar) with the energy set as 1, 5, and 6 kV, working distances of 5 and > 35 mm, an opening size of 15 μm, and different magnifications.

2.7. Statistical analysis

The analysis of variance was performed, comparing the means by the Tukey test at 5% probability, using the Sisvar 5.6 software. The data were subjected to principal component analysis to verify the interrelationship between variables and treatments in each experiment. After, a scatterplot containing Pearson's and dispersion among the variables considering each formed group was constructed (Table 1) [20].

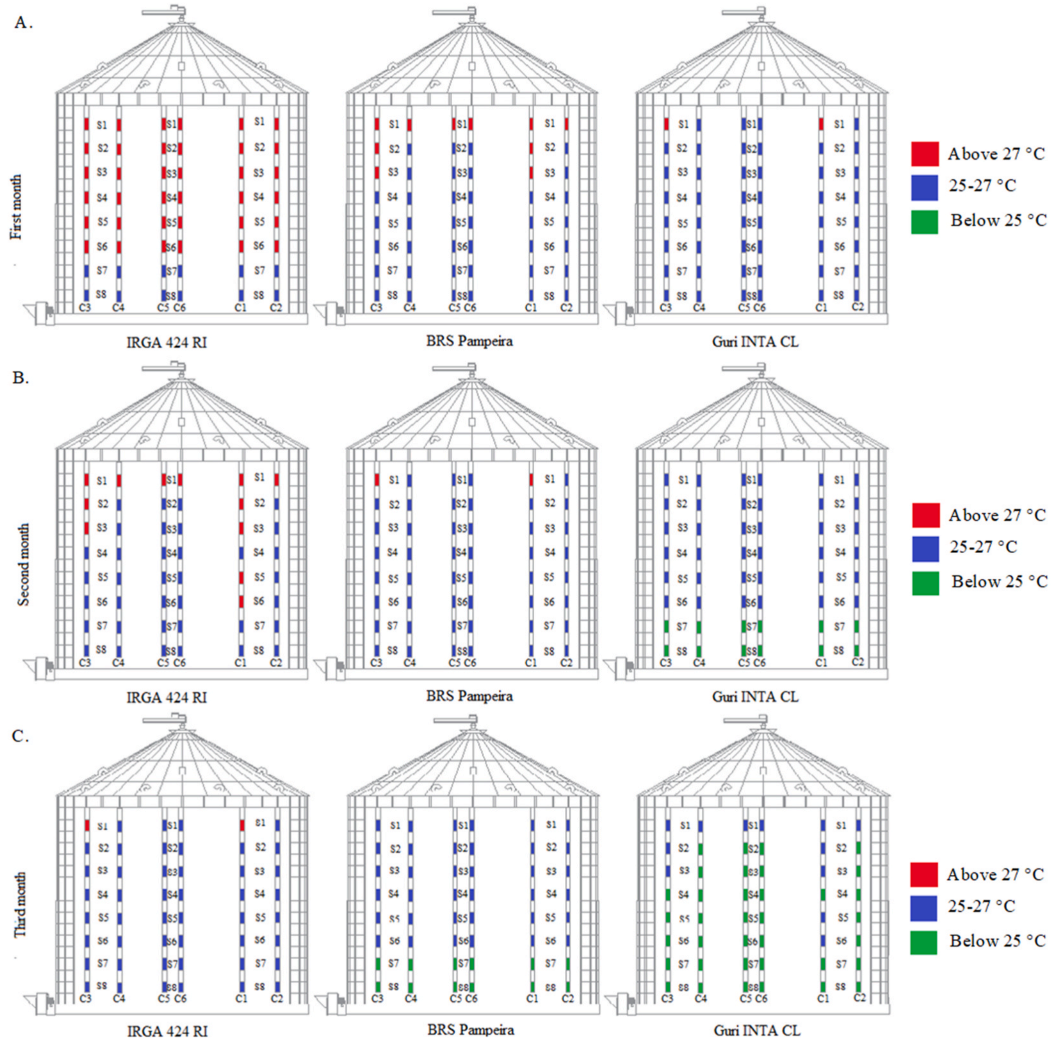


Fig. 3. Mean intergranular temperatures of the rice grain mass of the cultivars IRGA 424, BRS Pampeira, and Guri INTA evaluated in the lower and upper layers of the grain column in the silo-dryer-aerator: (A) first month, (B) second month, (C) third month.

3. Results and discussion

3.1. Kinetics of rice drying

Fig. 2A–C are the drying curves of rice cultivars IRGA 424, BRS Pampeira, and Guri INTA in the lower and upper layers in a silo-dryer-aerator over a period of 3 months. The moisture content of rice was reduced with the passage of natural air through the grain mass. This process took place for each layer (single load) of grains in the silo. The drying process transferred heat and moisture between the air and grains to reduce the moisture content.

As the drying time increased, equilibrium moisture content attained at 12% (w.b.) in the lower layer and 14% in the upper layer of the grain mass, with the greatest difference observed for cultivar IRGA 424. Drying at low temperatures (>25 °C) may be favorable for grain quality (Fig. 3A–C), as it reduces the external and internal stresses on the grains that lead to cracks and breakage [21,22]. However, the lower layer of the silo dried more intensely than the upper layers, affecting the uniformity of the moisture content of the grains (Fig. 3A–C) and consequently impaired the quality of the product [23]. The height of the grain mass also causes a delay in the reduction of the moisture content of the grains in the upper layers of the silo dryer.

The retention of high moisture content (above 15% w. b.) in the upper layers for a long period (first 2 months) led to heating of the grain mass (above 27 °C) (Fig. 3A–B and Table 2), which may have influenced the rice quality. Using a small-scale silo dryer and the rice cultivar Guri INTA, Santos et al. [24] evaluated the drying air temperature (30, 55, and 80 °C) and thickness of the grain layer on the drying time. With a maximum thickness of 0.45 m, divided into three equal layers, that is, lower, middle, and upper sections, the authors found that the thickness of the grain layers increased the drying time by at least 3 h.

Table 2
Average temperature (°C) of the mass of rice grains stored over the three months.

Silo-dryer-aerator	Cables	First month								Second month								Third month							
		Sensors								Sensors								Sensors							
		1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
IRGA 424	1	30	29	29	28	29	29	27	27	29	28	28	27	28	28	26	26	28	27	27	26	27	27	25	25
	2	29	28	28	28	28	28	27	27	28	27	27	27	27	27	26	26	27	26	26	26	26	26	25	25
	3	30	29	29	28	28	28	27	27	29	28	28	27	27	27	26	26	28	27	27	26	26	26	25	25
	4	29	28	28	28	28	28	27	27	28	27	27	27	27	27	26	26	27	26	26	26	26	26	25	25
	5	29	28	28	28	28	28	27	27	28	27	27	27	27	27	26	26	27	26	26	26	26	26	25	25
	6	29	28	28	28	28	28	27	27	28	27	27	27	27	27	26	26	27	26	26	26	26	26	25	25
Guri INTA	1	28	27	27	26	27	27	25	25	27	26	26	25	26	26	24	24	26	25	25	24	25	25	23	23
	2	27	26	26	26	26	26	25	25	26	25	25	25	25	25	24	24	25	24	24	24	24	24	23	23
	3	28	27	27	26	26	26	25	25	27	26	26	25	25	25	24	24	26	25	25	24	24	24	23	23
	4	27	26	26	26	26	26	25	25	26	25	25	25	25	25	24	24	25	24	24	24	24	24	23	23
	5	27	26	26	26	26	26	25	25	26	25	25	25	25	25	24	24	25	24	24	24	24	24	23	23
	6	27	26	26	26	26	26	25	25	26	25	25	25	25	25	24	24	25	24	24	24	24	24	23	23
BRS Pampeira	1	29	28	28	27	28	28	26	26	28	27	27	26	27	27	25	25	27	26	26	25	26	26	24	24
	2	28	27	27	27	27	27	26	26	27	26	26	26	26	26	25	25	26	25	25	25	25	25	24	24
	3	29	28	28	27	27	27	26	26	28	27	27	26	26	26	25	25	27	26	26	25	25	25	24	24
	4	28	27	27	27	27	27	26	26	27	26	26	26	26	26	25	25	26	25	25	25	25	25	24	24
	5	28	27	27	27	27	27	26	26	27	26	26	26	26	26	25	25	26	25	25	25	25	25	24	24
	6	28	27	27	27	27	27	26	26	27	26	26	26	26	26	25	25	26	25	25	25	25	25	24	24

Table 3
Analysis of variance of the rice grains quality for different cultivars submitted to drying in silos-dryers-aerators.

VF	MC (%)	ASM (kg m^{-3})	IN (%)	YD (%)	BRO (%)	PLA (%)	GD (%)	CP (%)	FAT (%)	CF (%)	AS (%)	ST (%)
	Pr > Fc	Pr > Fc	Pr > Fc	Pr > Fc	Pr > Fc	Pr > Fc	Pr > Fc	Pr > Fc	Pr > Fc	Pr > Fc	Pr > Fc	Pr > Fc
Cultivars (C)	0.0000[a]	0.0000[a]	0.0104[a]	0.0000[a]	0.0000[a]	0.2046[ns]	0.0000[a]	0.0137[a]	0.2157[ns]	0.0000[a]	0.0000[a]	0.0354[a]
Lower/Upper - grain column (LU)	0.0000[a]	0.0000[a]	0.0044[a]	0.0000[a]	0.0000[a]	0.0000[a]	0.0000[a]	0.0000[a]	0.0000[a]	0.0227[a]	0.0000[a]	0.4564[ns]
C x LU	0.0000[a]	0.0000[a]	0.8260[ns]	0.0004[a]	0.0000[a]	0.8364[ns]	0.0000[a]	0.0056[a]	0.0006[a]	0.0000[a]	0.0000[a]	0.2587[ns]
VC (%)	5.67	3.09	2.12	5.22	23.41	43.24	17.11	4.73	4.23	0.90	5.33	1.26
General average	12.11	530.35	72.25	59.35	8.34	2.33	12.80	8.20	1.80	2.08	0.96	71.80

[ns]Not significant ($Pr < 0.05$); VF: Variation Function; VC: Variation coefficient; MC: Moisture content, ASM: Apparent specific mass; IN: Income; YD: Yield; BRO: Broken, PLA: Plastered; GD: General defects; CP: Crude protein; FAT: Fat; CF: Crude fiber; AS: Asches; ST: Starch.
[a] Significant at 1% probability of error ($Pr < 0.05$).

Table 4
Analysis of the physical quality of different cultivars submitted to drying in silos-dryers-aerators.

Grain column	IRGA 424				BRS Pampeira				Guri INTA			
	ASM (kg m^{-3})	YD (%)	BRO (%)	GD (%)	ASM (kg m^{-3})	YD (%)	BRO (%)	GD (%)	ASM (kg m^{-3})	YD (%)	BRO (%)	GD (%)
Upper	568.25 Aa	62.30 Aa	5.55 Ac	8.82 A b	523.99 A b	54.73 B b	13.82 Aa	17.14 Aa	527.30 A b	56.44 B b	12.15 A b	15.82 Aa
Lower	521.25 Ba	61.99 Aa	4.10 B b	10.14 A b	501.12 B b	59.57 Aa	7.06 Ba	12.68 Ba	534.49 Aa	61.97 Aa	6.07 Ba	11.53 Bab

*Means followed by the same capital letter in the column and lowercase in the row differ from each other by Tukey's test by 0.05 error probability. MC: Moisture content, ASM: Apparent specific mass; BRO: Broken, GD: General defects.

The relative humidity of the air, moisture content, and temperature must be balanced to maintain the ideal storage conditions for long periods and ensure the quality of the rice grains is not compromised in terms of color; reserves; nutritional properties; and structure of carbohydrates, lipids, proteins, and vitamins; and production of toxins. Several studies [25] reported the possibility of storing rice grains with 12% (w.b.) moisture content between 15 and 25 °C, without any major changes in the final characteristics of the product in the first 3 months of storage. However, for grains with 15% moisture content, safe storage is possible for only up to 30 d at 15–20 °C.

The high moisture content and temperature of the grain mass alter the metabolic activity and respiration of the stored product [15]. Adhikarinayake et al. [26] observed a loss of 2.1% of dry matter and other physicochemical constituents from the mass of rice grains in husks stored in metallic silos, when the temperature of the grain mass increased from 23 to 32 °C [27]. According to Juodeikiene et al. [28], the respiratory rate is directly proportional to the temperature, depending on the moisture content of the grains. Garcia-Cela et al. [29] verified loss of quality on the stored grains with increase of the water activity and temperature on the grains mass.

Fig. 3A–C and Table 2 shows that high temperatures caused excessive reduction in the moisture content of rice grains, affecting the protein, lipid, and ash contents. The increase in grain mass temperature induced an intense respiratory process and, consequently, accelerated grain metabolism, thus altering the physicochemical composition of the grains [30].

3.2. Physical and physicochemical quality of rice

According to Table 3, the interactions between cultivar type (IRGA 424, Guri INTA, and BRS Pampeira) and layer of grain mass (lower and upper) were significant at 5% probability for the variables evaluated. The coefficients of variation were relatively low for most of the variables analyzed (except for total defects, broken grains, and plastered grains), indicating good homogeneity of the experimental conditions.

On analyzing the physical quality of the grains (Table 4), we found that the apparent specific mass varied from 501.12 kg m^{-3} to 568.25 kg m^{-3} for variations in the moisture content from 10.80 to 14.21%. According to Maldaner et al. [5], in rice drying, the physical integrity of the grains may vary according to the cultivar. At the end of the drying process, the cultivar IRGA 424 grains had higher specific mass in the upper layers than in the lower layers, while the cultivar Guri INTA grains in the lower layers of the silo dryer. Müller et al. [31] found that the apparent density of paddy rice grains ranged from 518.2 to 551.0 kg m^{-3} when the moisture content was 11% (w.b.).

The whole grain yield ranged from 54.73 to 62.30%, and broken grains ranged from 4.10 to 13.82%. The results showed that the drying process in the silo-dryer-aerator affected the polished rice quality (Table 4). The cultivar IRGA 424 had higher whole grain yield than the other cultivars, with no statistical differences in the yields between the upper and lower layers in the grain column, while the other cultivars had higher percentages of whole grain yield in the lower layers (Table 4).

According to Tong et al. [32], rice drying affects the physical properties and physicochemical composition of the rice grain through abiotic stresses, resulting in cracks in the grain and reduced whole grain yield. Cracks in rice grains are stress fractures that develop in the inner or outer layers of the endosperm of the grain, caused by a combination of moisture absorption and thermal and mechanical stress, mainly during the drying operations [33]. In addition, the characteristics of the variety/cultivar influence the quality of the grains, for example, the susceptibility of the grains to cracking may also be associated with the cultivar type. Dong et al. [34] found fewer cracks in long-grain husked rice, with high amylose content, than in short-grain husked rice.

As shown in Fig. 2, in the lower layers of the grain column, drying occurred faster and hygroscopic equilibrium was attained at moisture content of 12% (w.b.) in the first 2 months of storage, and the effect of grain respiration on the physical and chemical constituents was mitigated. According to Montanuci et al. [23] the grain drying system in a silo-dryer not only has low speed but also low uniformity. We found that the lower layer of grains that was already dried continued to receive air flow that eventually reached the upper layers until the grains were completely dried, without significant interference in quality (Table 4).

Coradi et al. [35] evaluated the operational performance and physical quality of rice grains stored in silo-dryers. The authors observed that the height variations and the method of processing the grain mass influenced on the performance of the dryer, interfering with the quality of the grains. The authors observed incomplete drying in the upper layers, due to the increase in static pressure. However, when the grain mass was re-sieved, the movement of intergranular air was promoted. In this sense, the authors concluded that for the silo-dryer system to be efficient, it is necessary to homogenize the moisture content of the grains and completely eliminate unwanted materials on grain mass.

Table 5
Analysis of the physical-chemical quality of different cultivars submitted to drying in silos-dryers-aerators.

Grain column	IRGA 424					BRS Pampeira					Guri INTA				
	MC (%)	CP (%)	FAT (%)	CF (%)	AS (%)	MC (%)	CP (%)	FAT (%)	CF (%)	AS (%)	MC (%)	CP (%)	FAT (%)	CF (%)	AS (%)
Upper	14.21 Aa	7.94 Ba	1.90 Aa	2.07 A b	0.85 Bc	11.78 A b	7.88 Ba	1.81 A b	2.12 Aa	1.02 Aa	11.61 B b	7.82 Ba	1.84 A b	2.07 A b	0.93 B b
Lower	11.21 B b	8.75 Aa	1.71 Ba	2.03 Bc	0.92 Ac	10.80 B b	8.23 A b	1.77 Aa	2.13 Aa	1.01 A b	12.82 Aa	8.79 Aa	1.71 Ba	2.07 A b	1.07 Aa

*Means followed by the same capital letter in the column and lowercase in the row differ from each other by Tukey's test by 0.05 error probability. MC: Moisture content, CP: Crude protein; FAT: Fat; CF: Crude fiber; AS: Asches.

Table 6
Analysis of the physical-chemical quality of different cultivars submitted to drying in silos-dryers-aerators.

Cultivars	ST (%)	IN (%)
IRGA 424	71.84 A B	71.70 B
BRS Pampeira	72.08 A	72.18 A B
Guri INTA	71.49 B	72.86 A
Grain column	PLA (%)	IN (%)
Upper	1.93 B	71.84 B
Lower	2.81 A	72.74 A

*Means followed by the same capital letter in the column differ from each other by Tukey's test by 0.05 error probability. ST: Starch; IN: Income; PLA: Plastered.

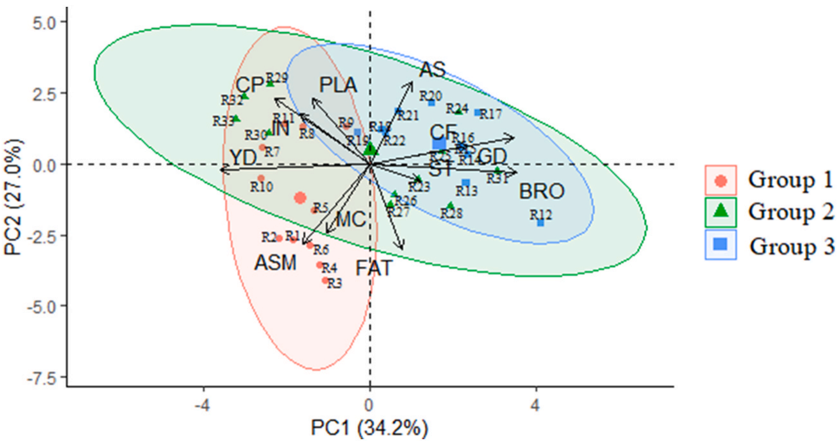


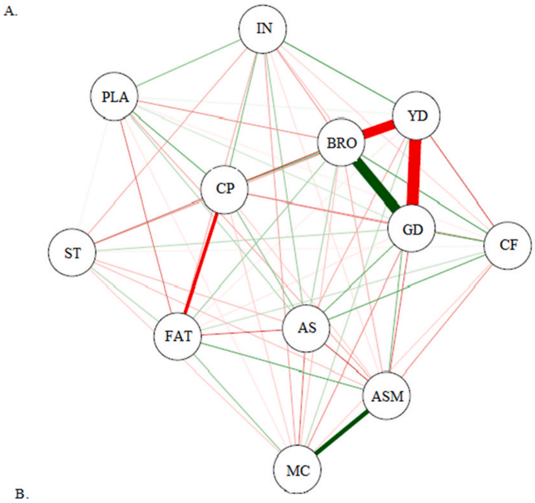
Fig. 4. Principal component analysis for different rice cultivars submitted to drying in a silo-dryer-aerator (assessment in the lower and upper position of the grain mass column) MC-moisture content, IN-income, YD-yield, ASM-apparent specific mass, BRO-broken grains, PLA-plastered grains, CP-crude protein, CF-crude fiber, ST-starch, FAT-fat, AS-ashes, and GD-defective grains.

According to Sadaka [36], there are two risks associated with layer drying: the risk of excessive drying of the lower layers and deterioration of the grains in the upper layer owing to the high moisture content of the grains. The longer the high moisture content was retained in the grains, the more strongly it affected the quality, mainly for the cultivars BRS Pampeira and Guri INTA, which showed high percentages of broken and defective grains and, consequently, a lower yield of whole grains (Table 4). This result is attributed to the longer drying time and moisture gradient. Lang et al. [37] studied the influence of the drying temperatures of 20, 40, 60, 80, and 100 °C on the physicochemical and thermal properties of black rice grains, using an experimental fixed-bed dryer. The low drying temperatures of 20 °C and 40 °C did not cause changes in the grain structure; however, at temperatures above 60 °C cracks were observed, which consequently led to reduction in whole grain yield.

On evaluating the technology quality of the rice grain cultivars (Table 5), it was found that the IRGA 424 and Guri INTA had higher percentages of crude protein in the lower grain layer than in the upper layer. The highest fat content was observed in the upper layer of grains, mainly for the IRGA 424 cultivar. Excess drying in the lower layers of the grain column caused alterations in the lipid chain, altering the fat composition. Regardless of the position in the grain column and the cultivar, the crude fiber content ranged from 2.03 to 2.13%. However, statistically, the cultivar BRS Pampeira had a higher percentage of crude fiber in the lower and upper layers than the other cultivars (Table 5). The highest percentage of ash was observed in the upper layer for BRS Pampeira and in the lower layer for Guri INTA and IRGA 424.

The thickness of the layer of the grain mass in the silo-dryer must be carefully determined because the thicker the layer of grains, the lower the temperature of the drying air must be to avoid thermal shock and overheating of the grains; in some cases, gradual drying with air at increasing temperatures is preferred. Studies carried out with the cultivar IRGA 424 b y Scariot et al. [18] revealed that increasing air temperature decreased the drying time but increased ash content and reduced lipid content in polished rice. The same authors observed that the increase in ash content was related to the degradation of the organic fraction and changes in mineral composition [18,38]. The lowest percentages of plastered grains were observed in the upper layers. The cultivar Guri INTA led to higher income, while the cultivar BRS Pampeira led to higher starch yield, although the results were very close between cultivars (Table 6) due to the low drying temperature.

Donlao and Ogawa [9] investigated the effects of drying with ambient air on the total starch content and concluded that increasing temperature (40–115 °C) led to an increase in the starch concentration, which can be explained by the partial gelatinization and retrogradation of amylose. Ramos et al. [39] observed that continuous drying at 40 °C and 100 °C led to starch yields of 56.1% and 50.4%, respectively, whereas in ambient air and under intermittent drying, the yields were 58.4% and 56.1%, respectively. The



B.

Variables	CP	FAT	CF	AS	ST	MC	ASM	IN	YD	BRO	PLA	GD
CP	1.0000	-0.6759	-0.2719	0.2799	-0.3544	-0.1190	-0.1098	0.3310	0.4160	-0.5510	0.4076	-0.3140
FAT	-0.6759	1.0000	0.1387	-0.5062	0.1699	0.2680	0.4402	-0.2030	-0.0378	0.2212	-0.3863	-0.0573
CF	-0.2719	0.1387	1.0000	0.4347	-0.0337	-0.1095	-0.2862	-0.1021	-0.4793	0.4772	-0.0375	0.4940
AS	0.2799	-0.5062	0.4347	1.0000	-0.1727	-0.4240	-0.4912	0.2577	-0.2089	0.2047	0.1751	0.3690
ST	-0.3544	0.1699	-0.0337	-0.1727	1.0000	-0.1255	-0.1607	-0.2031	-0.2490	0.1761	-0.0201	0.1770
MC	-0.1190	0.2680	-0.1095	-0.4240	-0.1255	1.0000	0.7011	-0.2504	0.1658	-0.1499	-0.0584	-0.2984
ASM	-0.1098	0.4402	-0.2862	-0.4912	-0.1607	0.7011	1.0000	-0.0739	0.3612	-0.2049	-0.2043	-0.4362
IN	0.3310	-0.2030	-0.1021	0.2577	-0.2031	-0.2504	-0.0739	1.0000	0.5063	-0.2553	0.3164	-0.1440
YD	0.4160	-0.0378	-0.4793	-0.2089	-0.2490	0.1658	0.3612	0.5063	1.0000	-0.8564	0.0346	-0.9231
BRO	-0.5510	0.2212	0.4772	0.2047	0.1761	-0.1499	-0.2049	-0.2553	-0.8564	1.0000	-0.3077	0.8711
PLA	0.4076	-0.3863	-0.0375	0.1751	-0.0201	-0.0584	-0.2043	0.3164	0.0346	-0.3077	1.0000	0.1023
GD	-0.3140	-0.0573	0.4940	0.3690	0.1770	-0.2984	-0.4362	-0.1440	-0.9231	0.8711	0.1023	1.0000

Fig. 5. Pearson's correlation (A), and coefficients of the associations (B), between the physical and physicochemical variables MC-moisture content, IN-income, YD-yield, ASM-apparent specific mass, BRO-broken grains, PLA-plastered grains, CP-crude protein, CF-crude fiber, ST-starch, FAT-fat, AS-ashes, and GD-defective grains.

reduction in the final viscosity of the starch and the increase in the final viscosity of the flour were attributed to the high drying temperatures and residual protein. Moisture input is limited by the protein content in the starch granules, which influences the gelatinization and leaching of the compounds [39].

3.3. Multivariate analysis

In the principal components analysis (Fig. 4), two main components were responsible for 61.2% of the total variation between treatments for the variables analyzed, resulting in the formation of three groups. Group 2 included most treatments, with the exception of R1, R2, R3, R4, and R6. The drying treatments of rice grains of the cultivar IRGA 424 were less uniform in the upper layers, with the exception of the analysis of apparent specific mass (ASM) and fat content (FAT). Group 1, formed by R1, R2, R3, R4, R5, R6, R7, R8, R9, R10, R11, R19, R29, R30, R32, and R33, were similar for cultivars IRGA 424 and Guri INTA in the lower layers and higher values of grain mass for the analysis of moisture content (MC), whole grains (YD), income (IN), apparent specific mass (ASM), plastered grains (PLA), crude protein (CP) and fat contents (FAT).

In Group 3, the three cultivars (IRGA 424, Guri INTA, and BRS Pampeira) stood out in the different layers (lower and upper) in treatments R9, R12, R13, R14, R15, R16, R17, R18, R19, R20, R21, R22, R23, R24, R25, R26, R27, and R28 with regard to the variables of plastered grains (PLA), broken grains (BRO), general defects (GD), crude fiber (CF), starch (ST), and ash (AS). The variables IN and CP predominate the cultivars Guri INTA CL and IRGA 424 RI in the lower column of grains (R29, R30, R32 and R33, R8, and R11, respectively). The variables GD and CF prevail in the BRS Pampeira cultivar in the upper grain column (R14 to R16). The higher the proportion of BRO, the lower the YD indices (Fig. 4). Regardless of the drying condition, Lang et al. [37], Junka et al. [40], and Norkaew et al. [41] observed that the increase in drying temperature negatively affected the physicochemical composition of the rice grains. These results were confirmed in the upper layers of the rice grain mass when the grains were heated by exposure to high moisture contents as a function of the extended drying time.

Pearson's correlation coefficients for the associations between physical and physicochemical quality variables are shown in Fig. 5A–B. Among the variables, there was a positive and strong correlation between BRO and GD (0.8710) and moderate correlation between MC and ASM (0.7011). There were negative and strong correlations between YD and BRO (−0.8564) as well as between YD and GD (−0.9280); there was a moderate correlation between FAT and CP (−0.6758). The other variables had weak correlations. The higher the absolute value, the stronger the correlation (both positive and negative) between the variables. As the percentage of broken grains increased, the percentage of defective grains increased. The same was true for the relationship between moisture content and

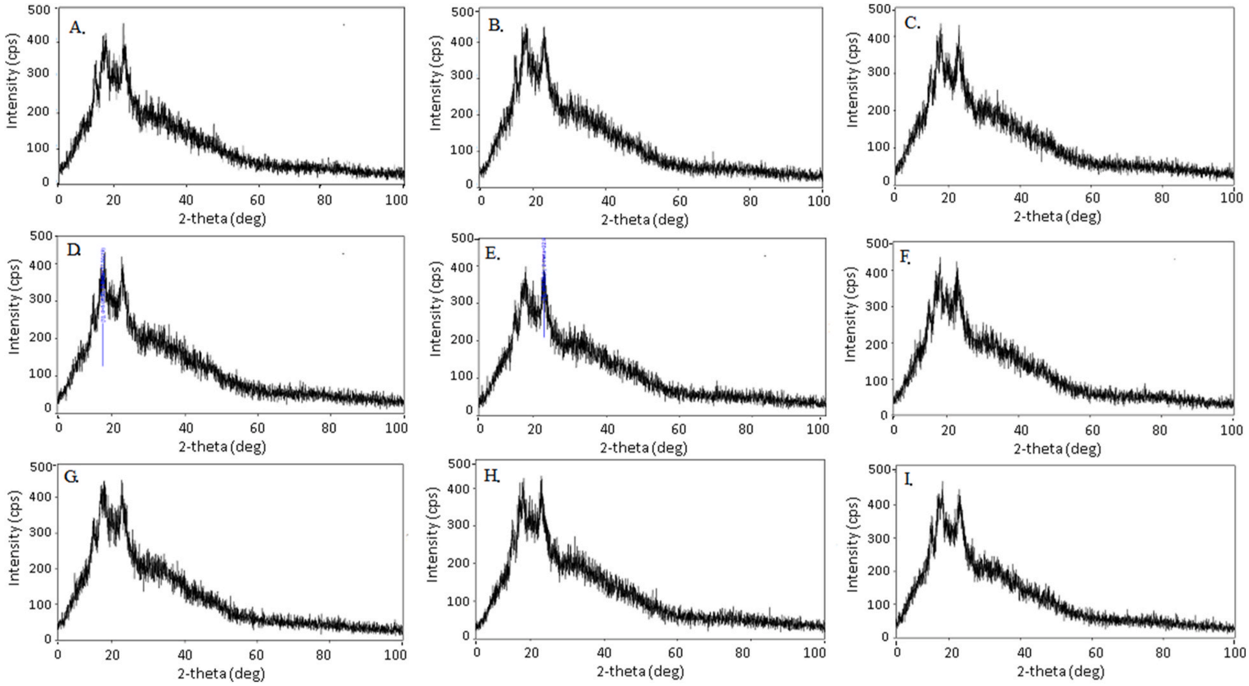


Fig. 6. Rice grain X-ray diffraction spectrum in function of the starch content. (A) Low-IRGA 424, (B) Medium-IRGA 424, (C) High-IRGA 424, (D) Low-BRS Pampeira, (E) Medium- BRS Pampeira, (F) High-BRS Pampeira, (G) Low-Guri INTA, (H) Medium-Guri INTA, (I) High-Guri INTA.

apparent specific mass. There was a negative correlation between the percentages of broken and defective grains and whole grain yield. We also observed that the higher the percentage of fat, the lower the percentage of crude protein.

3.4. Crystallinity of rice starch

In the XRD analysis (Fig. 6A–I), the crystallinity of the starch in the rice grains of the different cultivars was evaluated. Fig. 6A, B, and 6C display images of rice grains of the cultivar IRGA 424 with low (upper layer), medium (lower layer), and high (lower layer) starch content, respectively, while Fig. 6D, E, and 6F display images of the rice grains of the BRS Pampeira cultivar with low (lower layer), medium (upper layer), and high (lower layer) starch content, respectively. Lastly, Fig. 6G, H, and 6I display images of the rice grains of the cultivar Guri INTA with low (lower layer), medium (upper layer), and high (lower layer) starch content, respectively.

Starch quality was observed for the different cultivars, with a difference between the peaks according to the variation of the starch content, although all cultivars had a type A semi-crystalline structure, with a diffraction angle of 2θ between 15° and 23° [5] (Maldaner et al., 2021). The peak intensity indicated that the crystallinity of the starch granules was dependent on the composition of amylopectin and amorphous layers of the starch [42,43].

Thermal control in the drying process was needed to avoid overheating of the grain mass and physicochemical changes as well as the breakdown of starch chains [13]. When comparing the XRD results with other rice drying methods and temperatures, we observed that the method of drying in a silo-dryer had important and favorable features. Ramos et al. [39] (2019) evaluated the changes in the starch of rice grains subjected to temperatures ranging from 40 to 110 °C, with intermittent drying in three stages: 70, 90, and 110 °C. The authors verified that the relative crystallinity of rice starch decreased with increasing temperature, which was attributed to the degradation of the amylopectin chains.

3.5. Microstructure of starch rice

Fig. 7A–F displays the SEM images of the rice grains of the IRGA 424, BRS Pampeira, and Guri INTA cultivars with low and high starch contents. Physical modifications in the starch structure were observed, due to the simultaneous actions of factors such as temperature, humidity, pressure, and shear on the starch content [43]. There were alterations in the structure of the starch, ruptured tissues, and cavities along the starch layer. The images showed changes in the granular morphology, indicating that the starch suffered structural collapse due to the drying process. These alterations varied according to the cultivar and starch content, mainly of amylose and amylopectin in the starch granules. The grains of the IRGA 424 and Guri INTA cultivars with high levels of starch (Fig. 7B, D, and 7F) in the lower layer of grains had a porous surface with cavities. On the other hand, the grains of the IRGA 424 and BRS Pampeira cultivars with low starch content (Fig. 7A and C) had a less porous surface structure than the grains of the Guri INTA cultivar (Fig. 7E). According to Amagliani et al. [43], rice starch granules form a polyhedral, which is a typical feature of this cereal.

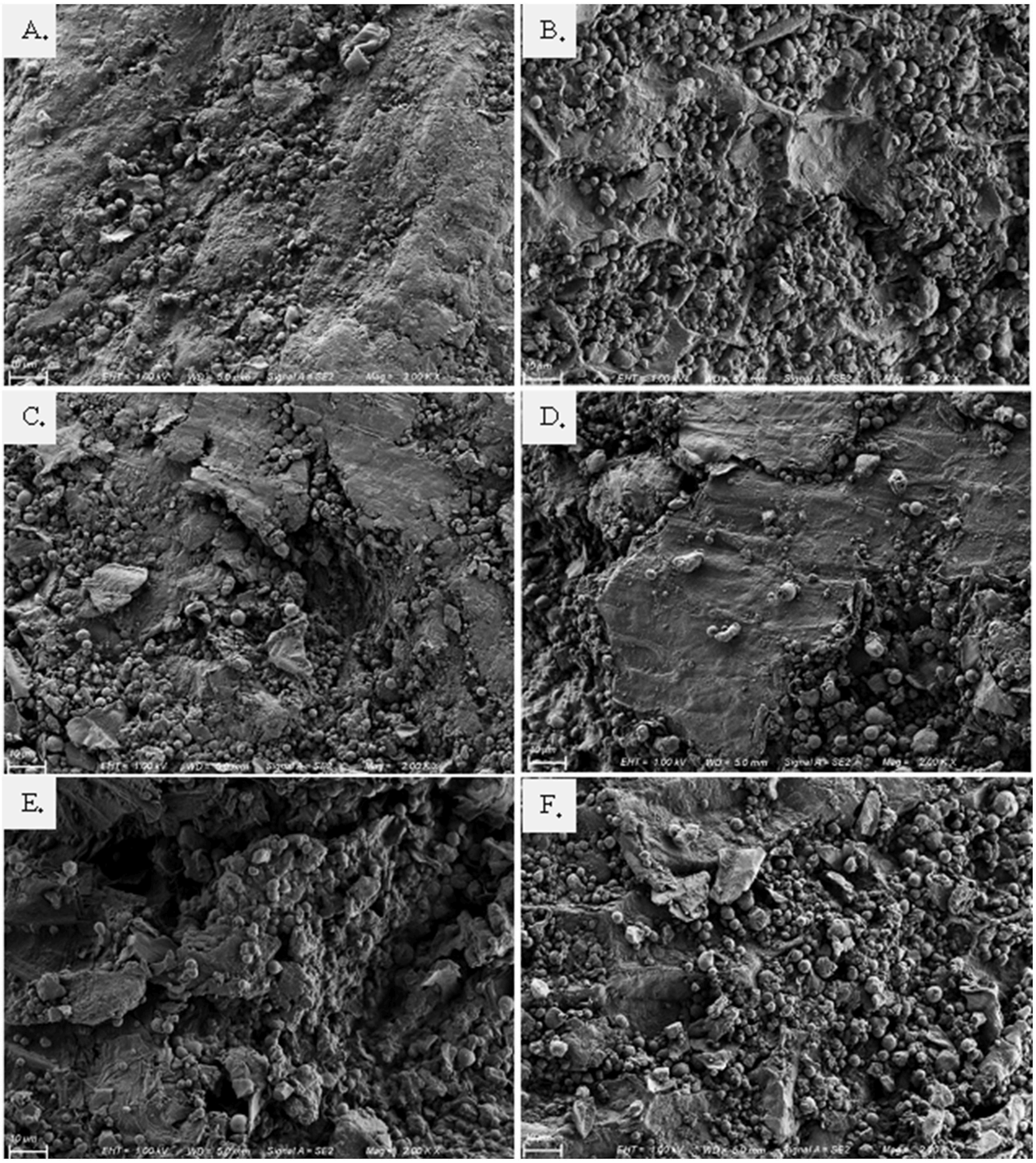


Fig. 7. Scanning electron microscopy images of cultivars of rice grains captured at 2000× magnification in the lower and upper layers of the silo-dryer-aerator (A) Low-IRGA 424, (B) High-IRGA 424, (C) Low-BRS Pampeira, (D) High-BRS Pampeira, (E) Low-Guri INTA, (F) High-Guri INTA.

4. Conclusions

Drying of paddy rice in a single thick layer at low temperatures in a silo-dryer-aerator preserved the physical quality, the physicochemical constituents of the grains, and the morphology of the starch in the lower layers of rice until the period of 2 months of drying. The cultivars Guri INTA and BRS Pampeira showed greater drying uniformity and higher quality of the rice grains than the cultivar IRGA 424.

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Ethical guidelines

Declare that approval of ethics was not necessary for the conduct of the research.

Author contribution statement

Rosana Santos de Moraes: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper. Paulo Carteri Coradi, Paulo Eduardo Teodoro: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. Marcela Trojahn Nunes: Performed the experiments; Analyzed and interpreted the data. Marisa Menezes Leal: Performed the experiments. Edson Irineu Müller, Erico Marlon Moraes Flores: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper. Data availability statement: Data will be made available on request. Declaration of interest's statement: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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