Review

Post-harvesting of soybean seeds – engineering, processes technologies, and seed quality: a review**

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Abstract. Superior agricultural yields are obtained from seeds which have a high physiological potential, these are conserved in the post-harvest stage. Thus, it is crucial to implement post-harvest projects with appropriate technologies related to the equipment used and the control of operations. This article presents a review of the technical-kinetic developments in the area of the technology of processing post-harvest soybean seeds, with a particular focus on the evolution and current circumstances of the sector. The findings from this research reveal significant technological advances in the drying, processing and storage of seeds at different levels and in various areas of soybean production. In drying systems, temperatures of up to 40°C are recommended, while seed batches must remain static in drying chambers. When processing and standardizing seeds, it is recommended that low-moving equipment and abrupt contacts with mechanical systems, such as pneumatic and gravity separators, be employed to minimize dropping and contact with seeds. In soybean storage, the applications of technologies that can control temperature and relative humidity, and also maintain the storage moisture content in a hygroscopic balance are recommended. The storage of seeds in coated big bags and artificial cooling; a controlled and modified atmosphere serve to preserve essential seed qualities. This review concludes that over the years, there has been a reduction in the cumulative losses due to post-harvest processes.

Keywords: seed drying, soybean storage, seed processing, physiological seed quality, seed processing unit, seed post-harvest technology

INTRODUCTION

Soy (*Glycine max* L. Merril) stands out as the main oilseed grown and consumed in the world, due to its numerous uses. However, the improvement of its productivity is still hot topic and is possible through the adoption of certain practices, such as the use of seeds with a high-quality physiology (Nagel and Börner, 2010). The quality of a seed can be defined via a set of attributes, which could be genetic, physical, physiological, and sanitary (Balasubramanian *et al.*, 2012; Groot *et al.*, 2015). Among the various physiological attributes, vigour has an important role in expressing the physiological potential of the seed, and is associated with essential seed function characteristics, such as longevity, germination, rapid and uniform emergence, as well as tolerance to environmental adversity (Vieira *et al.*, 2013; Ballesteros *et al.*, 2020). Inadequate post-harvest practices can affect both the physiological and physical quality of

seeds, leaving the product susceptible to contamination by pathogens. Thus, seed processing is an essential means to guarantee quality and reduce losses (Njonjo *et al.*, 2019).

Processing involves a series of steps, from delivery to a seed processing unit (UBS) to storage and dispatch. Not all materials arriving at a UBS follow the same process; they are carried out according to the cultivar and physical characteristics of the lot. Typically, for processing soybean seeds, equipment such as pre-cleaning machines, spiral separators, width standardizers, gravity tables and dryers are used (Horabik *et al.*, 1992; Maryam and Oskouie, 2011). Unlike other seeds that have protected embryos, the embryos of soybean seeds are exposed, which makes them susceptible to physical injuries caused by external agents during the processing stages, this eventually affects their physiological qualities. Therefore, the equipment used for seed processing needs to be well designed and regulated in order to obtain satisfactory results (Moreano *et al.*, 2018).

Among the seed processing stages, drying is one of the most important steps for preserving the integrity of the embryo. Drying is characterized by a decrease in the biological activity of the seeds, which reduces possible chemical and physical changes that could occur in the product while it is in storage (Park and Yoon, 2019).

The drying methods as well as the particular drying conditions used directly influence the seed quality (Chua *et al.*, 2007). The conditions that promote high drying rates, such as the use of high temperatures and/or the low relative humidity of the air, could cause problems and yield undesirable results, for example, a deterioration of the seed. Inadequate humidity can cause internal and external cracks in the seed as well as damage to the meristematic tissues, and as a consequence, lead to an abnormal development of the embryonic axis. Therefore, drying conditions must be controlled and monitored to achieve high-quality seeds for storage (Petry and Weber, 2015).

During the storage period, a certain degree of seed deterioration is unavoidable, however, the rate of deterioration can be mitigated through appropriate conservation techniques. The careful control of temperature, relative humidity, fungal growth, and the insect population ensures a high storage potential and consequently, high-vigour seeds (Sorour and Toshitaka, 2004a).

The quality of the seed is a very important factor in the growth of crops with expected productivity indices. The success or failure of agricultural production depends on this factor, as the quality of the seed carries all of the productive potential for generating vigorous plants (Su *et al.*, 2015). In order to minimize the loss in quality, technology has been applied to an increasing extent in recent years in the areas of drying, storage and rapid testing to assess the degree of quality (Kong *et al.*, 2008; Rahman and Cho, 2016). Various technologies are associated with the use and implementation of sensors, resources and tools to detect and monitor certain quality parameters (Yang *et al.*, 2015; Horng *et al.*, 2020).

It is generally understood that the quality of soybean seeds depends on factors that involve monitoring technologies and the appropriate handling of the lots in post-harvest operations (Santos *et al.*, 2004). Thus, this review discussed the advances made and the current post-harvest scenario for soybean seeds.

STRUCTURE AND OPERATIONS FOR POSTHARVEST SOYBEAN SEED PROCESSING

The post-harvest processes aim to preserve the physical and physiological quality of the seeds through the application of a set of operations (Figs 1 and 2). The structure of the seed processing and storage unit contains a seed reception and unloading area, pre-cleaning and cleaning machines, dryers, seed classification machines, storage silos and a shipping area (Figs 2 and 3). The transport of seeds between operations is carried out by means of conveyors, such as conveyor belts, pneumatic systems and bucket elevators (Figs 2 and 3).

Drying of soybean seeds

Drying kinetics

Seed drying is an essential unit operation for the preservation of quality (Minea, 2015). The main objective of drying is to reduce the moisture content of the seeds, this occurs through the diffusion and evaporation of water, in a process involving the transfer of seed energy and mass (Perea *et al.*, 2012). Figure 4 represents the partial drying of soybean seeds.

Fig. 1. General flowchart of seed pre-processing and storage operations.
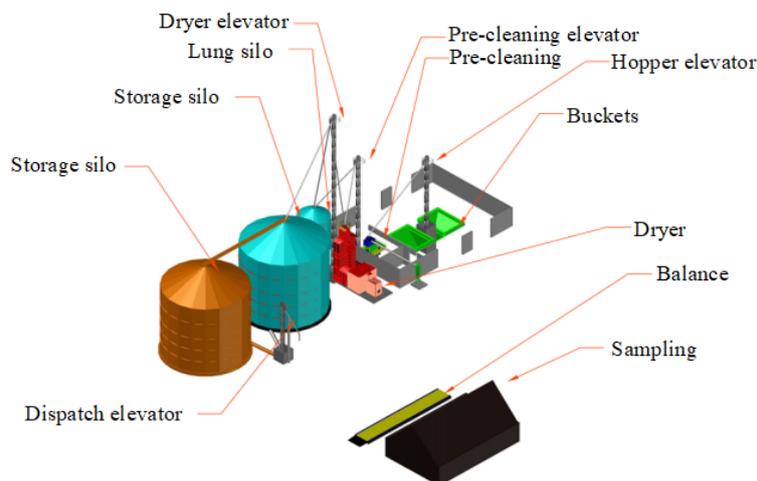
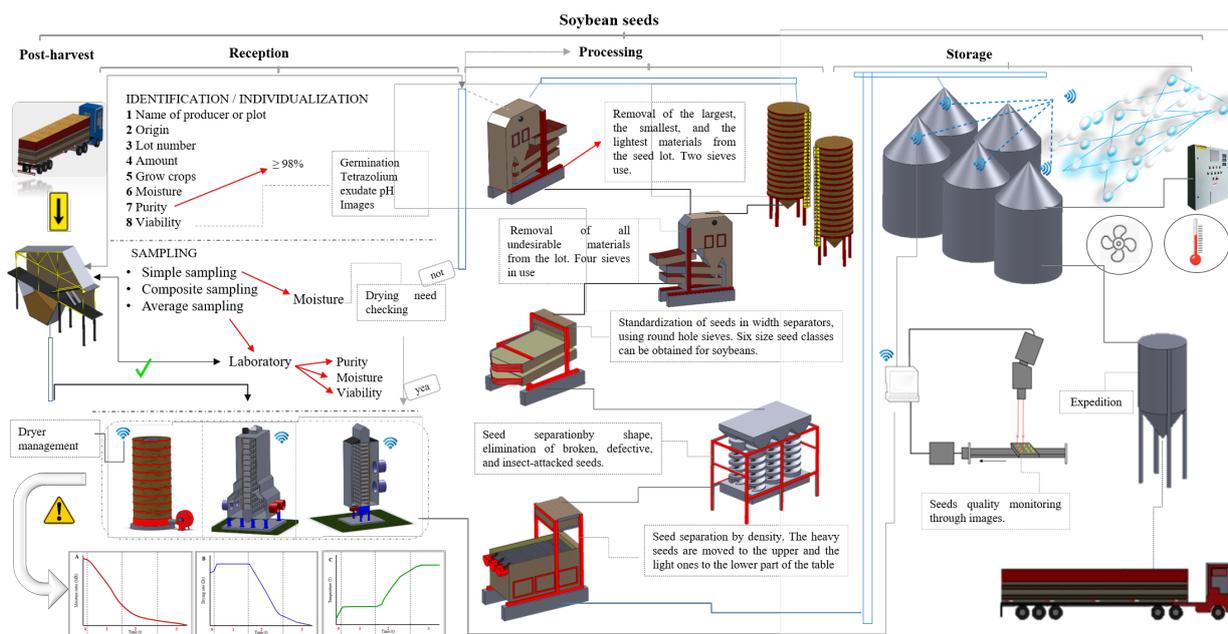**Fig. 2.** Structure of a seed receiving, drying and storage unit.

Fig. 3. Detailing of processing, drying and storage of soybean seeds.

Drying is a dynamic, non-linear thermal process, which may be described by different semi-theoretical, empirical and theoretical mathematical models, which are based on a description of the moisture ratio and drying kinetics (Silva *et al.*, 2019). Semi-empirical models are based on Newton's Law, assuming that conditions are isothermal and that resistance to moisture transfer is restricted to the product surface only (Ali *et al.*, 2017). In considering all of the models, two terms, Henderson & Pabis and Page, may be cited as those used for simplicity and adequate adjustment. The empirical method consists of forming dimensionless physical groups that can easily be investigated through performing laboratory experiments based on external conditions, such as temperature, humidity ratio and drying air speed (Laoretani *et al.*, 2017). However, these modules do not provide any indications about the phenomena of energy and mass transport within the grains and assumes that the entire drying process only occurs in the period of a decreasing rate of drying (Babaki *et al.*, 2020).

Theoretical models account for the external conditions under which the operation takes place, as well as the internal mechanisms of energy and mass transfer and their effects. The liquid diffusion model is the most common model and stands out among the rest of the theoretical models applied to the drying process of agricultural products (Johann *et al.*, 2018). The diffusion model explains the behaviour of the main thermodynamic properties involved in the drying process. Due to the diversity of mechanisms involved in
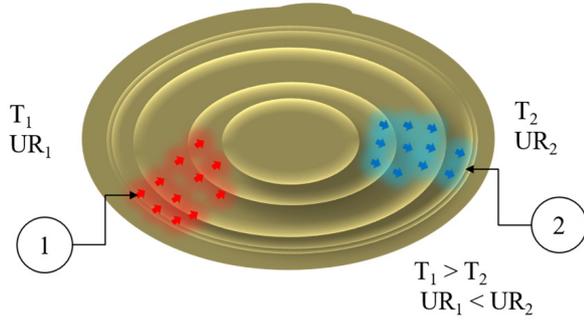
Fig. 4. Partial representation of the drying process: (A) heated air inlet and (B) exhaust air outlet.

mass transfer, some authors have studied drying mechanisms and have proposed equations suitable for predicting drying kinetics (Park and Yoon, 2018). For determining the ratios of moisture during the drying process under different conditions, the following expression was used (Eq. 1):

$$MR = \frac{\overline{X} - X_e}{X_0 - X_e}, \qquad (1)$$

where: $\overline{X}$ – moisture content of the product (d.b.), X_0 – initial moisture content of the product (d.b.), X_e – equilibrium moisture content of the product (d.b.).

The mathematical models which are frequently used to represent the drying curves of agricultural products are presented in Table 1.

In order to evaluate the models, a non-linear regression analysis is used, the definition of the best model that describes the drying conditions is based on the values of the coefficient of determination (R^2), the estimated mean error (*SE*) and the relative mean error (*P*). For an adequate

representation of the drying phenomena, the R^2 values must be greater than 96%, as this parameter assesses the variation of the experimental data, together with low *SE* values, and *P* values less than 10%. The *SE* and *P* values are calculated using the following equations, respectively (Eqs 13 and 14):

$$P = \frac{100}{n} \sum \frac{\left| Y - \hat{Y} \right|}{Y}, \qquad (13)$$

$$SE = \sqrt{\frac{\sum \left(Y - \hat{Y} \right)^2}{GLR}}, \qquad (14)$$

where: Y – experimentally observed value, $\hat{Y}$ – value calculated by the model, n - number of experimental observations, GLR – degrees of freedom of the model.

Theoretical methods are used to assess the movement of water in soybeans, which take account of the external conditions and the internal mechanisms of energy and mass transfer and their effects. Depending on the drying conditions of the soybeans, moisture was transported through mechanisms of liquid diffusion, capillary diffusion, surface diffusion, hydrodynamic flow, vapour diffusion or thermal diffusion (Jahanbakhshi *et al.*, 2020).

The theory of liquid diffusion media has been widely used and some assumptions that must be made for its implementation with regard to a particular material, such as reducing the volume of the material, reducing the volume of discarded material, the absence of thermal capillary products with temporary air and the effects of mass and energy transfer from one body to another are considered negligible (Lima *et al.*, 2015). However, due to practical

Table 1. Mathematical models used to represent the drying curves of agricultural products

Models	Models references
$MR = \exp(-kt)$ (2)	Newton
$MR = \exp(-kt^n)$ (3)	Page
$MR = \exp(-kt)^n$ (4)	Page Modified
$MR = a\exp(-kt)$ (5)	Henderson and Pabis
$MR = a\exp(-kt) + c$ (6)	Logarithmic
$MR = a\exp(-k_0 t) + b\exp(-k_1 t)$ (7)	Two Terms
$MR = a\exp(-k\tau) + (1-a)\exp(-kat)$ (8)	Two Exponential Terms
$MR = 1 + at + bt^2$ (9)	Wang and Singh
$MR = a\exp(-kt) + b\exp(-k_0 t) + c\exp(-k_1 t)$ (10)	Henderson & Pabis Modified
$MR = a\exp(-kt^n) + bt$ (11)	Midilli
$MR = a\exp(-kt) + (1-a)\exp(-kbt)$ (12)	Diffusion approximation

MR – moisture ratio (dimensionless), t – drying time (h), k, k_0, k_1 – drying constant (h^{-1}), a, b, c – model coefficients, n – number of terms of the equation.

limitations, when liquid diffusion is used for organic products, these assumptions are generally considered satisfactory.

In liquid diffusion theory, the moisture rate may be expressed by Fick's second law (Eq. 15):

$$\frac{\partial}{\partial t} = \frac{\partial}{\partial r}\left(D\frac{\partial X}{\partial r}\right), \qquad (15)$$

where: X – moisture content (kg$_{water}$ kg$^{-1}_{DS}$), D – the diffusion coefficient of the liquid phase applied to the motion (m^2 s^{-1}), R – distance from a reference point of the body (m), T – time (s).

Some studies propose the determination of the diffusion coefficient of agricultural products, taking into account, in addition to temperature, the product's moisture content (Malekjani and Jafari, 2018). The variation in moisture content with the drying time of those materials with a homogeneous and constant diffusion coefficient is represented by the Eq. (16):

$$\frac{\partial X}{\partial t} = \frac{D}{r^2}\left[\frac{\partial}{\partial r}\left(r^2\frac{\partial X}{\partial r}\right)\right], \qquad (16)$$

For different geometric shapes, various solutions have been used for the drying of agricultural products, which are considered in the following conditions (Eq. 17):

$$X(r, 0) = Xi \ \text{ and } \ X(R, t) = Xe. \qquad (17)$$

A sphere with a particular initial moisture content, which is subjected to the drying process in the open air, under constant conditions, may be described by Fick's theory, having the following analytical solution (Eq. 18):

$$MR = \frac{\overline{X} - X_e}{X_0 - X_e} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(\frac{-D\,n^2\pi^2 t}{R^2}\right), \qquad (18)$$

where: R – sphere radius (m), n – number of terms. It is common to consider the value of the diffusion coefficient constant or linearly dependent on the temperature of the air drying (Putranto et al., 2011). This relationship has been expressed by the Arrhenius model (Eq. 19):

$$D = A\exp(-\frac{E}{RT}), \qquad (19)$$

where: A – constant (m^2 s^{-1}), E – activation energy (kJ kmol^{-1}), R – universal gas constant (8.314 kJ kmol^{-1} K^{-1}), T – absolute temperature (K).

The coefficients of the Arrhenius expression were linearized by applying a logarithm of the form (Eq. 20):

$$LnD = LnA - \frac{E}{RT}\frac{1}{Ta}. \qquad (20)$$

The values of water activity, temperature and equilibrium moisture content were obtained from the soybean grain desorption isotherms, using the model that best fit the experimental data (Ayadi et al., 2020). For the calculation of the integral isosteric heat of desorption, the following expression (Eq. 21) was used:

$$Q_{st} = q_{st} + L = a\exp(-bUe) + L, \qquad (21)$$

where: Q_{st} – integral isosteric heat of sorption (kJ kg^{-1}), L – latent heat of vaporization of free water (kJ kg^{-1}), a, b – coefficients of the model.

The free water latent heat of vaporization was obtained using the average temperature (Eq. 22):

$$L = 2502.3 - 2.39T_m, \qquad (22)$$

where: T_m – average temperature (°C).

Using mathematical models, it is possible to describe both the kinetics and the drying rate of seeds (Fig. 5). The drying curves represent the relationship between the humidity ratio and time (Barrozo et al., 2006; Coradi et al., 2016). It may be observed that under the same humidity ratio, the higher the temperature, the shorter the drying time.

In Fig. 5 it is apparent that Curve (A) represents a reduction in the moisture content of the product during the drying time. Curve (B) represents the drying rate of the seeds, that is, the variation in the moisture content of the seeds over time (dX/dt) (Albini et al., 2018). Curve (C) represents the variation in the temperature of the seed mass with drying
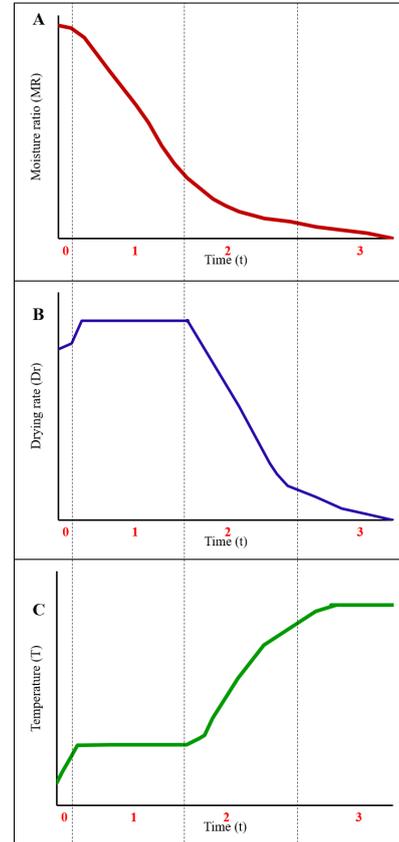

Fig. 5. (A) Drying kinetics, (B) drying rate, and (C) seed mass temperature in the drying process.

time. Region (0) represents the initial drying period, during which the free liquid water is removed from the seed surface. The drying rate increases with increasing seed temperature. Region (1) indicates the period of constant drying rate. In this phase, the free water in the liquid state is continuously evaporated from the solid surface. Region (2) corresponds to the first period of the decreasing rate of vaporization of the seed water, this is caused by a difference in the vapour pressure of drying and that of the seed. Region (3) corresponds to the second stage of the decreasing rate of seed water vaporization, in which water from the inner layers of the seed moves to the periphery and is removed by the difference between the vapour pressure of the drying air and that of the seed (Nadi and Tzempelikos, 2018).

As the drying air temperature increases, the coefficient of liquid diffusion and vaporization increases significantly (Garvin *et al.*, 2017). Thus, knowledge of the relevant thermodynamic properties, such as enthalpy, entropy, and Gibbs free energy, is essential to understand the diffusivity of water and also to calculate the energy required for the drying process (Borges *et al.*, 2018).

Enthalpy is the energy present in the air, which influences the drying process of the seeds; the higher the temperature of the drying air, the greater the enthalpy (Coradi *et al.*, 2014). Entropy is a thermodynamic quantity that defines the degree of order or disorder in the seed-water system; the greater the degree of disorder, the greater the entropy. During the drying process, the level of entropy is expected to decrease with the increase in temperature; alternatively, decreasing the temperature results in a lower excitation of the water molecules and increases the degree of order in the water-seed system; as a result, the level of entropy increases with decreasing temperature (Borges *et al.*, 2018; Guilherme and Nicolin, 2020).

Negative entropy may be attributed to the existence of structural changes in the adsorbent, thereby indicating that the seeds are thermally more stable. Gibbs free energy indicates the spontaneity of energy in a water-solvent interaction; that is, how much water is bound to the product; furthermore, it allows us to determine if the drying process is characterized as spontaneous or not spontaneous (Jung and Yoon, 2018). A positive Gibbs energy indicates heat losses in the seed during a non-spontaneous drying process (Hartmann Filho *et al.,* 2016).

Effect of drying on the quality of soybean seeds

An appropriate drying process implies the preservation of the physical integrity and physiological quality of the seeds, this is associated with an energy and operational efficiency (Brito *et al.*, 2020a). The drying conditions and methods used should minimize the quality losses in the seeds. For this reason, high drying rates should be avoided in high-temperature applications (Mahjabin and Abidi,

2015). The use of high temperatures during drying leads to the rapid heating of the seed mass and an abrupt movement of the water molecules, which cause fissures and disruptions in the cell membranes of the meristematic tissues, and consequently, of the embryonic axis, thus causing a deterioration in the seeds (Brito *et al.*, 2020b).

Some studies have observed that there was a reduction in the percentage of germination and in the level of seed vigour, in addition, changes in the length of the hypocotyl and of the seed root were not significant with increases in the temperature of the drying air (Rosental *et al.*, 2014; Brzezinski *et al.*, 2017). Therefore, it was considered that drying at a temperature of 35 °C and a relative humidity of above 35% would guarantee improved physiological quality (Brito *et al.*, 2020b).

Although there are several types of dryers for drying seeds, stationary dryers are the most highly recommended. The process of the stationary drying of seeds consists of passing the drying air through the seed mass, while the seeds remain static in the drying chamber (Sdayria *et al.*, 2015). However, some studies have reported that the heterogeneity of the air temperature and seed mass, and also the moisture content in the fixed drying bed makes it difficult to optimize the process, which in many cases, could become technically infeasible (Levien e*t al.*, 2008; Coradi *et al.*, 2021a).

The authors observed that during the drying process of soybean seeds in a stationary dryer with a radial air distribution, at a drying temperature of 40°C, there were differences in the physiological quality of the seeds in different vertical and axial locations of the fixed drying bed (Coradi and Lemes, 2018). The seeds that were packed close to the central tube of the radial distribution did not experience a reduction in their germinative potential, however, there was a reduction in seed vigour for those seeds located at a radial height of 0.20 m (Avelar *et al.*, 2011).

The drying technology that employs a continuous flow of seeds and drying air is considered to be more efficient and produces a greater degree of homogeneity and faster drying (Silva *et al*., 2020). However, continuous drying has the disadvantage of compromising the seed quality, for example, through physical and mechanical damage caused by the excessive movement of the seeds, and the exposure of the seeds to the high temperatures of the drying air, this causes latent damage to the seeds owing to the high rates of water vaporization during the drying process (Izli *et al*., 2009; Konopatzki *et al.*, 2019).

Some studies have been conducted to evaluate the effect of intermittent drying with air temperatures of 60 and 80°C, and intermittence times of 30 and 120 min on the quality of soybean seeds. The authors observed that a high drying temperature, together with a short intermittence time caused cracks in the integument, and reduced the germinative potential by 66.7%. On the other hand, at an air

temperature of 60°C and intermittency of 120 min, the quality of the seed was maintained and the integrity of the cell tissue membrane was not affected (Ong *et al.*, 2012).

In studies concerning the quality of soybean seeds in drying, several authors have concluded that the germination rate of the seeds was drastically reduced after drying, and this effect was intensified during the storage period of the seeds (Aghbashlo *et al.*, 2014). The increase in the drying air temperature from 40 to 80°C decreased the germination rate of soybean seeds from 100 to 1% at the end of a storage period of six months, under ambient conditions (Zhu *et al.*, 2016).

Another significant factor in reducing the seed quality upon drying is the initial moisture content and the drying air temperature applied (Anand *et al.*, 2020). When soybean seeds with a high initial water content are submitted to high drying temperatures, an increase in the vapour pressure gradient between the seed and drying air, results in a high drying rate and, consequently, the greater probability of the occurrence of cracks (Arruda *et al.*, 2009). Damage to the integument from a high drying rate makes the seed more susceptible to microbial attack during storage, resulting in a loss of physiological potential (Atungulu and Olatunde, 2018).

## Technologies and methods of drying soybean seeds

Drying of soybean seeds may be classified according to the movement of the seed mass into stationary or continuous techniques, or according to the air flow in the drying chamber, which may be co-current, counter-current, mixed, or crossed with the seed flow (Afrakhteh *et al.*, 2013). Continuous dryers are composed of drying chambers with or without cooling and the reuse of drying air. The intermittent drying process is characterized by a discontinuous passage of air and seeds in the dryer. The seeds are recirculated through an intermittent chamber (Brooker *et al.*, 1992; Barrozo *et al.*, 2014)

At regular intervals, the seeds remain without drying air. During the application of the intermittence technique, a diffusion of moisture from the interior to the seed surface occurs, thereby promoting an equalization of humidity and a reduction of the thermal damage (Hashemi *et al.*, 2014). During intermittent drying, drying air temperatures ranging from 70 to 80°C are applied, without an excessive increase in the temperature of the seed mass (which must not exceed 40°C). Intermittent drying can serve to minimize energy consumption and reduce qualitative losses, as it is a less aggressive drying process (Ong *et al.*, 2012).

Stationary drying is characterized by the forced passage of air in an axial or a radial flow through a layer of seeds that are resident in the drying compartment (Aghbashlo *et al.*, 2014). The drying process of the seeds occurs in layers, with the formation of drying zones. In this method there is a non-uniformity of the drying process, with variations in both the drying speed and in the final moisture content in different positions of the dryer (Coradi and Lemes, 2018; Coradi *et al.*, 2021b).

Although this system is free from mechanical considerations, as there is no movement of the seeds, the heterogeneity of the air and seeds makes it difficult to optimize the process (Avhad and Marchetti, 2016; Jan *et al.*, 2019). However, if stationary seed dryers are used, it is recommended that the air distribution should be along the radial flow, as the entire duct offers a drying front. Regardless of the drying system employed, it is essential and indispensable to monitor the temperature of the seed mass to avoid a loss of physiological quality (Souza *et al.*, 2015a). Figure 6 shows a schematic diagram of the drying principle of dryers with continuous, intermittent, and stationary systems for soybean seeds as well as the location of air and seed monitoring sensors during drying.
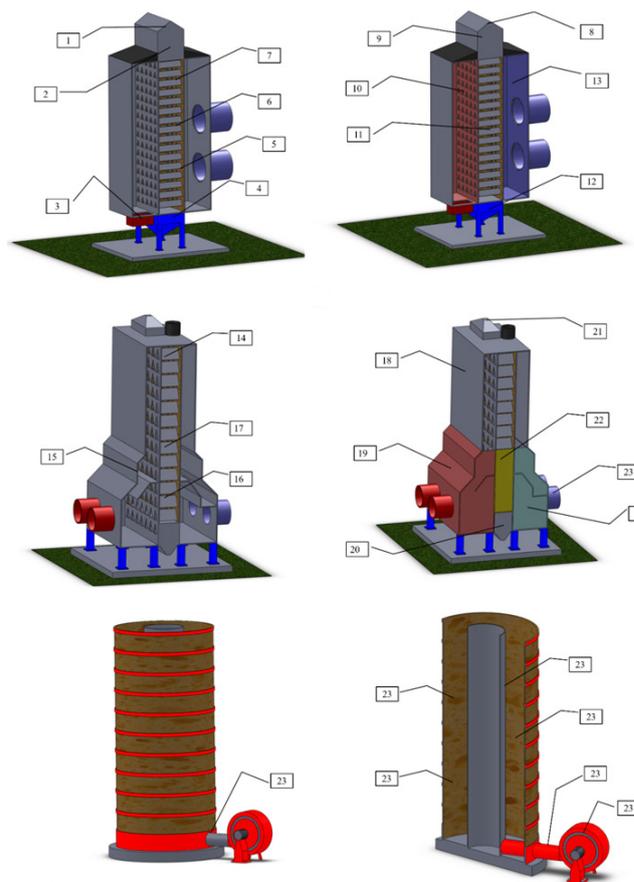
Fig. 6. Dryers of soybean seeds: 1 – Sensor maximum level, 2 – Sensor minimum level, 3 – Hot air inlet sensor, 4 – Stop sensor, 5 – Mass sensor, 6 – Mass sensor, 7 – Mass sensor, 8 – Input product, 9 – Loading box, 10 – Drying chamber, 11 – Drying tower, 12 – Discharge table, 13 – Drying air, 14 – Maximum level sensor, 15 – Sensor hot air inlet, 16 – Sensor ground, 17 – Sensor minimum level, 18 – Equalization chamber, 19 – Hot air chamber, 20 – Discharge table, 21 – Product entrance, 22 – Drying tower, 23 – Fans, 24 – Cold air chamber.

The drying of the seeds is accomplished through the desorption of water by passing air, this air may be heated using firewood, wood chips, liquefied petroleum gas, or electricity (Striugas *et al.*, 2017). The latest drying technologies utilize radiofrequency air heating (Feng *et al.*, 2014; Jiang *et al.*, 2020). The heating of the seeds occurs through molecular rotation and ion oscillations, therefore the seed mass can be heated without creating a thermal gradient (Rudobashta and Zueva, 2016). According to some studies, radiofrequency heating accelerates drying rates and maintains seed vigour, in addition to reducing energy consumption (Souza *et al.*, 2015b).

Another method that has been yielding satisfactory results is microwave drying. Some studies have observed that during microwave drying, the temperature of the seed mass remains lower than in conventional drying, with time optimization and energy savings (Souza *et al.*, 2015c). Furthermore, a dehumidification technique for ambient air, which reduces the humidity ratio and enhances air drying at low temperatures, has been used to an increasing extent to dry soybean seeds (Cao *et al.*, 2017).

The automation of drying with the use of sensors and computer systems has improved the precision of the process (Martynenko, 2017). Microwave or capacitive sensors are also used to monitor the flow and heating of seed air (Hemis *et al.*, 2016). Microwave sensors operate on the principle of electromagnetic waves, it may be considered to be a sensor which is insensitive to environmental conditions such as steam and dust, and is less sensitive to material accumulation and safe at low power levels (Serowik *et al.*, 2018).

Microwave sensors may be used to obtain satisfactory results in monitoring moisture content because the measurement is not limited to the seed surface, and is independent of the density or charge of the seed mass, colour, and structure of the seed surface (Bai *et al.*, 2018). Moreover, capacitive sensors are used in seed dryers owing to their simple structure and sensitivity to moisture content (Bai *et al.*, 2018). Indirect measurement involves correlating the moisture content of the seeds and capacitance (Walters, 1998). The incremental change in the dielectric constant of the sensor is almost directly proportional to the relative humidity of the environment (Bai *et al.*, 2018). Table 2 summarizes some key technologies which have been applied in seed drying.

Heating systems for drying soybean seeds

Heating is a universally adopted method used to dry seeds. In this process, energy is supplied to the drying air in the form of heat (Romdhana *et al.*, 2015). Firewood is the most commonly used source in industry for heating air during the drying process (Kleinhans *et al.*, 2018). Other fuel sources, such as liquefied petroleum gas and rice husks are economically viable and are widely used in Brazil, in addition to electric heating (Razmjoo *et al.*, 2016).

Indirect heating furnaces are used to burn fuels for seed drying (Vorotinskienė *et al.*, 2020). The thermal energy from combustion is transferred to the seeds through the use of a heat exchanger (Poláčik *et al.*, 2021). Although an indirect fire furnace with a heat exchanger is the most suitable arrangement for drying seeds, as the drying air temperature can be controlled, such a system causes losses in thermal energy (Striugas *et al.*, 2017).

Therefore, it is desirable to find an effective method for storing excess heat, and use it consistently and efficiently. Some studies have been used to evaluate heat storage and increase thermal efficiency in a combustion chamber built with bricks of different heights. Their thermal efficiencies ranged from 28 to 33%, when the height of the bricks was 50-150 cm, while the drying time was also reduced to 78 h (Wang *et al.*, 2019).

Figure 7 represents the working principle of a seed drying furnace. The furnace consists of a combustion chamber, grill, heat exchanger, and an ash control system (Silva *et al.*, 2014). The combustion chamber is where the fuel burns, and can be fed manually or automatically (Tekasakul *et al.*, 2017). It is equipped with cast iron grilles, which normally keep the solid fuel suspended during the combustion process while the combustion air circulates over its surfaces (Vorotinskienė *et al.*, 2020).

State-of-the-art systems use a staggered air supply, wherein the combustion zone on the grid makes use of a low stoichiometry to suppress nitric oxides (Silva *et al.*, 2014). The heat exchanger consists of several combustion tubes, these are used to dissipate the heat generated by the burnt fuel. The furnace operates with the passage of ambient air through heat exchanger tubes, these are heated by flue gases. The desired drying air temperature is achieved through the use of a controller. The flue gas is expelled by a chimney (Kleinhans *et al.*, 2018).

Figure 8 shows three views and an isometric view of an indirect fire furnace. The steam drying system offers advantages over drying with hot air, including low energy consumption, the effective use of exhaust steam, the absence of oxidative reactions, and the emission of gases, dust, and dirt into the environment (Ge *et al.*, 2016). Steam can be produced using electricity, solar heaters, or agricultural waste, which are easily available energy sources (Mendonça *et al.*, 2015; Verma *et al.*, 2017).

Steam drying provides clean drying air, which is free from impurities and odours, and therefore direct contact with the seeds is allowed, and consequently a better quality final product is achieved. In most conventional dryers, steam may be used to heat the drying air, with the system replacing a masonry furnace (Kleinhans *et al.*, 2018). The structure consists of a steam generator, a heat exchanger, and ducts for conducting hot air to the dryer, there is no need to change the characteristics of the dryer (Alfy *et al.*, 2016). Figure 9 shows the working principle of steam drying.

**Table 2.** Technologies applied in drying soybean seeds

Technology	Description	Reference
Heat pump	Its purpose is to recover energy from the exhaust, as well as to independently control the temperature and humidity of the drying gas	Chua *et al.* (2007) Ong *et al.* (2012) Minea (2015) Zhu *et al.* (2016)
Dehumidification	This technique removes humidity from the air, cooling it below the dew point by means of refrigerators, where part of the humidity is condensed and drained from the air	Avelar *et al.* (2011) Putranto *et al.* (2011) Mbofung *et al.* (2013) Zuchi *et al.* (2013) Coradi *et al.* (2014) Carvalho *et al.* (2016) Krzyzanowski *et al.* (2006) Ferreira *et al.* (2017) Jung and Yoon (2018)
Infrared radiation	The radiation penetrates through the exposed surface of the product and propagates in the material to create molecular vibration. This allows for the removal of water from the surface	Rudobashta and Zueva (2016)
Ultrasound	Intensified drying process. Acoustic energy produces oscillation and micro extraction speeds at the interfaces that can break the connection between water molecules and the product surface and minimize the thickness of the diffusion limit layer	Peres *et al.* (2012) Yang *et al.* (2015)
Microwave	Microwaves penetrate the material and the material can be dried without the aid of a thermal gradient. Heat is transferred from the inside to the outside by the rapid rotation of the polar molecules due to changes in the electric field	Hemis *et al.* (2016) Cao *et al.* (2017) Bai *et al.* (2018) Serowik *et al.* (2018) Jilani *et al.* (2019) Anand *et al.* (2020) Babaki *et al.* (2020) Jahanbakhshi *et al.* (2020)
Radio frequency	RF generates heat in the seeds through ionic depolarization and dipole rotation, which can supply energy uniformly and rapidly in food materials and thus, significantly reduce the processing time	Jiang *et al.* (2020)
Hydrodynamics	Used to monitor and control hydrodynamic conditions using sensors	Aghbashlo *et al.* (2014) Fu *et al.* (2015) Sdayria *et al.* (2015) Lheonye *et al.* (2020)
Computational technology	Non-destructive technologies used to provide information concerning the characteristics of the internal and external structure of the seed. Among the main technologies used are hyperspectual imaging, magnetic resonance imaging, spectral imaging in the infrared and X-rays	Wójcik and Tejchman (2009) Huang *et al.* (2014) Aghbashlo *et al.* (2015) Su *et al.* (2015) Malekjani and Jafari (2018) Park and Yoon (2019) Salimi and Boelt (2019) Guilherme and Nicolin (2020) Horng *et al.* (2020)
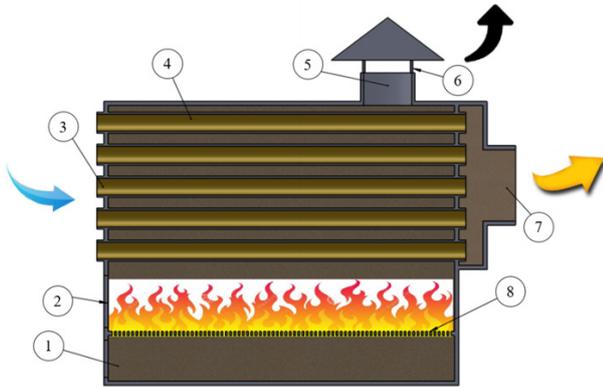
Fig. 7. Cross-sectional view of the indirect fire furnace: 1 – Ashtray, 2 – Combustion chamber, 3 – Ambient air inlet, 4 – Heat-extinguishing tubes, 5 – Chimney, 6 – Flue gas, 7 – Drying air outlet, 8 – Grill.
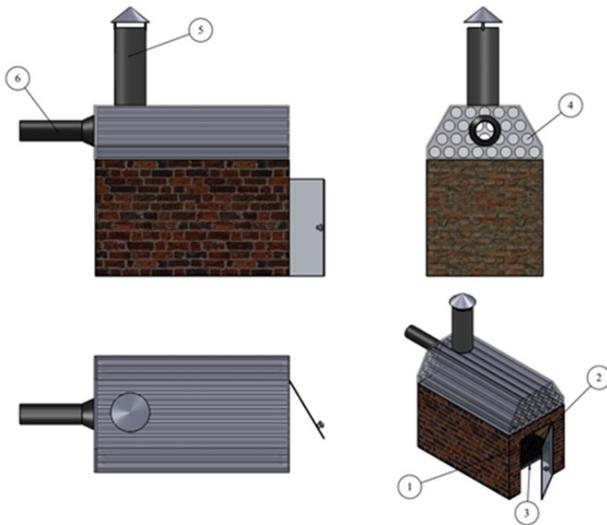
Fig. 8. Indirect fire furnace in three views and in perspective: 1 – Combustion chamber, 2 – Grill, 3 – Ashtray, 4 – Heat exchanger, 5 – Chimney, 6 – Hot air outlet.
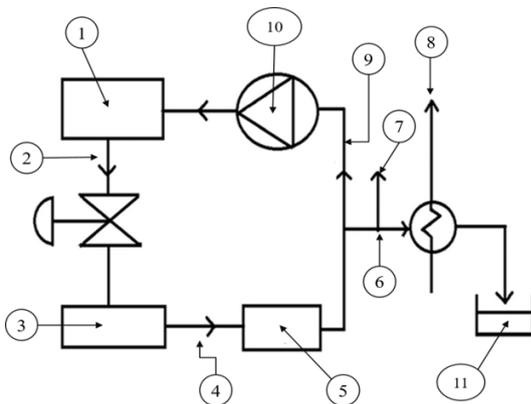
Fig. 9. Principle of steam drying using a boiler: 1 – Boiler, 2 – Steam, 3 – Heating, 4 – Heated steam, 5 – Drying chamber, 6 – Steam purged, 7 – Direct use of steam, 8 – Heat reuse, 9 – Overheated steam, 10 – Fan, 11 – Condenser.

Superheated steam drying is a technology that uses steam heated to a temperature above the boiling point (Sehrawat *et al.*, 2016). The principle of steam drying is based on the recirculation of superheated steam in a closed circuit. When water is heated to a specific pressure, it forms saturated steam at its boiling point (Shatters *et al.*, 1994). Additional heating, above the boiling point, causes the saturated steam to be converted into superheated steam (Chryat *et al.*, 2015).

The amount of steam removed from the system is equal to the amount of water evaporated during drying. Excess steam can be reused and/or recycled, as a heat source, which saves costs, and therefore, results in a better use of energy (Li *et al.*, 2016). The difference between drying using steam and conventional drying is in the diffusion stage of seed moisture (Khatchatourian *et al.*, 2014). In drying with heated air, the diffusion of moisture occurs from inside the seed to its surface, whereas, in a steam drying system, the diffusion of moisture occurs with the expansion of the cells, as the liquid moisture becomes steam, thereby increasing the porosity of the seed, as it dries (Le *et al.*, 2017).

STORAGE OF SOYBEAN SEEDS

The purpose of storage is to preserve the quality of the seeds for as long as possible and for this purpose, the form and conditions of storage must be taken into account (Sorour and Uchino, 2004b; Yang *et al.*, 2011a). Among the different forms of storage, bulk storage in vertical or horizontal silos is emphasized, along with conventional storage in sacks (Wójcik and Tejchman, 2009; Tefera *et al.*, 2011). Seed storage silos are constructed using steel, wood, concrete or masonry, in circular or rectangular shapes (Vertucci and Roos, 1993; Williams *et al.*, 2014; Coradi *et al.*, 2020a). The loading and unloading systems are limited to flow and pressure distribution in the walls and in the moving seeds, thereby generating structural forces, for example, shear forces (Yang *et al.*, 2011b).

Storage environments can be airtight or semi-airtight with a modified or controlled atmosphere (Coradi *et al.*, 2020b). Hermetic storage is based on the creation of modified atmospheres that limit the presence of oxygen inside the storage structures (Coradi *et al.*, 2020d). As a result, hermetic storage achieves an improved final seed quality as compared to conventional storage systems, by reducing harmful oxidative processes and increasing seed longevity during the storage period (Hudson *et al.*, 2015; Coradi *et al.*, 2020c).

The silo bag is a form of storage that can be used to achieve an airtight seal (Cardoso *et al.*, 2014). Some studies have evaluated the modelling of the respiration rate of soybean seeds in airtight storage and concluded that the storage of seeds with a moisture content close to 12% (w.b.) was safe, while the storage of seeds with a moisture content above 12% (w.b.) resulted in a qualitative loss (Odjo *et al.*, 2020).

During storage, physical, chemical, and biological changes may occur in the seeds, depending on the relevant conditions, shape, and storage time (Krzyzanowski *et al*., 2006). Biotic and abiotic factors affect the quality of the seeds stored (McGilp *et al.*, 2020). The ambient temperature and ambient air in the storage container the temperature of the seed mass, the relative humidity of the ambient air and storage environment, and also the relative humidity of the intergranular air, in addition to the moisture content of the seeds must be monitored to control the respiratory activity of the seed mass, and minimize both quantitative and qualitative losses during storage (Demito and Afonso, 2009; Coradi *et al*., 2020d).

The technology of thermocouple sensors connected to a meteorological station and aeration exhausters has been widely used to monitor stored seeds (Fu *et al*., 2015). Currently, digital thermometry is being used with real-time information concerning the seed mass temperature, with access available from anywhere and at any time through applications.

In research carried out by some authors, in uncontrolled storage environments a greater reduction in the physiological potential of soybean seeds was observed when the initial storage period was followed by storage in a dry chamber and then a cold chamber. Variations in temperature and moisture content cause physical damage to the seeds (Flor *et al*., 2004). In view of this, it is essential to adopt methodologies that would allow for an evaluation to be carried out in an agile and efficient way, to assess the physiological quality of the seeds and, thus facilitate appropriate decision making with regard to storage and other post-harvest stages.

Image analysis has been used to determine the degree of physical damage to seeds. Some studies have concluded that image analysis would allow for the identification of external and internal mechanical damage in soybean seeds, and help to correlate them with the variables causing the damage, such as moisture and insects (Tahir *et al*., 2007; Forti *et al.*, 2010).

Storage in an artificially cooled environment slows the deterioration of soybean seeds. Some studies have evaluated the physiological quality of soybean seeds during storage for a period of six months under different temperature conditions and observed that air-conditioned environments were better for the conservation of seed quality (Zuchi *et al*., 2013; Ferreira *et al.*, 2017).

In conventional storage, the seeds are stored in bags made from different types of materials. The relationship between the storage condition and the type of packaging material used in seed packaging influences the maintenance requirements, viability, and vigour of the seeds owing to the exchange of water vapour with the ambient air (Smaniotto *et al*., 2014).

Packaging has numerous applications, such as identification, ease of transport and storage and it also serves to protect against attack by living organisms, microorganisms and environmental adversities. However, the packaging must have desirable characteristics, such as transport resistance, porosity or impermeability, flexibility and rigidity, durability and the possibility of reuse, ease of printing, transparency or opacity and resistance to insects and rodents (Bakhtavar *et al*., 2019). The packaging used in the storage of seeds may be classified according to the degree of its permeability, into permeable, semi-permeable, and impermeable (Araújo *et al*., 2017).

Permeable packages are those which allow a greater exchange of water vapour between the seeds and the atmospheric air, therefore, they are typically recommended for shorter storage times, however this packaging should preferably be located in dry places (Anankware *et al*., 2012). On the other hand, semipermeable packaging offers high resistance to water vapour exchange and therefore, the moisture content of the seeds in the initial stage of storage should be lower than recommended (Bartosik, 2012). However, waterproof packaging does not allow the exchange of water vapour the seeds and the ambient air, furthermore, it reduces the availability of oxygen inside the packaging. Soybeans are stored and transported from seed processing units to farmers in semi-permeable large raffia bags.

In these conditions, the intergranular relative humidity can change with the storage conditions, thereby causing an increase or a decrease in the moisture content until it reaches a hygroscopic balance, which can deteriorate and reduce the rate of germination and vigour of the seed lots (Kandil *et al*., 2013). Some authors verified that the use of raffia packaging with a laminated material coating maintained the physiological quality of the stored soybean seeds for longer durations.

In assessing the physiological quality of soybean-vegetable seeds, stored in different packages for a period of 360 days, the authors found that permeable packages reduced the moisture content, the rate of germination and the speed of emergence and vigour of the seeds by air temperature and relative humidity (McNair *et al*., 2012).

Studies related to the types of packaging used in soybean seeds have found that woven polypropylene packaging performed at a similar level to multi-layered paper packaging in ensuring the quality of soybean seeds during storage (Wijewardana *et al*., 2019). Some authors studied the storage of soybean seeds for 120 days in raffia bags and found that the seeds had a lower physiological potential and a high incidence of pathogens (Bell, 2014). However, other authors found that storage in a refrigerated environment is more efficient at preserving the physiological quality of soybean seeds, regardless of the type of packaging used (Chojnowski *et al*., 1997).

Temperature variations and the moisture content of the seeds and the storage environment indirectly influence the respiration of the seed mass, thus correlating negatively with the germination of the seeds (Nambara *et al.*, 2010). In a study, researchers found that moisture content and temperature were the most significant variables in increasing the respiration rate, with values ranging from 0.341 to 22.684 mg CO_2 / (kg MS^{-1}), and from 0.130 to 20.272 mg CO_2 / (kg MS^{-1}), for seeds with a moisture content of 13 and 17% stored at temperatures of 15 and 35°C, respectively (Ochandio *et al.*, 2017). Several researchers have studied the relationship between conditions, time, and storage packaging on seed quality (Table 3).

Soybean seeds are unusually sensitive to storage conditions because the levels of oils and fatty acids present in the seeds are higher than those in seeds with a higher percentage of starch, as lipids have a lower chemical stability (Coradi *et al.*, 2017). The conservation of the storage temperature to 10-15°C allows the seeds to maintain their chemical composition, germination rate, and vigour even after six months, with 95% of the seeds producing normal and vigorous seedlings (Saux *et al.*, 2020).

The seed of any vegetable product is hygroscopic, and thus has the capacity to absorb water from the air, and store and release back the same amount. In oilseeds, the water activity in storage is more intense owing to the high oil content present in the seed (Coradi *et al.*, 2017). Several studies have observed that soybean seeds stored at a temperature of 10°C maintained a hygroscopic balance with moisture levels close to ideal conditions at the end of the storage period, this is different from seeds stored in a natural environment, in which case, there would be a significant reduction in the moisture content of the seeds and as a consequence, a reduction in their physiological quality (Ziegler *et al.*, 2016).

Due to the high oil content in their composition, it is recommended that oil seeds should be stored with a moisture content of 0.5-1% below that of the grass seeds, to avoid a loss of quality owing to the intensity of the breathing processes during the time of storage (Silva *et al.*, 2018). Seeds stored with a high moisture content are vulnerable to attack by fungi and insects. The main fungi that affect the quality of soybean seeds in storage originate from *genus Aspergillus* and *Penicillium*, which can survive in environments of both low and high water activities (Nobrega *et al.*, 2019).

Insect infestation in stored seeds causes their physical deterioration along with a reduced weight of the seed mass. Among the main pest insects present in the storage of soybean seeds are *Lasioderma serricorne, Oryzaephilus surinamensi,* also *Cryptolestes ferrugineus, Ephestia kuehniella* and E. *Elutella moths* (Rathod and Pawar, 2012). To monitor and prevent the loss of stored seeds owing to the proliferation of fungi and insect infestation, the respiratory intensity of the seed mass should be determined through the measurement of CO_2 concentrations within the storage environment (Noor *et al.*, 2011).

Some studies have reported that the relationship between CO_2 concentrations in storage is proportional to the level of insect infestation, owing to the biological activity caused by the association between living organisms and stored seeds (Anwar *et al.*, 2013). However, there are other, less accurate methods that are still used to identify insect infestation in storage, such as naked eye assessment, detection probes or traps, kernel staining, uric acid, funnels, and other heat-based methods (Walters *et al.*, 2010).

Some emerging techniques have gained in popularity in recent years; these improve the accuracy of detecting seed deterioration which is caused by the storage ecosystem (Xia *et al.*, 2019). These assessments make use of PCR techniques, thermal imaging, bioacoustics analysis, electronic conductance, X-ray imaging, computed tomography, resonance imaging, near infrared spectroscopy (NIRs), electronic noses (Grudzień *et al.*, 2011; Huang *et al.*, 2014; Grudzień *et al.*, 2018). Thus, it is understood that a fusion of technological practices and the proper management of lots, together with the use of analyses with rapid responses will allow for the monitoring and conservation of soybean seeds with a higher quality in storage.

PROCESSING OF SOYBEAN SEEDS

The standardization of soybean seed lots is conducted through processing operations, wherein the seeds are classified according to their size and density (Teles *et al.*, 2013). For the processing of soybean seeds, air and sieve machines, spiral separators, and density standardizing machines are used. Figure 10 presents a layout-flowchart showing the equipment used in receiving, drying and processing seeds and also the storage units for soybean seeds.

Batches of soybean seeds are received at the processing units via hoppers or unloading bins, in this case, vibrating hoppers are recommended, with shock-absorbing systems to reduce physical and mechanical damage, and also to provide self-cleaning capabilities to reduce dust emissions and toxic gases that are harmful to employees (Kibar and Ozturk, 2008; Neves *et al.*, 2016). Subsequently, the seed lots are subjected to pre-cleaning for foreign matter and impurities in machines with air flow systems and sieve movements with different depths of drilling (Molenda *et al.*, 1998; Oksanen, 2018). The quality of the pre-cleaning operation will allow for a greater uniformity of soybean batches for drying and storage operations.

Very frequently, the soybean seed lots arrive in the processing units with moisture contents above those recommended for safe storage therefore, the batches must necessarily be subjected to drying. The drying process is considered to be a complex step that involves simultaneous heat and mass transfer, causing intrinsic changes to the seeds (Scariot *et al.*, 2017).

Ta b l e 3. Influence of storage conditions on soybean seed quality (storage time 0-12 months)

| Storage conditions	Seed quality	Reference
Raffia without and with coating	Uncoated raffia packaging and coated raffia packaging to maintain the seed quality during storage	Bakhtavar *et al.* (2019) Coradi *et al.* (2020a) Coradi *et al.* (2020b) Coradi *et al.* (2020c)
Bag without and with cooling	Artificial cooling and ambient conditions to maintain the physiological quality of soybean seeds	Nagel and Börner (2010) Anankware *et al.* (2012) Bartosik (2012) Williams *et al.* (2014) Ochandio *et al.* (2017) Bakhtavar *et al.* (2019) Coradi *et al.* (2020a) Odjo *et al.* (2020)
Paper	Permeable packaging to maintain the physiological quality of soybean seeds	Chojnowski *et al.* (1997) Bell (2014) Hartmann Filho *et al.* (2016) Coradi *et al.* (2017) Nobrega *et al.* (2019)
Polyethylene	Waterproof packaging to maintain the physiological quality of soybean seeds	Forti *et al.* (2010) Noor *et al.* (2011) Kandil *et al.* (2013) Groot *et al.* (2015) Araújo *et al.* (2017)
Silo	Silo aeration to maintain the physiological quality of soybean seeds	Sorour and Uchino (2004b) Tefera *et al.* (2011) Atungulu and Olatunde (2018) Krzyzanowski *et al.* (2019) Coradi *et al.* (2020d)

Drying causes a reduction in the moisture content of the seeds, and consequently a reduction in the metabolism of the seed and deterioration over the storage time. Soybean seed dryers may be continuous, static, or intermittent systems (Coradi *et al.*, 2020e). Monitoring drying temperatures and seed mass is essential to achieving operational performance and reducing the physical, mechanical and latent damage to the seeds (Konopatzki *et al.*, 2019).

After drying, the seed lots follow the flow process to the cleaning stage. The cleaning of the seed mass is carried out by air machines and sieves, which aim to increase the physical purity of the seeds, thereby separating the seeds based on their size and specific mass.

The air machine and sieves must have provision for adequate and continuous feeding by batches of seeds, furthermore, the seeds should be evenly distributed over the sieves. The use of flat sieves limits the classification of soybean seeds. Therefore, an adequate adjustment of the inclination and cleaning of the sieve is performed to increase the quality of separation and classification of the seeds (Molenda *et al.*, 2004; Coradi *et al.*, 2020c).

Subsequently, the soybean seeds pass through a spiral classification system. This equipment allows for the movement of seeds by gravity, and separates them in terms of shape, density, and sphericity. Spherical seeds with good quality reach a higher speed, and are thrown to the external spirals by gravity, irregular seeds, on the other hand, move at lower speeds and remain in the internal spiral. After that, the soybean seeds are classified in terms of their width in 0.5 mm intervals. The separation of seeds by width contributes to an improved sowing precision and plays a role in avoiding the occurrence of seedling failures in the crop (Konopatzki *et al.*, 2019).
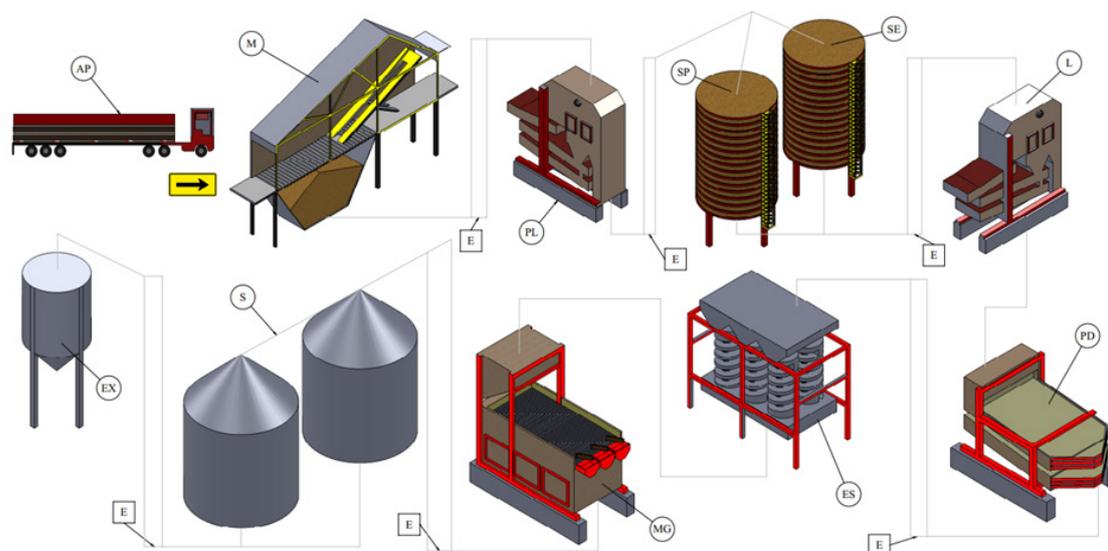
Fig. 10. Layout and flowchart of a soybean seed receiving, drying, processing, and storage unit: AP – Sampling and procedures, M – Hopper, PL – Pre-cleaning, SP – Lung silo, SE – Dryer, L – cleaning, PD – Standardizing, ES – Spiral, MG – Gravity table, S – Storage silos, EX – Expedition, E – Elevator.

Finally, in the beneficiation stage, the seed lots are subjected to density separation on a gravity table, in order to standardize the seeds based on their specific mass. In this case, lighter seeds are influenced by an air flow, while the heavier ones remain in direct contact with the surface of the separation table in the lower part of the discharge zone of the densimetric table. The seeds processed in the low zone of the gravity table are of compromised physiological quality and must be discarded from the batch (Coradi *et al.*, 2020a).

The improvement of the seed lots is related to the vigour of the seeds. Soybean seeds with a lower vigour achieve a low stratification compared to other lots in the initial stages of processing, in contrast to the seeds benefited by the gravity table (Vitis *et al.*, 2020). According to the same authors, fungal contamination during storage was lower in the seeds submitted for separation until the densimetric stage (Anwar *et al.*, 2013), from which it may be inferred that there is a relationship between the specific mass and the incidence of pathogens in the seeds, this is because the infected seeds, in addition to low density, showed a reduction in germination rate and vigour (Ebone *et al.*, 2020). In order to obtain seeds with a high quality, processing is essential.

Different stages of beneficiation seek to improve the physical characteristics of the seed lots, since as the appropriate physiological quality is only maintained according to the production conditions in the crop (Krzyzanowski *et al.*, 2019). Therefore, it may be said that seeds have a dual function in economically important cultures, (i) as a source material used for the multiplication of plants and (ii) as a food source harvested for commercial purposes.

In general terms, seed quality is defined as the sum of the genetic, physiological, physical and health attributes that determine their ability to produce plants with a high degree of productivity. These attributes may be a reflection of the quality of plant care implemented during the production process in the field, namely during harvesting, drying, processing, and storage (McDonald, 1998).

A seed lot must have certain physical and physiological characteristics that allow for the establishment of an adequate population of plants (Midorikawa *et al.*, 2014). Therefore, the equipment used to process the seeds needs to be well-designed and regulated, as they are essential for the production of good results. The adjustments made to the air and sieve machine are related to their functions of feeding, air speed, vibration, inclination, the selection of sieves and cleaning.

The appropriate adjustment of the feed as well as the feed rate to the machine must be constant and continuous, as a basic rule, and the seeds must be distributed uniformly in the sieves, as a layer of approximately two cm in height. The air inlet speed of the seeds into the machine must be less than that at the outlet, and a good arrangement is one in which some desirable seeds emerge with light materials. The vibration of the sieves must be low to avoid a rapid passage of the seeds, and the inclination of the first sieve must be less than that of the second so that the seeds have a greater time of contact through the holes (Peres *et al.*, 2012).

The adjustments made on the gravity table are related to the flow of the seed mass, the lateral and longitudinal inclinations, air flow, the vibration of the table and the frac-

tionation of the load terminal axis. The flow of the seed mass in the gravity table should vary by between 2 and 4 cm, and the seed layer and the distribution must also be uniform.

The lateral inclination must be such that it makes it difficult for the seeds to rise, otherwise, owing to vibration, all of the seeds tend to discharge at the highest part of the table. On the other hand, a very low degree of inclination may cause the seeds with a greater weight to be discharged to the lowest part of the table. The longitudinal slope is used to a very limited extent, it only serves to increase or decrease the flow of the seed in the gravity table (Pinto *et al.*, 2007).

The separation of light, intermediate and heavy seeds on the gravity table is conducted by air, the seeds with the highest specific mass remain in contact with the base, while the lighter seeds float. A high flow of air interferes with the stratification of the seeds, mixing the light and heavy seeds. The vibration of the gravity table in the direction transverse to the flow of the seeds causes the heavy ones to be carried to the terminal part of the table. This vibration cannot be too high or too low, to avoid unloading the seeds in inappropriate parts of the table. The appropriate adjustment of the table should provide at least 7% of the volumetric weight difference between the high and the low fractions of the table (Moreano *et al.*, 2018).

It is important to note that the beneficiation stage can also cause physical and mechanical damage to the seeds, which indicates that, during this stage, the seeds may lose their germination viability and as a consequence, their capacity to produce normal plants would be reduced owing to the mechanical injuries caused by seed shocks and abrasions against hard mechanical surfaces or other seeds (Pinto *et al.*, 2007). Mechanical damage may be a factor that explains the loss of quality in soybean seeds during processing, as mechanical injury is caused by contact between the seeds and rigid surfaces, which may cause breaks, cracks and scratches (Carvalho *et al.*, 2016). It is important to point out that the embryos of the soybean seeds are exposed, and become susceptible to mechanical injuries caused by other external agents, this means that the seeds might suffer from mechanical damage during the processing stages (Salimi and Boelt, 2019).

The recommended rapid tests to determine the incidence of mechanical damage to the seeds are the electrical conductivity test, sodium hypochlorite test and tetrazolium test (Prado *et al.*, 2019). Several authors have carried out works on the processing processes and their effects on seed quality. These studies were based on improving the efficiency of the processing line in order to optimize the processes and flow planning. The scientific research focused on the effects of these parameters on the quality of soybean seed, the data collected throughout the processes, shows that handling and transportation operations in the processing line decreased physiological quality (Chormule *et al.*, 2018). Among the most current research work, it was observed that the vigour

of the soybean cultivar BMX Poder RR produced differences in the physiological quality of the seeds between the processing stages of the soybean during the processing and storage periods (Mbofung *et al.*, 2013).

REAL-TIME MONITORING, THE INTERNET OF THINGS (IOT) AND MACHINE LEARNING (ML) TO PREDICT SEED QUALITY DURING POSTHARVEST STAGES

Monitoring indirect qualitative variables produced favourable results in terms of the conservation of seed quality during transport, drying and storage operations. The use of temperature and relative humidity sensors to determine the equilibrium moisture content of the seeds with intergranular air, as well as the monitoring of the carbon dioxide concentration to measure the respiration of the seed mass are alternatives used to predict and control seed quality during post-harvest phases.

In addition, the use of the Internet of Things (IoT) on postharvest processes has contributed to the creation of databases and intelligent decision making in a computational environment (Aghbashlo *et al.*, 2015; Jilani *et al.*, 2019). Based on the IoT, technologies with digital platforms provide information concerning seed conditions and risk prevention caused by operational failures, this is accomplished through monitoring using high precision sensors that can be used to evaluate individual items of equipment, or an entire drying unit either individually or remotely (Bai *et al.*, 2018). The communication between technologies and synchronization with servers means that losses during postharvest processes are minimized and, at the end of the process, high-quality seeds are obtained (Lheonye *et al.*, 2020). Figure 11 shows a monitoring system using sensors and computer technologies to control post-harvest processes and predict the quality of the soybean seeds.

Thus, in order to predict seed quality based on easily monitored variables, Machine Leaning models can be applied: Artificial Neural Network (ANN), decision tree algorithms REPTree and M5P, Random Forest (RF). Figure 12 is a flowchart model applied to predict the quality of the soybean seeds at the storage stage. The ANN tested consists of a single hidden layer formed by a number of neurons that is equal to the number of attributes plus the number of classes, all divided by 2 (Egmont-Petersen *et al.*, 2012). The REPTree model is an adaptation of the C4.5 classifier that can be used in regression problems with an additional pruning step based on an error reduction strategy (Snousy *et al.*, 2011). The M5P model is a reconstruction of Quinlan's M5 algorithm based on a conventional decision tree with the addition of a linear regression function to the leaf nodes (Blaifi *et al.*, 2018). The RF model can produce several prediction trees for the same data set and uses a voting scheme among all of the learning trees to predict new values (Belgiu and Drăguţ, 2016).
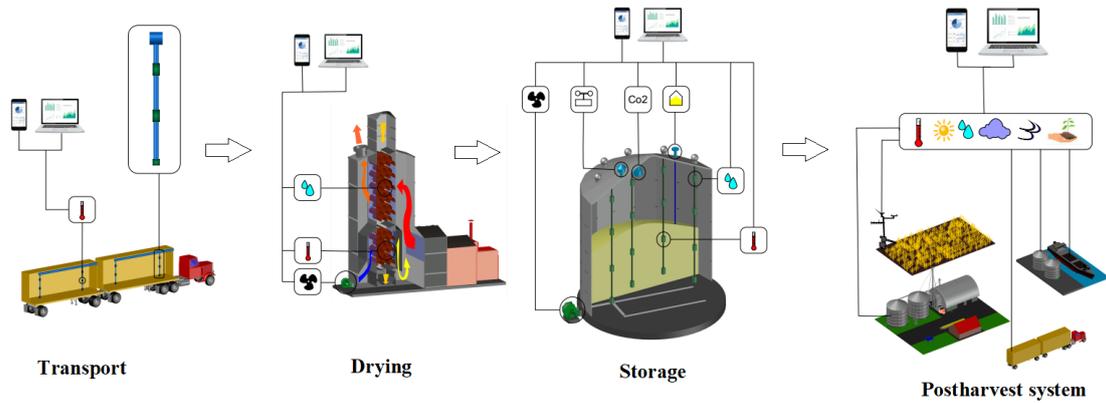
L.B.A. JAQUES *et al.*

Fig. 11. Application of a real-time monitoring system to the post-harvest processes, using sensors and computer technology.
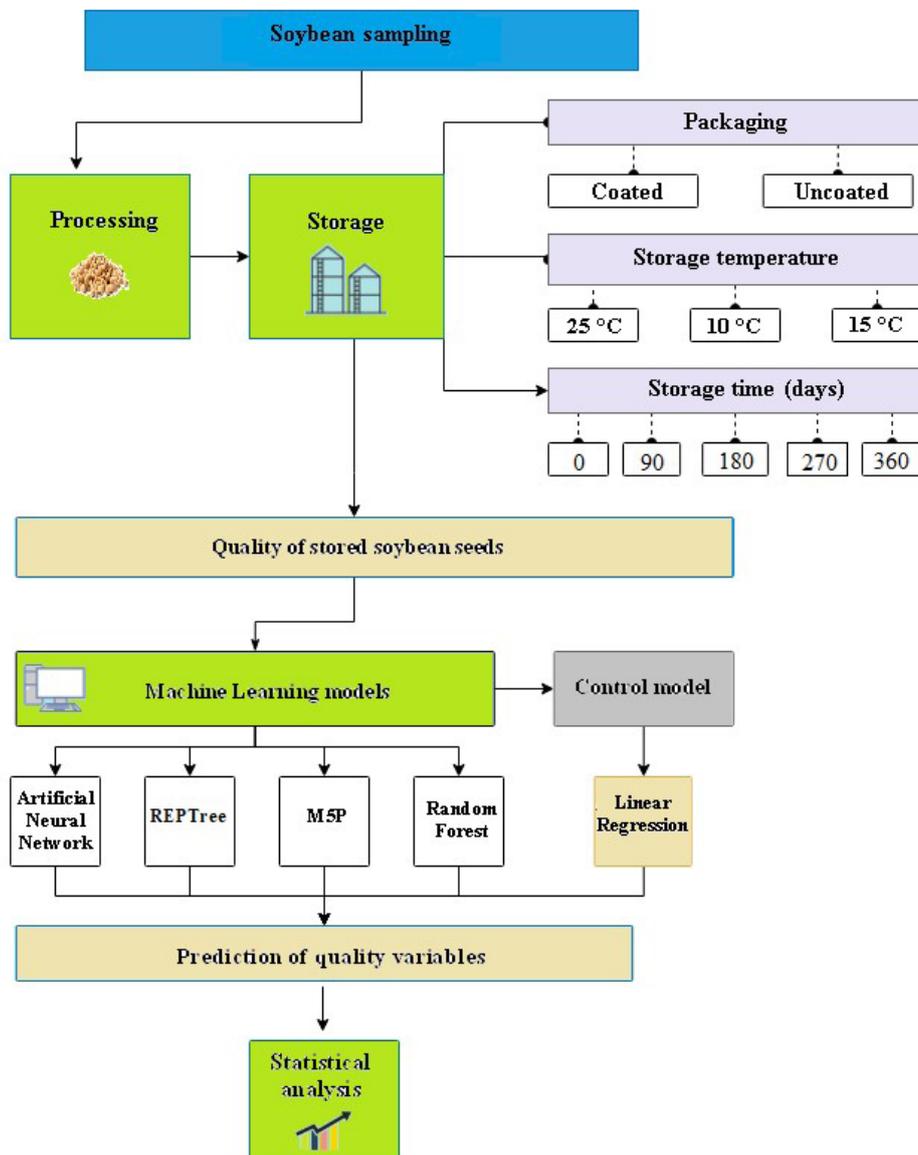

Fig. 12. Demonstration flowchart of the application of Machine Learning algorithms to predict the soybean seed quality on the storage.

CONCLUSIONS

The advances made to date through scientific studies concerning the post-harvesting of soybean seeds have improved the technological aspects of the sector, thus contributing to a reduction in losses in terms of seed quality and increasing the productive potential of the soybean culture. The technologies used in the drying and processing of soybeans as well as the storage equipment associated with new techniques of analysis and the monitoring of the quality of the seeds in accordance with certain requirements in terms of the physical-chemical and physiological attributes of the biological material has enhanced the production of soy in several regions.

In drying systems, temperatures of up to 40 °C are recommended, while seed batches must remain static in drying chambers so that the air flow passes through the seed layer, thus largely determining the physical, mechanical and latent damage accruing in the process. While processing and standardizing seeds, it is recommended that low-moving equipment and abrupt contacts with mechanical systems, such as pneumatic and gravity separators, be employed to minimize dropping and contact between seeds

While some soy producing countries have favourable climatic conditions for maintaining the physiological quality of seeds for a longer period, in other countries certain measures (temperature and relative use) cannot be avoided, they are implemented to ensure that the seeds maintain a favourable germination rate until sowing.

Therefore, it is imperative to find solutions that can assist in the control of storage conditions, and increase our understanding of quality standards. With regard to soybean storage, the application of environment control technologies that can be used to control the temperature and relative humidity are recommended. The maintenance of the storage moisture content in a hygroscopic balance, artificial cooling, a controlled and modified atmosphere and finally, coated bags are also recommended, especially in airtight systems, bags, and airtight containers.

Commercially, soybean seeds are stored and transported from processing units to agricultural producers in bags called "big bags". Although the seeds are stored in favourable environments and/or refrigerated in processing units, when they are transported from a rural producer, they could be exposed to natural environments, without a relative temperature control. The storage of seeds in coated big bags has resulted in the need for artificial cooling and the preservation of the seeds after their dispatch from the processing units until sowing.

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