Bibliographic prospecting for dryeration process system evaluation in the face of the conventional grain drying

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Abstract

The increase in grain production causes a significant increase in the demand for suitable places to receive and store these products for a more extended time and preserve the harvested grains' properties. The drying system in the storage units has become the bottleneck for grain reception. One solution to reduce bottlenecks in the reception of grain storage units is adopting the dry-aeration operation. This work aims to present a bibliographic review of grain drying and the drying system called dryeration, based on prospecting in textual and referential databases of good factors and impact. The use of the dryeration system allows to increase the flow in the reception of the storage units, which, compared with conventional drying methods, generates an increase of over 50% in the capacity of the dryer, reduces energy consumption by up to 30%, removing up to 2% additional grain moisture and provides grains less susceptible to cracking and breaking.

Keywords: Drying methods, dryer, dryeration, grain production.

1. Introduction and Objectives

The modifications resulting from the modernization process with the insertion of technological innovations resulted in the improvement of agricultural productivity in Brazil, generating a significant increase in the

production of some types of grains such as soybeans and corn, making the country one of the largest agribusiness producers in the world, breaking consecutive production records, harvest by harvest [1].
The new Brazilian crop 2020/2021 results should surpass 4.2%, the record obtained in the season just finished. Grain production is estimated at 268.7 million tons, exceeding the record of 257.7 million tons from the last harvest by approximately 11 million tons. Soy production is estimated at 133.7 million tons and maintains Brazil as the world's largest producer of oilseeds, and corn production is expected to reach 105.2 million tons, considered the largest harvest of these grains, with an increase of 2.6 % over the previous harvest [2].
The increase in grain production causes a significant increase in the demand for suitable places to receive and store these products for a more extended period and preserve the harvested grains' properties [3]. Grains are usually harvested with very high moisture content for safe storage, and drying is the most common post-harvest process for long-term grain preservation [4].
The increase of production results in the drying of these grains at higher levels than that recommended for safe storage in the collecting storage units close to the grain production units (farms). Due to the large volume received, the existing drying system for grains sized to work during the whole grain receiving time is undersized for the new demand, and the solution found is drying acceleration, with an increase in the temperature of the grain. air, not controlling the temperature of the grain mass [5]. The grain drying operation is usually the bottleneck that limits a storage unit's capacity [6].
This paper aims to present a review of the drying system called "dry aeration" (reported in the literature or other documentary sources) and discuss its main characteristics, increasing the storage units' reception flow. This system generates an increase of over 50% in the capacity of the dryer, reduces energy consumption by up to 30%, provides the removal of up to 2% of additional grain moisture, and provides grains less susceptible to cracking and breaking.

2. Material and Methods

To survey the works carried out on grain drying, qualitative bibliographic research is presented [7] of academic scientific productions with a good impact factor, published in the textual and referential databases available on the Internet. Few works address the theme in Brazil, and the vast majority are published in international journals. The searches were performed by the titles of articles, dissertations, and theses, with an initial reading of abstracts and, in specific cases, a full reading of the document. After a gradual analysis, the theoretical reference framework that supports the conclusions of this paper is constructed [8].

3. Results and Discussion

3.1 Grain drying

Among the methods used for grain conservation, drying is the most economical from the point of view of processing and allows preserving the product in a natural environment for an extended period [9]. The purpose of reducing the water content is to prolong the useful life of products of biological origin by reducing the growth of microorganisms, insects and inhibiting enzymatic reactions [10].
Microflora and insects naturally only develop in grains at relative humidity above 65% [11], so, according

to [12], grains with a high moisture content must be dry artificially up to a moisture content, which will result in an equilibrium relative humidity within the stored grain mass of less than 65%. Corn in good condition must be dried to a moisture content below 14% for safe storage, whereas soy requires a storage moisture content of less than 12.5%. Table 1 summarizes the equilibrium moisture content in three levels of equilibrium relative humidity and a temperature of 25º C [4].

	Equilibrium Relative Humidity (%)		
Grain	**60**	**65**	**70**
Corn, shelled	12,4	13,2	14,0
Soybeans	10,5	11,5	12,5
Rough Rice	12,0	12,6	13,2
Wheat, hard	12,9	13,6	14,4
Wheat, soft	11,8	12,3	13,0

Table 1. The equilibrium moisture content of various grains [4]

The main objective in a drying operation is to provide the necessary heat in an ideal way to produce the best product quality with minimum total energy expenditure [13]. The removal of moisture occurs by evaporating it by transferring mass and heat between the solid and gaseous phases [14].

The evolution of these simultaneous heat and mass transfers during the drying operation causes it to be divided schematically into three periods described below. Figure 1 shows the evolution curves of the product's water content (X), its temperature (T), and its drying speed (dX / dt), called the drying rate [15].

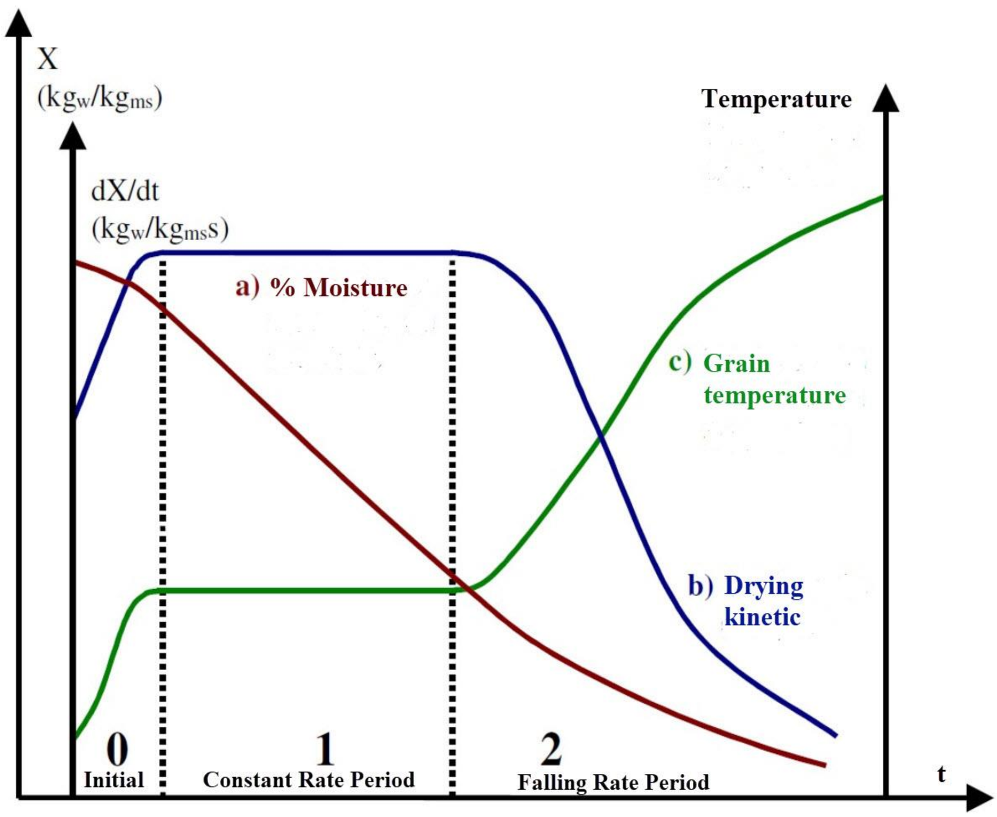

Figure 1. Typical drying curve [15]

According to the authors, in this Figure1, curve (a) represents the decrease in the water content of the product during drying; curve (b) represents the speed (rate) of drying of the product, and curve (c) represents the variation in the temperature of the product during drying. [15] then describe the three periods:

- Period 0

In the initial drying phase, where the grains are initially colder than air, the partial pressure of water vapor on the product surface is low, and the mass transfer and drying speed are also low. The heat raises the temperature of the product, with an increase in pressure and drying speed. This phenomenon continues until the heat transfer exactly compensates for the mass transfer. If the air temperature is lower than the product temperature, it will decrease until it reaches the same equilibrium state. This period's duration is too short concerning the total drying period, gradually changing to period 1.

- Period 1

It is the period where the drying rate (speed) is constant. During this period, the amount of water available within the grains is very large. The water evaporates like free water. The water vapor pressure on the surface is constant and is equal to the water vapor pressure at the product temperature. The product's temperature is also constant and is equal to the wet bulb's temperature, characteristic of the fact that the heat and mass transfer are precisely compensated.

This period lasts as long as water migration from the interior to the product surface is sufficient to supply the loss by evaporation of water on the surface.

- Period 2

It is the period of decreasing speed (rate) of drying. From the moment that water starts to be scarce on the grain surface and the drying speed decreases.

During this period, the heat exchange no longer compensates, increasing the grains' temperature and tending asymptotically to the air temperature. At the end of this period, the drying rate (speed) is zero.

Heat is the energy that flows due to the temperature difference. In our paper occurs between the drying air and the grains. Specific heat is a characteristic of each material or fluid. The higher the specific heat of a substance, the greater the energy required to vary its temperature [16].

The same author also points out that the sensitive heat is that which is added or removed from a substance, causes a temperature change without causing a phase change. That is, it only changes the temperature of the substance. Sensitive heat is related to the concept of thermal capacity, which corresponds to the amount of heat required that the total mass of a body needs to receive or lose in order for its temperature to change by one centigrade. On the other hand, latent heat is the amount of heat supplied or removed from a body. It does not change its temperature but causes a change in its aggregation state.

When a product is subjecting to the drying process, water is extracted in steam by heat. This steam yields a certain amount of heat called the latent heat of vaporization [17].

[18] affirm that the air's sensitive heat is equal to the latent heat of vaporization necessary to evaporate the grains' water to the desired final moisture. In this way, sensitive heat is converting to latent heat, and this conversion can be represented by equation 1:

$$60 \cdot \left(\frac{Q}{V_e}\right) \cdot C_a \cdot (T_a - T_e) \cdot t = h_v \cdot DM \cdot (U_o - U_e) \quad \text{Eq (1)}$$

Where:

Q: flow of drying air (m³ / min);

Ve: specific volume of the drying air (m³ / kg dry air);

Ca: specific air heat (kcal / kg ºC);

Ta: drying air temperature (ºC);

Te: equilibrium temperature (ºC);

t: drying time (h);

hv: latent heat of vaporization (kcal / kg water);

DM: dry material in the product (kg);

Uo: initial humidity (decimal, d.b.);

Ue: equilibrium humidity (decimal, d.b.).

Grains are hygroscopic products and can yield or receive water vapor from the air surrounding them [19]. According to the author, a thin layer of air forms on its surface, which constitutes a microclimate, whose state conditions are regulated by the product's temperature and moisture content. It also highlights that the air surrounding the grains also has its relative humidity related to the amount of vapor diluted in the air. The direction and intensity of the water vapor flow between the grains and the air is according to the difference of the values of relative units of the grain microclimate (URg) and the air surrounding the grain (URac) [19]

- URg> URac → Grains dry;
- URg <URac → Moistening of the grains occurs, and
- URg = URac → Hydroscopic balance occurs, there is no vapor flow

The direction of water vapor flow will always be from the highest relative humidity to the lowest (Fig. 2).

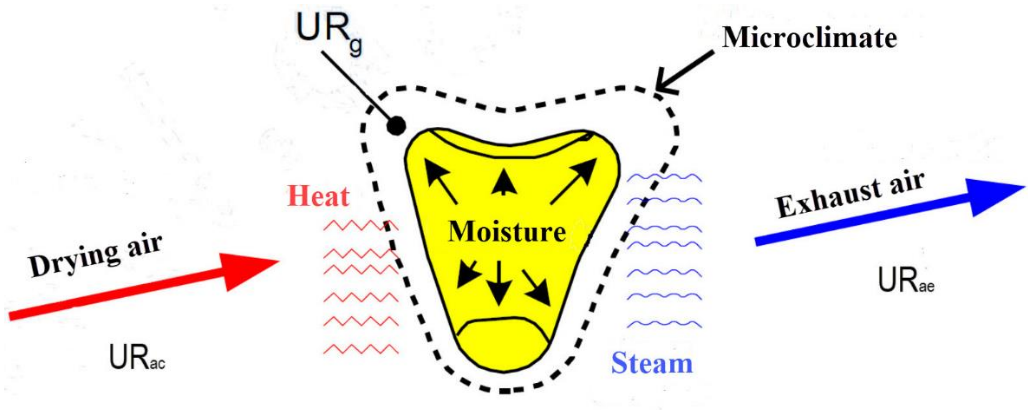

Figure 2. Demonstration of the grain drying process [19]

Heat is generally supplied during drying by heating the air, either artificially or by natural means, and the vapor pressure or concentration gradient thus created causes the movement of moisture from within the kernel (grain core) to the surface. The speed and efficiency of drying depend on the drying air temperature and humidity [20].

According to [21], energy efficiency and capacity increase as the drying air temperature increases. According to the authors, the correct way to decrease the relative humidity of the drying air is by heating, which can be naturally utilizing solar radiation or artificially using firewood or biomass furnaces, gas burners, or steam radiators. They also emphasize that increasing the temperature of the drying air leads to a decrease in the grain's quality due to cracks' appearance. Breakings and cracks in the grains are a quality indicator used by engineers and operators to determine the severity of damage done during drying.

3.2 Drying system

According to [22], drying methods are classified according to the use of equipment (natural or artificial), the periodicity in the heat supply (continuous or intermittent), and the movement of the seed mass (stationary or continuous). [23] classified the drying systems for agricultural products for didactic reasons, due to the lack of an official classification, according to Chart 1:

Drying system	**Natural air - in the field or on the farm**				
	Artificial	**Natural ventilation**	**court or barn**		
			Solar drying		
			Others		
		Forced ventilation	**Natural air**		
			High temperature	**Flow**	Fixed bed
					Crossflow
					Concorrent flow
					Counterflow
					Cascade
					Rotary
					Fluidized
					hybrid solar
				Operation	Batch
					Continuos
			Low temperature		
			Combination		
			Dryeration		
		Convection			

Chart 1 – Drying system [23]

According to [24], the simplest classification of grain drying methods is based on the temperature of the air used for drying and can be classified into:

- Drying in natural air
- Artificial drying at low temperatures
- Artificial drying at high temperatures

Artificial drying at high temperatures is a technique widely used in farms, processing industries, collecting, and intermediate storage units worldwide. This type of drying is the fastest and does not depend on the place's climatic conditions [25].

According to [26], for medium and large quantities of grains, the technical drying systems are recommended (artificial drying system with forced ventilation), which are classified as stationary (with axial or radial airflow), conventional (continuous) intermittent) and mixed (dryeration). Among these, the most used dryer in Brazil is the conventional continuous flow or cascade type [27].

3.2.1 Conventional continuous flow dryer

The Conventional continuous flow dryers, also called cascade type dryers, are the most popular because they contribute to better drying uniformity throughout the grain column since the entire width submits to the same air. All grains are mixed with the hot air as it passes through the dryer [28].

In the conventional continuous dryer (Figure 3), the drying air is distributed in the upper part of the drying column, with 2/3 of the column height, and the cold air (ambient air) is distributed in the lower part of the drying column, whose purpose is to remove the heat of the grain mass [29].

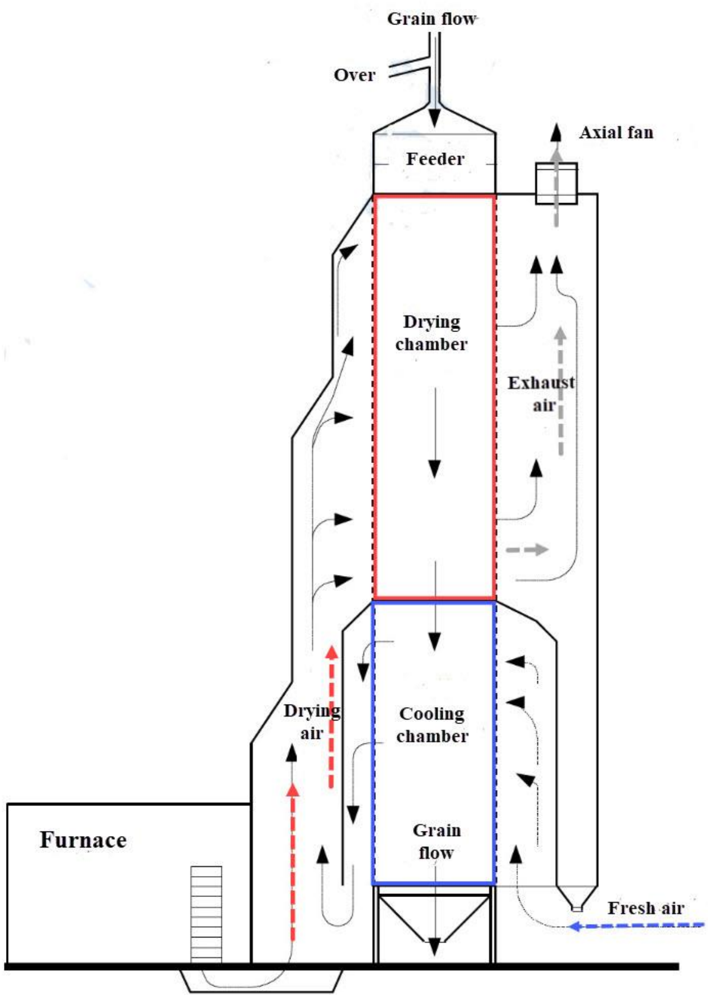

Figure 3. Conventional continuous flow dryer [27]

Fast cooling inside the continuous flow dryer results in a significant increase in stress cracks and susceptibility to breakage [30] generating environmental problems due to the emission of large amounts of particles in the form of husks and small pieces of grains, contaminating the surroundings of the reception and drying sector [31]; [32].

3.2.2 Dryeration systems

Discharging the hot and partially dried grains into a silo and delaying cooling allows the dry aeration process to be used. This process will reduce the number of grains broken by tension than conventional high-temperature continuous flow drying. Dry aeration was introduced to increase the dryer's capacity (uses the entire column as a drying chamber), improve energy efficiency, and increase the quality of grains [33]. The grain dry-aeration method was created in the United States in the 1960s by George Foster, a professor in the Department of Agricultural Engineering at Purdue University, Indiana [34].

Research on the new drying process called dry aeration (Dryeration) began in 1962. The first information was reported in the Purdue Farm Science Days survey in January 1964 [35]. Dryeration consists of drying with a conventional continuous high capacity dryer, accumulated in a metal silo for temperature equalization, followed by cooling in the same silo before transfer to final storage (Figure 4).

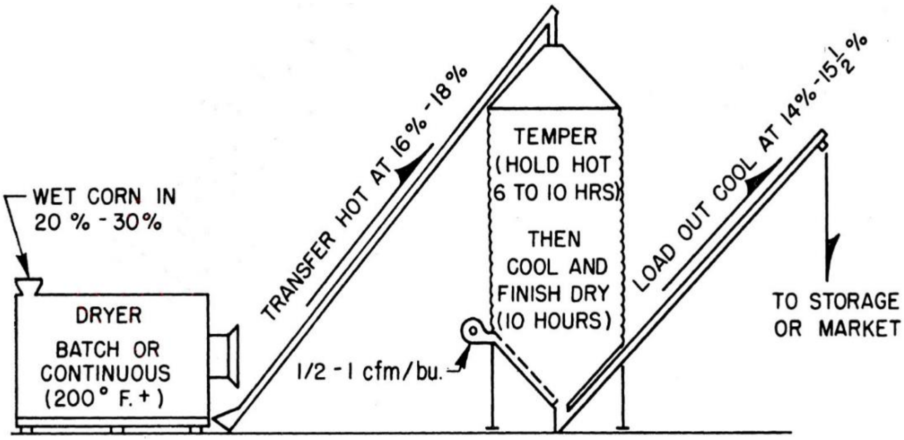

Figure 4. Dryeration system [35]

Figure 5 shows a flowchart of a grain receiving installation with a dryeration system.

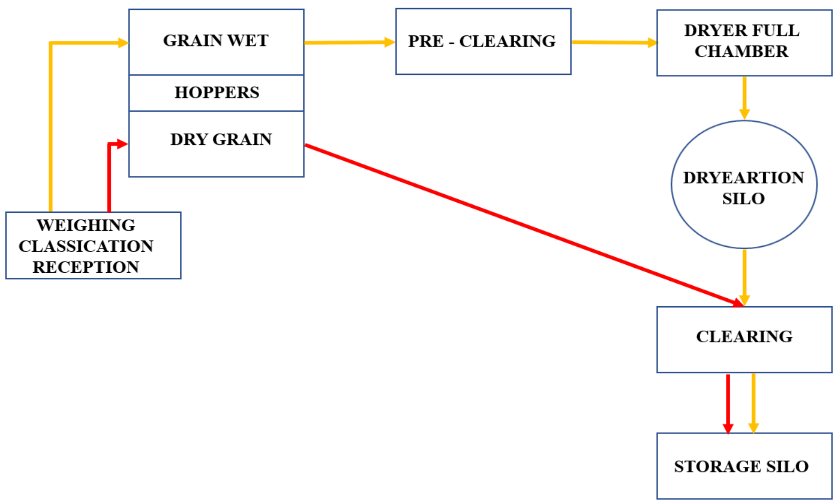

Figure 5. Grain receiving installation with a dryeration system

Reception, classification, and weighing is the initial stage of receiving the grains, where the moisture and impurity analyzes of the grains and weighing of the cargo are made. According to the moisture content contained in the grains, the load will be directed to wet grain hoppers or dry grains.

The dry grains will be sent directly to the cleaning sector for dry grains and then to the bulk carrier, where they will be stored.

The wet grains will be pre-cleaned in the pre-cleaning sector and will pass to drying in a full column dryer, being removed hot and sent to the aerator dryer silo where they will remain in maturation for 6 to 10 hours and then will cool with air at room temperature.

After maturation and cooling, the beans go to the cleaning sector and then go to the storage silo where they will be stored.

This system increases the drying capacity by 50 to 75% due to a series of factors: eliminating the cooling inside the dryer (Figure 4), where the entire column is used as a drying chamber, removing less humidity, and a significant increase in the amount of heated air used in the dryer [21].

[29] says that the great importance of the dryeration system is in increasing the dryers' real capacity, causing the reception problems at the peak of the harvest to decrease, the queues next to the grain unloading hoppers. The same author also states that the system represents the following gains:

- A significant increase in dryer capacity is much faster to dry a grain load from any initial moisture up to 16% (b.u.) than up to 13%. This 3% humidity, unless the dryer stops removing, can mean little water removed, but it represents an extended drying time because moisture will have to migrate from the center of the grain to its periphery.
- Capacity gain because the dryer does not cool the beans in the cooling chamber has become the drying chamber, increasing the drying capacity by 33% (or 1/3).

Because forced ventilation to cool the grains occurs after a reasonable time and in a large grain layer, there is practically no shedding and other solid residues, contributing to the environment's improvement.

Figure 6 shows a conventional continuous flow dryer, adapted for the dryeration system, working with a drying chamber in the dryer's entire body, without the cooling chamber. This adaptation consists of removing the ambient air guiding plates next to the cooling chamber and closing the ambient air inlet to the dryer, with insignificant costs compared to acquiring the dried product. In this way, the cooling chamber starts to receive drying air, transforming it into a drying chamber.

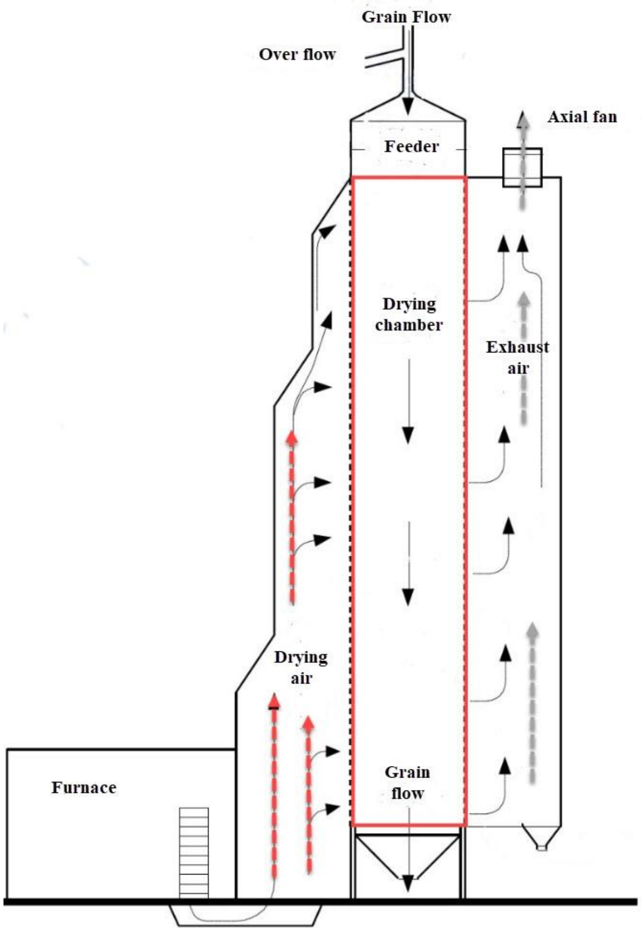

Figure 6. Conventional continuous grain dryer adapted for dryeration

The grain is discharged hot between 43 and 54 ° C from the dryer to a separate metal silo (Figure 7) without initial cooling and product moisture with two or three percentage points above the desired level. After equalization rest for 8 to 12 h, the grain is cooled with ambient air at an airflow rate of 0.5 to 1.0 m³ / min x ton. Delayed cooling allows a large percentage of the corn's sensitive heat to be used to evaporate some of the remaining moisture.

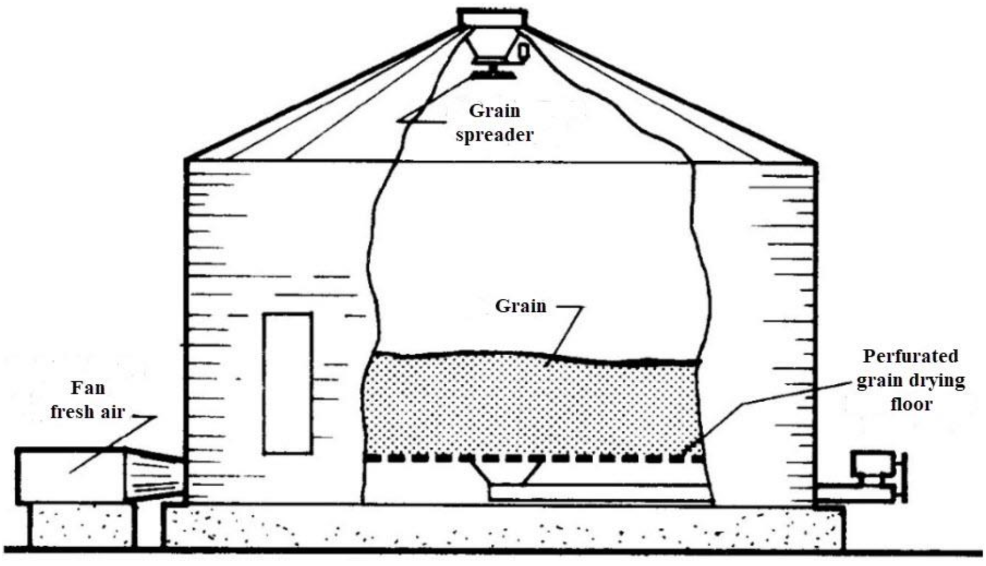

Figure 7. Equalization and drying metallic silo [36]

Vertical silos have a height more prominent than the diameter of one of the dimensions of the base. They are usually of metallic construction, constructed of corrugated sheets, of galvanized steel. They are equipped with aeration systems [37].

3.2.2.1. Energy consumption

In the specific case of corn drying, in a properly designed dry aeration system, [23] state that a reduction of 25% to 15% (bu) in the moisture content, it results in an increase of around 50 % in the capacity of commercial dryers and, consequently, a 20 to 30% reduction in fuel consumption spent per ton of dry product.

Table 2 shows the drying air temperatures for each drying system, showing the lowest temperature used in the dry aeration system [38].

Grain	**Drying systems**		
	Batch	Continous	Dryeration
Rice	70-115		60-80
Wheat	70-110	70-120	70-90
Corn	80-120	90-130	79-90
Soybean	80-120	90-130	79-90
Bean	80-100	80-110	60-80

Table 2. Drying air temperature at the entrance of different grain drying systems

The dryeration method provided an increase in the dryer's operational cadence, improved the utilization of the installations, and reduced energy costs in drying. Although these advantages were desirable for the sector, their limitations restricted their consolidation to industrial plants that contained the necessary equipment for their application [35].

3.2.2.2. Drying quality

The grains suffer physical changes caused by a temperature and humidity gradient, which cause expansion, contraction, changes in density, and porosity, during the conventional drying process (continued). The conventional drying process significantly increases the percentage of broken grains and can cause internal or surface cracks, making them more susceptible to breakage during cleaning and storage [38].

The multiple tension cracks decrease from more than 40% to less than 10% when dryeration is compared to conventional high-temperature drying [39]. Confirming this statement, [40] highlights that the index of broken grains in conventional drying was 43.6%, while in dryeration it was 7.60%, with a significant reduction in damage to grains.

[41] analyzed the variables that can contribute to grain quality changes during drying. They found that the delayed cooling of the grains in the dry aeration process effectively reduces the possible susceptibility to breakage compared to conventional drying and cooling in a continuous dryer.

In general, dryeration provides better grain quality than other grain drying systems.

3.2.2.3. Environmental considerations

The main factor influencing Brazilian agribusiness's energy-environmental sustainability is the high dependence on thermal energy in the pre-processing of grains, mainly in drying [42].

Studies carried out in the State of Paraná point to firewood as the primary fuel used in drying the grains, reaching about 85% of the total demanded [42].

The use of firewood on a large scale as an energy source requires attention to the ways of obtaining this energy source since it would be necessary to implement large areas of reforestation in a monoculture that lead to other ecological problems of an ecological nature, as the decrease in biodiversity [43].

The dry aeration system, reducing energy consumption by 15 to 30% and increasing the drying capacity above 50%, provides a significant reduction of fuel for heat generation. Consequently, we will have a reduction in firewood consumption and a decrease CO_2 emissions.

3.2.2.4.Disadvantages of the dryeration systems

The disadvantages of dry aeration are the increased grain handling and additional equipment required for tempering. The silos need to be equipped with larger fans to provide air flows of at least 0.5 m³ / min x ton. Table 3 shows the comparison of airflow values indicated by the type of drying installation [44].

Installation type	**Air Flow** (m³ / min.ton de produto)
Ventilation - flat bulk warehouse	0,10 a 0,20
Ventilation - Silo	0,03 a 0,10
Ventilation - unprocessed grain Silo	0,30 a 0,50
Dryeration	0,50 a 1,00
Colling	mínimum 0,12

Table 3. Airflow recommendation for grain aeration [43]

4. Conclusions

Drying plays an essential role in improving agricultural products' quality, improving storage conditions, and increasing storage times.

Drying methods that minimize fuel consumption with increased thermal yield and have low environmental degradation should reduce the drying cost, increase the drying flow, and preserve the environmental resources.

The dry aeration system has shown significant gains in drying capacity, increased energy efficiency with reduced fuel consumption, improved product quality with a significant reduction in grain breakage, and reduced environmental impact due to drying.

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