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Drying of soybean seeds and its influence on quality: a review

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Abstract

Drying is a crucial step for soybean seed storage. This is because during storage, seeds may lose their viability due to high moisture content. The high-water content of the seeds promotes higher respiration rates, with a consequent increase in seed temperature, which may affect the development of insects and fungi that can hinder the commercialization of the product. As a result, the drying process should be performed as soon as possible using methods that preserve the physical and physiological qualities of soybean seeds. Drying methods can be broadly divided into natural and artificial; continuous and intermittent, depending on the periodicity of the heat supply; and fixed bed and moving bed, depending on the movement of the seed mass. In the comparison of natural drying to artificial drying, the former has the disadvantage of exposing the product to psychrometric changes in the air, which may cause physicochemical variations. Among artificial dryers, fixed bed dryers are used on a large scale because they allow the temperature and relative humidity to be controlled and checked and the physiological quality of the seeds to be preserved. Nevertheless, moving bed drying of soybeans is an approach with the main advantages of low energy input, a low first investment cost, and homogeneous drying. In line with these factors, this review discusses the methods used for drying soybean seeds and their relationship with the physiological qualities of the seeds, pointing out important results from current scientific research.

Keywords: fixed bed, prototype, dryer, agriculture, seed.
Abbreviations: Dry technol_ drying technology, p_g _ surface vapor pressure, p_{air}_ water vapor pressure in air, a_w_ water activity.

Introduction

The cultivation, storage and consumption of soybeans date back centuries, with the first records appearing in the years 2883 and 2838 in the book “Pen Ts'ao Kong Mu”, which described the plants of China to Emperor (Keshun Liu, 1997). With constant advances, knowledge on soybean storage has produced new techniques to enable the maintenance of seeds during prolonged storage (Vertucci and Roos, 1990).

The basic soybean seeds postharvest processes include receiving, drying, cleaning, classification, storage, and transport (Quirino et al., 2019). Each of these processes affects seed viability Balesevic-Tubic et al. (2011) and drying plays a key role in keeping the quality of the product in storage.

For safe storage, it is necessary to reduce the water activity (a_w) associated with the water content because higher a_w promotes an environment favorable to the occurrence of chemical, biochemical, physical, and microbiological changes (Kusumaningrum et al., 2017). High seed water content promotes higher respiration rates, with a consequent increase in product temperature (Carteri et al., 2020). Higher temperature and relative humidity around the seeds favor the development of insects and fungi (Silva et al., 2017).

Knowledge of the structure of seeds should guide their processing. Seeds have an embryo, food reserves (endosperm or cotyledons), and an outer protective coating (Halvankar et al., 1990). Some structures can significantly affect seed storage, such as the seed coat and hilum, which allow the entry or exit of moisture in seeds. Under certain conditions, the hilum can be damaged, allowing fungi to enter the seed (Bewley and Black, 1994). Soybean seeds need specific conditions to remain strong enough to produce healthy and hardy plants (Ebone et al., 2020). Temperature and humidity are the main factors that cause seeds to lose their ability to germinate (Coradi and Lemes, 2018a). In addition to these factors, the constant movement of seeds in drying systems should be evaluated so that they do not cause mechanical and latent damage to the seed structure (Neves et al., 2016; Kostić et al., 2020).

In general, temperatures above 50 °C are not recommended for drying soybean seeds Filho et al., (2017), Cao et al., (2017) Silverio et al., (2019) because latent damage, i.e., microscopic damage, to seeds is seen at such temperatures, with internal injuries to the embryo (Barrozo et al., 2007a).

There are many methods and dryers used in the drying of soybean seeds (Barrozo et al., 2007b; Coradi and Lemes, 2018b; Coradi and Lemes, 2018a; Silverio et al., 2019; Volkhonov et al., 2019). Most of the dryers used for soybeans are fixed bed or moving bed dryers. Fixed bed dryers have the advantage of low seed movement and the disadvantage of nonuniform drying at some points of the dryer (Silverio et al. 2019). In moving bed dryers, the control of all process phases must be rigorous because these dryers can cause mechanical damage; however, they tend to

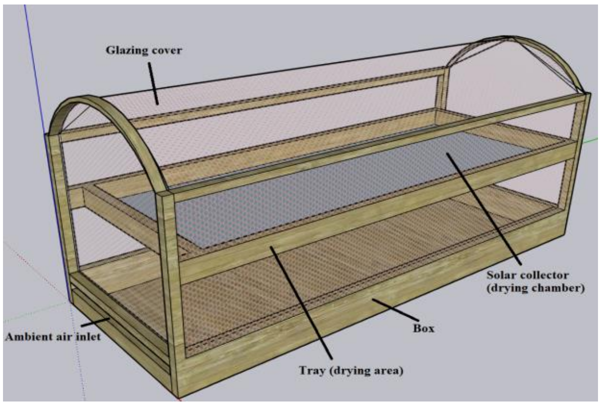

Fig 1. Solar dryer with a suspended platform and thermal circulator.

produce homogeneous drying (Felipe and Barrozo, 2007; Pfeifer et al., 2010; Souza et al., 2015).
This article provides the reader with a review of the methods commonly used to dry soybean seeds and discusses the different dryers and their effects on the physiological quality of seeds.

Basics of seed drying
Seeds are hygroscopic materials capable of absorbing and keeping water, but their moisture can also be eliminated when in thermodynamic equilibrium with a surrounding dry air atmosphere (Ptasznikl et al., 1990; Adu and Otten, 1993).
Producing quality seeds requires exceptional care to keep their physical and physiological qualities (Eichol and Peres, 2008). The ideal time to harvest seeds is at the physiological maturity stage, i.e., at once after physiological disconnection from the mother plant (Silverio et al., 2019). Filho et al., (2017) evaluated the physiological potential of soybean seeds at different physiological maturity stages and concluded that the maximum physiological potential is reached at the time of maximum dry matter accumulation, and at this time, the highest germination index, vigor, and dry mass are also reached, factors essential for seed quality.
Further emphasizing the subject, other studies (Zuffo et al., 2017; Zuffo et al., 2019) investigated the physiological changes in soybean seeds subjected to delayed harvest. They concluded that delayed harvesting of soybean seed impairs vigor and germination and may lead to considerable losses in the postharvest period.
With these studies pointing to the need to harvest seeds with high water contents, scientific research has sought to develop drying methods aimed at improving the drying process (Barrozo et al., 2014; Coradi and Lemes, 2018a).
Drying is widely used throughout the food industry (Moreira et al., 2020; Mello et al., 2021). For the drying process to occur, the vapor pressure on the product surface (pg) must be greater than the water vapor pressure in the drying air (pair) Boyd (2021), and the greater the difference between these pressures is, the higher the drying rate (Bissaro et al., 2020).

Drying methods for soybean seeds
After harvest, grains and seeds must be subjected to a precleaning operation. This is because reducing impurities reduces the risk of spontaneous ignition, eases air movement, and allows greater drying uniformity, reducing costs and damage to the product (Panasiewicz et al., 2020).
Veerakumar et al. (2014) noted that the dryers of agricultural products may have different configurations based on the optimization of the contact between the solid and gaseous phases involved in drying.
The seed drying process may be classified as sun drying or artificial drying depending on the energy source supplied; as continuous or intermittent depending on the periodicity of the heat supply; and as fixed bed or moving bed depending on the movement of the seed mass (Vijayavenkataraman et al., 2012; Janjai and Bala, 2012; Barrozo et al., 2014; Sontakke and Salve, 2015).

Sun drying
Sontakke and Salve (2015) reviewed sun drying technology and note that this method is based on the direct influence of wind and solar rays on moisture removal from seeds. When started in the plant, in the period between physiological maturity and harvest, it is known as natural drying, which is a more uneven process and more associated with exposure to insects, pests, and animals. Outside the plant, sun drying is performed on threshing floors, trays, or tarps and the seeds are moved during drying.
Aggarwal (2018) conducted a review on the sun drying of agricultural products and found that its use for seed drying is, for the most part, rustic and does not include control of the drying air temperature, making it unfeasible for large farms. Vijayavenkataraman et al. (2012) discussed several forms of sun drying on tarps, dirt floor, trays, and suspended dryers (Figures 1-2). Normally, the seeds are spread in a single layer that is after stirred to increase the drying surface, thus allowing air to pass through a larger number of seeds. When seeds are in suspended beds, sun drying needs frequent turning to achieve uniform seed temperature and thus prevent excessive heating Janjai and Bala (2012); when on a dirt or concrete floor, the moisture of the ground in contact with the seeds should be considered (Vijayavenkataraman et al., 2012).
Lawand (1975) built a box-shaped dryer to have seeds. Solar rays would hit the upper surface, made of a double layer of glass panels, and other thermally insulated surfaces. Its recommended application was domestic use, that is, lesser amounts of seeds. Although natural drying does not pose great risks in terms of mechanical damage to the seeds, the product can be exposed to psychrometric changes occurring over a single day that can cause physicochemical changes (Prakash and Kumar, 2014).
Due to the risks posed by the weather and the variation in ambient temperature and relative humidity, sun drying is a minimally used practice, concentrated in small scales and regions with scarce technology. Better solar dryer configurations should include directing the collectors for greater heat flow uniformity Motahayyer et al. (2019) or automated configurations that include other forms of energy (Alonge and Oniya, 2012).

Artificial drying
In artificial drying, the heat source varies. Artificial methods are performed with the aid of mechanical, electrical, or electronic alternatives and air forced through the seed mass (Garcia et al., 2004).
In artificial drying, the drying air temperature, ambient relative humidity, air flow, and all system automation is controlled, reducing the time of exposure of the product to heated air and favoring the efficiency of the process (Furtado et al., 2020). Thus, soybean drying can be performed in static systems or fixed beds and moving beds, and the air flow operations can follow a continuous or intermittent regime.

Fig 2. Example of natural drying on a concrete floor. Source: Author himself.

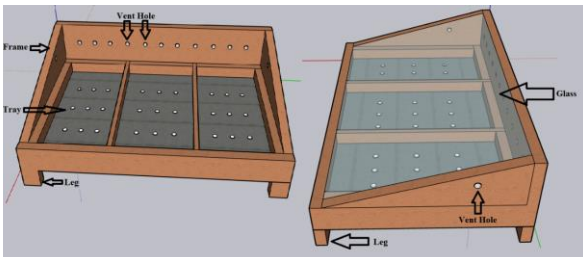

Fig 3. Box-type solar dryer. Source: Author himself.

Fixed bed drying

Stationary dryers, also called fixed layer or fixed bed dryers are like silos but do not necessarily have the same dimensions as a conventional silo. The fixed bed of seeds is supported by perforated plates, through which the drying air is blown (Silverio et al., 2019; Coradi et al., 2021). The air blown on the seedbed should not necessarily be heated and may have moisture and temperature fronts given by the air inlet conditions and by the drying of the seed mass along the height of the dryer (Jayas and White, 2003; Coradi and Lemes, 2018a). Boyd (2021) studied soybean drying in a silo with a suspended bed on a perforated plate and saw drying fronts arranged in successive layers (Fig. 4). When the first seed layer reaches hygroscopic equilibrium with the drying air, the second layer begins to dry. Meanwhile, the third layer stays moist because it is ahead of the drying front, and it may be at risk of increasing water content due to the condensation of moist air brought from the lower or inner layers.

Jayas et al. (2003) studied the stationary drying of grains and seeds in Canada. They found that because this type of drying is perfectly adapted to the harvesting environment, its use is practical due to the low operational cost and drying efficiency.

Another commonly used model is a stationary dryer with a radial drying air distribution. In this case, the drying front begins near the central air distribution duct (Fig. 5). Silverio et al., (2019) investigated the physiological qualities of seeds in a fixed bed dryer with radial air distribution. After the drying process, soybean seeds were collected at four radial distances and five vertical heights and subjected to germination and vigor tests. The authors found that in stationary drying with radial air distribution, super drying occurs in the lower layer of the dryer and that delayed drying occurs in the upper layer. Seeds near the air duct and found at the base of the dryer had worse physiological qualities.

To solve problems such as the one mentioned above, prototypes have been developed to obtain greater homogeneity and to keep the quality of agricultural products. Coradi et al. (2021) developed and confirmed a new silo-dryer-aerator concept for seeds where the main difference was four storage compartmented cells in a fixed and thick layer with the application of high and low air-drying temperatures (Fig. 6). The experimental fixed bed dryer prototype enabled uniform distribution of the heated air in the drying cells.

In another study, Coradi et al. (2018b) confirmed the same dryer (Fig. 6) using air temperatures of 30, 40, and 50 °C. There were no changes in the quality of the soybean seeds as a function of the drying cells, and the experimental stationary dryer prototype showed a uniform drying air distribution.

Hartmann Filho et al. (2016) worked with artificial drying using a fixed bed dryer with temperature and air flow control for the study of the thin layer drying of soybeans. Drying was performed at air temperatures of 40 °C, 50 °C, 60 °C, 70 °C, and 80 °C with an air flow velocity of 0.2 $m^3\ s^{-1}$, and the authors observed that the adopted methodology is efficient for the drying and preservation of the physiological qualities of seeds, where that temperatures above 40 °C negatively affect the physiological quality of soybean seeds.

Goneli et al. (2016) designed and built a stationary dryer that allowed working with various air temperatures and velocities for thick layer drying of soybean seeds and other agricultural products (Fig. 7). The prototype was built as a fixed bed with a longitudinal distribution of the drying air, coupled to a centrifugal fan with a power of 735.5 W. It was found that the dryer designed was able to solve problems related to the control of the drying air temperature and velocity.

The use of an electric air dehumidifier is a new technique and is being used for soybean seeds in stationary dryers. Konopatzki et al. (2019) evaluated the immediate and latent effects of dehumidified air on seed vigor and found that drying air dehumidification can keep the quality and germination vigor of soybean seeds.

Atungulu et al. (2017) investigated the implications of different fan control strategies, air flow rates, and water contents on drying performance. Regarding the operation of the fan, the strategies of running the fan continuously, only at night, and only during the day and drying with natural air with supplemental heating of ambient air were evaluated. The first water contents tested were 16% and 22% (wet basis), and the air flow rates were 1.04 and 5.0 $m^3 min^{1}$, respectively. The night drying strategy provided a longer drying time and resulted in higher electricity costs, and the general trend was that the energy consumption increased with the air flow rate. A high drying rate was found with seeds harvested at 20% water content (wet basis) and application of a drying air flow rate of 5.0 $m^3 min^{-1}$ and supplemental heating.

Although the control of drying is complex, the drying of soybeans with ambient air was studied by Young et al. (2016). The aim of the experiment was to simulate the conditions found in drying systems in farms and to investigate the impact on water content and germination and vigor rates. The results showed that the germination potential of soybean seeds fell from 98% to 27% with an increase in temperature from 20 °C to 40 °C.

Drying with continuous and intermittent air flow

The intermittent drying of soybeans was investigated by Zhao et al. (2017), who tested five drying strategies, assigning periods of continuous and intermittent drying to equalize the seed mass. The authors saw a 6% reduction in drying time when intermittent drying was applied with 30 minutes of equalization compared to that of continuous drying.

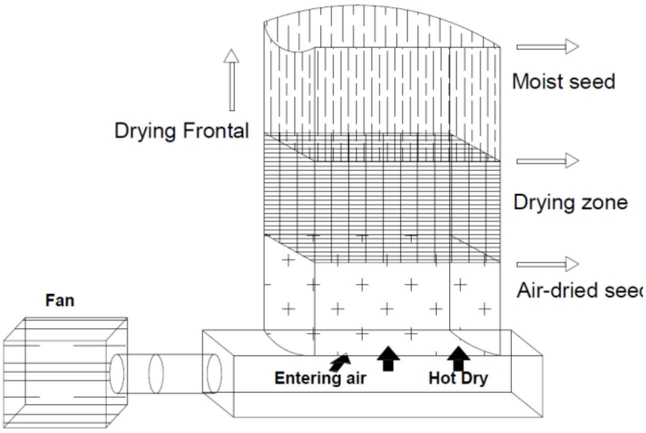

Fig 4. Stationary fixed bed dryer. Source: Adapted from Boyd, (2021).

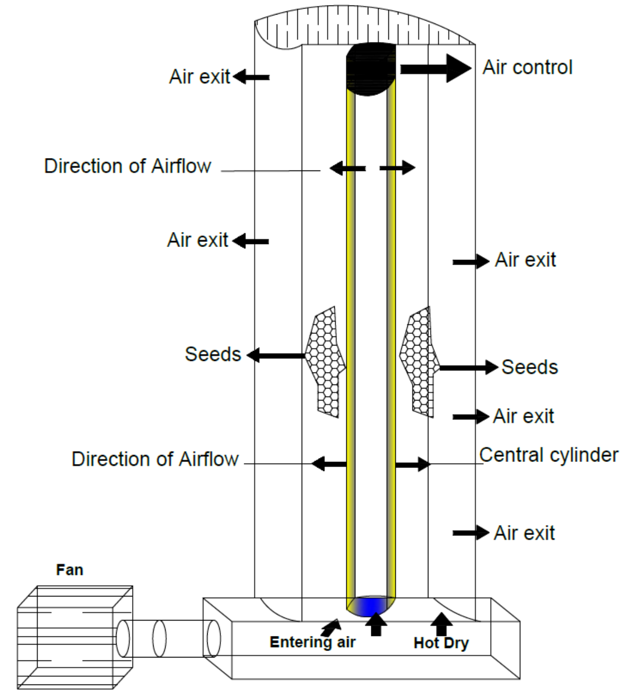

Fig 5. Representation of a fixed bed dryer silo with radial air distribution and the respective radial and vertical distances. Source: Adapted from Silverio et al. (2019).

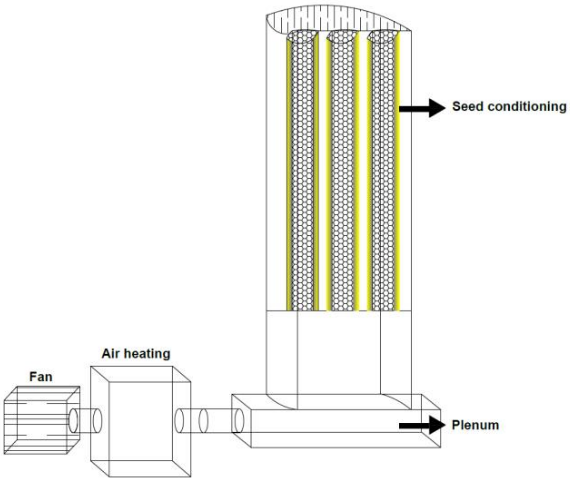

Fig 6. Longitudinal section of the silo-dryer-aerator. Source: Adapted from Coradi et al. (2021).

The same authors performed intermittent drying by periodically turning the fan on and off. When the fan was turned off, the seeds were in the tempering period (equalization) in which the temperature and relative humidity of the drying air were kept constant, and the air flow velocity was 0 ms^{-1}. During the experiment, the drying temperature was kept below 40 ℃. The intermittency ratio α was defined as the ratio between the tempering time and the drying time (Eq. 1).

$$\alpha = \frac{t_{equalization}}{t_{drying}} \qquad (1)$$

Park et al. (2018) studied the effects of drying temperature on the quality of soybean seeds under continuous and intermittent drying. A significant reduction in drying time was seen with the use of intermittent drying compared to that of continuous drying. Regarding the physical quality of the seeds, the proportions of cracked seeds under intermittent drying at temperatures of 35, 40 and 45 °C were reduced by 52.08, 27.59 and 18.24% compared to that of continuous drying.

Zhu et al. (2016) sought to understand the efficacy of intermittent drying by performing a drying experiment with a constant and time-varying intermittency ratio and comparing the results with those of continuous drying. For this purpose, the drying kinetics of green soybean seeds were analyzed using intermittency profiles. An increase in the intermittency ratio caused a decrease in the effective drying time and a consequent increase in the drying rate of soybean seeds. The intermittent drying rates were lower than those of continuous drying for first water contents of 23 and 28% (wet basis).

Aiming at energy optimization, Defendi et al. (2016) studied the intermittent drying of soybeans with variations in air temperature and velocity. The combination of elevated temperatures and low velocities led to lower energy consumption. Additionally, the reduction in water content was greater with intermittent drying.

Bissaro et al. (2020) studied the energy consumption and physiological qualities of soybean seeds in intermittent drying. The physiological qualities of the dried seeds were evaluated in terms of germination, vigor, and cracking and the energy consumption of the operation was evaluated. The results showed a 46% reduction in energy consumption with intermittent drying at an air temperature of 50 °C. It was also saw that the temperature of 70 °C caused a drastic reduction in the germination and vigor of the seeds, accelerating their deterioration.

Moving bed drying of soybean seeds

Moving bed soybean drying is a current approach and has been the focus of numerous studies (Barrozo et al., 2001; Lacerda et al., 2004; BARROZO et al., 2005; Felipe and Barrozo, 2007; Barrozo et al., 2007b; Lira et al., 2009; Pfeifer et al., 2010; Volkhonov et al., 2019). Research on this technique has sought solutions, especially in soybean drying. The main advantages of moving bed dryers are their low energy input, low first investment cost, and homogeneous drying.

In technical terms, moving bed dryers can be characterized as crosscurrent, concurrent, and countercurrent with respect to the flow of seeds and drying air. Barrozo et al. (2000) analyzed the quality of crossflow moving-bed dried soybean seeds and found that parallel flow configurations offer several advantages over crossflow systems, with the provision of homogeneous drying being the major advantage.

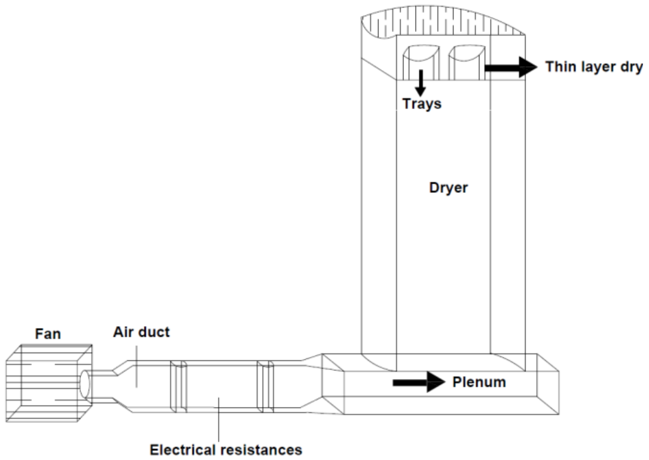

Fig 7. Front view of the dryer prototype. Source: Adapted from Goneli et al. (2016).

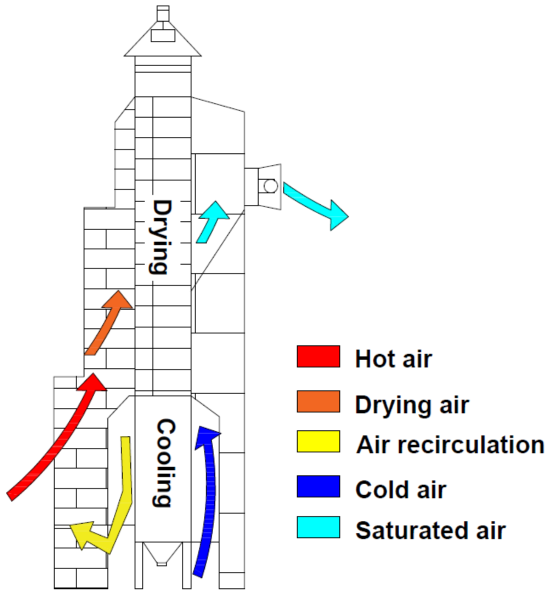

Fig 8. Layout of the continuous flow dryer. Source: Adapted from Winik et al. (2013).

Recent studies are seeking to understand the effects on the physiological qualities of soybean seeds dried in crosscurrent, countercurrent and concurrent moving bed dryers (Lacerda et al., 2004; Felipe and Barrozo, 2007). The main process variables that are investigated are the first seed moisture, seed flow rate in the dryer, drying air velocity and drying air temperature.

Barrozo et al. (2014) reported that in each configuration of the moving bed dryer, numerical correlations were obtained with the stipulated quality indices. Using these empirical equations, it was possible to quantify the effect of each drying variable on each seed quality index in each dryer configuration.

It has already been mentioned in this article that the loss of seed quality is directly associated with over drying (Silverio et al., 2019). Felipe et al. (2007) and Lacerda et al. (2004) note that over drying in moving bed dryer damages soybean seeds, which may lead to nonviable dry material.

Continuous drying

The continuous flow of this type of drying relates to the seeds, and the air flow can be constant or not. The drying agent can be a mixture of ambient and heated air, depending on the (Ps) conditions (Winik et al., 2013). In these dryers, there are two chambers, one for drying with heated air and the second for cooling the seed mass (Winik et al., 2013). Thus, the seeds enter moist on top of the dryer and leave dry at the base of the dryer.

It is well known that in a continuous drying system, for the seeds to dry with only one passage through the dryer, it is necessary to raise the drying air temperature or to delay the flow of the seeds inside the drying chamber (Pfeifer et al., 2010; Filho et al., 2017; Coradi and Lemes, 2018b; Coradi and Lemes, 2018a). However, heat can damage the seed structure, resulting in reduced germination and vigor (Coradi and Lemes, 2018a; Brito et al., 2020).

Winik et al. (2013) conducted a simulation study of a continuous flow dryer used for soybean drying. Figure 8 shows one of the investigated continuous flow dryer designs with three drying stages and their cooling chambers. The authors saw that the air leaving the third stage mixes with the heated air from the furnace and that the obtained mixture B enters the second stage. Similarly, mixture C enters the first stage, heats, and dries the seeds that enter from above in the first stage, and then the air used is expelled into the atmosphere. The study concluded that the efficiency of the dryer depends significantly on the reuse of the heated air.

Conclusions and future studies

Studies on soybean seed drying have undergone changes in the last 20 years. Moving bed drying, discussed in this review, contributed to the development and improvement of the control of the physical and physiological qualities of the dry product and drying uniformity.

Despite the drying method, there is a consensus that the temperature should not be higher than 50°C. High temperatures combined with low drying air humidity led to cracks and rupture of the seed coat, compromising vigor and germination.

In fixed bed drying with radial drying air distribution, drying is uneven, with the main problem being the super drying of the seeds found near the air duct in the lower part of the dryer. Thus, further studies are needed to improve the system to improve the uniformity of the drying process.

Research on continuous and intermittent drying showed that intermittent drying leads to energy savings and, if performed at low temperatures, promotes better seed quality.

The need to improve research on intermittent drying and control of relative air humidity, especially in fixed bed dryers with radial air distribution is highlighted. It should be noted that the use of intermittent drying in this system can promote greater uniformity in the drying process, thus reducing super drying.

With different focuses, approaches to the drying of soybean seeds in moving beds is a trend, given the lower operational costs, greater drying homogeneity, and reduction in seed damage indices.

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