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Roney Eloy Lima

SECAGEM E ARMAZENAGEM DE GRÃOS DE SOJA: EFEITOS SOBRE A QUALIDADE FÍSICA E FÍSICO-QUÍMICA, MODELAGEM E PREDIÇÃO

Santa Maria, RS
2024

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Tese de doutorado apresentada ao Programa de Pós-Graduação em Engenharia Agrícola, da Universidade Federal de Santa Maria, como requisito para obtenção do título de **Doutor em Engenharia Agrícola.**

Orientador: Prof. Dr. Paulo Carteri Coradi

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Muito obrigado!

Sem sonhos, a vida não tem brilho.

Sem metas, os sonhos não tem alicerces.

Sem prioridades, os sonhos não se tornam reais.

Sonhe, trace metas, estabeleça prioridades e corra riscos para executar seus sonhos.

Melhor é errar por tentar do que errar por se omitir.

Augusto Cury.

RESUMO

SECAGEM E ARMAZENAGEM DE GRÃOS DE SOJA: EFEITOS SOBRE A QUALIDADE FÍSICA E FÍSICO-QUÍMICA, MODELAGEM E PREDIÇÃO

AUTOR: Roney Eloy Lima
ORIENTADOR: Prof. Dr. Paulo Carteri Coradi

As perdas quanti-qualitativas de grãos na pós-colheita trazem um desequilíbrio no setor produtivo de grãos. Para reduzir as perdas é fundamental que a massa de grãos passe por processos de limpeza e secagem, para ser armazenada com baixos teores de água e impurezas. A heterogeneidade dos lotes de grãos colhidos no início e no fim da colheita também pode alterar a capacidade e a uniformidade dos processos. Assim, o objetivo geral do estudo foi avaliar diferentes tecnologias e manejos na pós-colheita da soja, a partir da colheita dos grãos com teores de água mais elevados, associados às condições e tecnologias de secagem e armazenamento e aos efeitos sobre a qualidade física e físico-química dos grãos. Especificamente objetivou-se: 1) avaliar diferentes tecnologias de secagem e armazenamento sobre as perdas de qualidade na soja; 2) avaliar os efeitos das operações de armazenamento e armazenamento na qualidade da soja processada; 3) verificar a utilização de modelos matemáticos e análises multivariadas para avaliar a relação da antecipação da colheita da soja com as condições de secagem e armazenamento e às influências sobre a qualidade físico-química dos grãos; 4) analisar a predição da qualidade dos grãos de soja nas diferentes tecnologias de secagem e armazenamento, em escala real, usando modelos de Aprendizado de Máquina. Entre os resultados obtidos, observou-se que: 1) o manejo da massa de grãos em silos-secadores e secadores contínuos reduziram as perdas e garantiram uma melhor qualidade dos grãos; 2) as perdas de qualidade dos grãos em função do manejo da secagem variaram de 0,23 a 3,26% em proteína bruta e de 0,15 a 3,05% no rendimento de óleo bruto. O gerenciando da secagem com secador contínuo + silo-secador-CDSD2, secador contínuo + silo-aerador-CDAS3 é uma alternativa para redução de perdas e conservação da qualidade dos grãos, melhorando o rendimento em relação aos teores de proteínas e óleo brutos extraídos em até 95%; 3) a colheita antecipada com teores de água acima de 23% e a adoção de sistemas de secagem com temperatura do ar de 80 °C em ambientes com temperaturas abaixo de 23 °C conservaram a qualidade físico-química dos grãos; 4) os grãos submetidos à secagem e armazenamento em silos-secadores mantiveram a melhor qualidade ao final do processo. Embora tenha havido diferenças relacionadas à tecnologia de secagem e armazenamento em relação às alterações na qualidade dos grãos, percebeu-se que o modelo de Redes Neurais Artificiais demonstrou desempenho superior na predição da qualidade dos grãos. O modelo de Redes Neurais Artificiais foi unanimidade em todos os processos e tecnologias avaliados. Assim, recomenda-se realizar a secagem pós-colheita da soja e posterior armazenamento dos grãos em silos-secadores, monitorando variáveis ambientais e intergranulares. Recomenda-se que esta abordagem seja associada à utilização de modelos de Redes Neurais Artificiais para prever perdas com maior eficiência nas etapas de secagem e armazenamento.

Palavras-chave: Monitoramento e qualidade de grãos de soja. Pré-processamento e armazenamento de soja. Processamento industrial da soja. Tecnologia pós-colheita.

ABSTRACT

DRYING AND STORAGE OF SOYBEANS: EFFECTS ON PHYSICAL AND PHYSICAL-CHEMICAL QUALITY, MODELING AND PREDICTION

AUTHOR: Roney Eloy Lima
ADVISOR: Prof. Dr. Paulo Carteri Coradi

The quantitative and qualitative losses of post-harvest grains bring an imbalance in the grain production sector. To reduce losses, it is essential that the grain mass goes through cleaning and drying processes, to be stored with low levels of water and impurities. The heterogeneity of the batches of grains harvested at the beginning and end of the harvest can also alter the capacity and uniformity of the processes. Thus, the general objective of the study was to evaluate different technologies and management in the post-harvest of soybeans, based on the harvesting of grains with higher water contents, associated with drying and storage conditions and technologies and the effects on physical and physical chemistry of grains. Specifically, the objective was: 1) to evaluate different drying and storage technologies on quality losses in soybeans; 2) evaluate the effects of storage and storage operations on the quality of processed soybeans; 3) verify the use of mathematical models and multivariate analyzes to evaluate the relationship between the anticipation of the soybean harvest and the drying and storage conditions and the influences on the physical-chemical quality of the grains; 4) analyze the prediction of the quality of soybeans in different drying and storage technologies, on a real scale, using Machine Learning models. Among the results obtained, it was observed that: 1) the management of the grain mass in drying silos and continuous dryers reduced losses and guaranteed better grain quality; 2) grain quality losses due to drying management ranged from 0.23 to 3.26% in crude protein and from 0.15 to 3.05% in crude oil yield. Managing drying with a continuous dryer + silo-dryer-CDSD2, continuous dryer + silo-aerator-CDAS3 is an alternative for reducing losses and conserving grain quality, improving yield in relation to the protein and crude oil contents extracted in up to 95%; 3) early harvesting with water content above 23% and the adoption of drying systems with an air temperature of 80 °C in environments with temperatures below 23 °C preserved the physical-chemical quality of the grains; 4) the grains subjected to drying and storage in drying silos maintained the better quality at the end of the process. Although there were differences related to drying and storage technology in relation to changes in grain quality, it was noted that the Artificial Neural Networks model demonstrated superior performance in predicting grain quality. The Artificial Neural Networks model was unanimous in all processes and technologies evaluated. Therefore, it is recommended to carry out post-harvest drying of soybeans and subsequent storage of grains in drying silos, monitoring environmental and intergranular variables. It is recommended that this approach be associated with the use of Artificial Neural Network models to predict losses with greater efficiency in the drying and storage stages.

Keywords: Monitoring and quality of soybeans. Pre-processing and storage of soybeans. Industrial soybean processing. Post-harvest technology.

SUMÁRIO

1. Introdução geral

A produção de soja ocorre em épocas específicas do ano, dependendo da região. A antecipação da colheita da soja pode contribuir no fluxo e no rendimento dos processos pós-colheita. Além disto, a colheita precoce da cultura pode reduzir os efeitos adversos das condições climáticas de campo, para obter grãos de melhor qualidade na pós-colheita. Para que as indústrias processadoras funcionem o ano todo, a soja deve ser adequadamente armazenada para suprir a demanda industrial. Mas, para realizar o armazenamento seguro dos grãos, os teores de água devem estar próximos a 12%. Sendo assim, é fundamental que os lotes de grãos sejam submetidos à secagem artificial.

Por outro lado, a eficiência da operação depende das tecnologias utilizadas e do manuseio da massa de grãos. Na secagem, há possibilidade de utilizar equipamentos estáticos, contínuos ou intermitentes, distinguindo-se em relação ao fluxo da massa de grãos, do ar e da temperatura de secagem empregada. No armazenamento, o ambiente determina a atividade de todos os componentes bióticos do sistema, o que leva ao armazenamento seguro ou à perda do produto. Durante o armazenamento, também ocorrem alterações nas propriedades físico-químicas e tecnológicas da soja. As mudanças estão relacionadas ao tempo de armazenamento, associado à temperatura e teor de água dos grãos.

Para obter fluxo dos lotes de grãos na safra nas unidades armazenadoras, a antecipação do período de colheita da soja e a adoção de sistema associados de secagem e armazenagem, pode ajudar a melhorar a eficiência nos processos de pós-colheita e também a qualidade dos grãos. Neste sentido, devido às complexidades experimentais, para auxiliar nas tomadas de decisões aplica-se a análise estatística multivariada, modelagem matemática e computacional para predição dos efeitos dos processos sobre a eficiência e a qualidade de grãos.

2. Hipóteses científicas

- A colheita precoce da soja com teores de agua mais elevados pode reduzir os efeitos adversos das condições climáticas de campo e resultar em grãos de melhor qualidade após as operações de secagem e armazenamento.
- A secagem artificial a altas temperaturas possibilita maior fluxo da massa de grãos nas unidades armazenadoras, porém afeta qualidade final do produto. Enquanto que, a secagem artificial a baixas temperaturas reduz o fluxo dos lotes de grãos nas unidades armazenadores, porém resulta em grãos de melhor qualidade.

- O tempo e as condições de armazenamento em estruturas semiabertas, em embalagens porosas e com temperaturas próximas do ambiente natural influenciam negativamente sobre a qualidade dos grãos. Já o armazenamento em ambientes à baixas temperaturas mantém a qualidade dos grãos por mais tempo.
- A otimização da secagem e a armazenagem em sistemas combinados pode aumentar o fluxo e a qualidade dos grãos pós-colheita.

3. Objetivos

3.1 Objetivo geral

O objetivo geral do estudo foi avaliar diferentes tecnologias e manejos na pós-colheita da soja, a partir da colheita dos grãos com teores de água mais elevados, associadas às condições e tecnologias de secagem e armazenamento e os efeitos sobre a qualidade física e físico-química dos grãos.

3.2 Objetivos específicos

- Avaliar diferentes tecnologias de secagem e armazenamento sobre as perdas de qualidade na soja
- Avaliar os efeitos das operações de secagem e armazenamento na qualidade da soja processada
- Utilização da modelagem matemática e análises multivariadas para avaliação da antecipação da colheita da soja associadas às condições de secagem e armazenamento e as influências sobre a qualidade físico-química dos grãos
- Analisar a predição da qualidade do grão de soja nas diferentes tecnologias de secagem e armazenamento em escala real usando modelos de Machine Learning

CHAPTER 1

(Paper published on the Journal of Food Process Engineering)

Postharvest engineering: effects of drying and storage operations on the quality of processed soybeans

Abstract: Sustainable production involves adapting processes and reducing losses in the post-harvest, processing, and industrialization stages of soybean. Currently, the scientific literature has a range of studies that address post-harvest losses and the technologies and procedures necessary to manage these processes. However, there is a knowledge gap about the approach to soybean and the entire production chain that involves it. This review established a detailed and comprehensive study of soybean post-harvest processes, with a broad discussion on the performance of different techniques and technologies applied during the drying, storage, and processing dynamics of the soybean.

Keywords: agricultural engineering, food security, soybean post-harvest engineering, soybean pre-processing, soybean post-harvest losses and quality.

Practical applications

The post-harvest stages aim the conservation of the grains quality and the reduction of losses, constituting a link between the primary production sector, industry, and the consumer market, with important participation in the logistics of the production chain. In this review, the current scenario of post-harvest and soybean processing was characterized, based on a survey of scientific studies that demonstrated the technological evolution in the area and the advances necessary to achieve maximum efficiency in the sector. The review conducted indicated the possibilities for further studies and decision-making in research in post-harvest and processing engineering and the updated adoption of control parameters applied to the industry.

1. Introduction

Due to the increase in the world population, there is a necessity for higher production of food in the world. Estimates reveal that an increase of up to 70% in food production is necessary in the coming years to satisfy future demands (Kumar & Kalita, 2017). Therefore, food distribution and food security are essential to compensate the population food requirements (Asselt, Fels-Klerx, Marvin, Veen & Groot, 2017). It is perceptible the effort of many countries to reach high levels of production and to satisfy a demand that has grown significantly over the years. However, quantitative and qualitative losses are notably verified throughout the grain production chain (Stathers et al., 2020).

Post-harvest losses (PHL) can be defined as the reduction in the amount of food produced along the stages of the food chain (Bendinelli, Su, Péra & Caixeta Filho, 2020; Kumar & Kalita, 2017). Furthermore, it is estimated that approximately 1/3 of all food produced is lost or wasted every year. On the other hand, about 160 million tons of grains are lost annually, considering the harvesting processes, and more than 210 million tons during the post-harvesting processes. In this context, this scenario highlights the necessity for actions aimed at reducing losses and waste throughout the food production chain (Barrera & Hertel, 2020; Mesterházy, Oláh & Popp, 2020).

Among the biggest challenges to minimize these losses, the insufficient infrastructure, the lack of technologies for the distribution of products, and the unavailability of a satisfactory marketing system are key points that demand attention (Henz, 2017; (Pohndorf, Meneghetti, Paiva, Oliveira & Elias, 2018). Additionally, the post-harvest process, such as drying, storage, processing, and transportation, interfere considerably with the quality of these products (Chen, Wu, Shan & Zang, 2018; Coradi et al., 2021; Kumar & Kalita, 2017). The alterations in drying and storage conditions can accelerate the grains metabolic processes and effect the physical and physicochemical stability of the grains (Bowkaew & Prasertsan, 2020; Coradi et al., 2020a; Graf et al., 2015; Henning et al., 2010).

Consequently, limiting post-harvest food losses and losses in the quality of grains is a major challenge to ensure food security and minimize costs in the production process (Kasso & Bekele, 2018). Accordingly, operational strategies aimed at optimizing conditions along the supply chain play a fundamental role for the potentialization of the grain production and minimizing quantitative and qualitative losses throughout the production chain (Galford et al., 2020). Thus, this paper reviewed the main results on the effects of drying and storage conditions on the quality of processed soybean. Therefore, we review the main methods of drying and storing soybeans and the factors that must be controlled by the industry. The results of the studies were presented and discussed in detail in this review, which had the following specific objectives: a) present and discuss the effects of drying conditions on the soybean quality; b) present and discuss the effects of storage conditions on the soybean quality; c) present and discuss the effects of the soybean processing: soybean bioproducts quality, biodiesel and vegetable oils production, soybean oil extraction procedures, soybean bioproducts for food production; d) present and discuss technological perspectives for the soybean bioproducts quality; e) case study on soybean postharvest in Brazil.

2. Current soybean postharvest scenario

Logistics in the soybean post-harvest process includes the transport of materials from the field to the industrial segments aimed at feedstocks processing (Nourbakhsh, Bai, Maia, Ouyang & Rodriguez, 2016; Sangkram & Noomhorm, 2002). The aggravation of failures in the logistics of the process contributes to maximize post-harvest losses, caused mainly by factors such as poor road infrastructure, products without the required standard, and the inadequate period and conditions of grain storage (Péra & Caixeta Filho, 2018).

The soybean production chain encloses different stages aimed at transporting the grains to storage systems and units, industries focused on the oil and grain derivate extraction, expedition to refineries, and the final product marketing and transfer (Oliveira, Resende, Smaniotto, Siqueira & José Neto, 2013; Tres, Nobrega, Carvalho, Oliveira & Di Luccio, 2012). Figure 1 presents a flowchart for the different soybean post-harvest logistic process stages and shows how the stages are closely interconnected. From the process logistic structure, it is possible to reach the quality of the products from the harvest to the final stages of the processing chain.

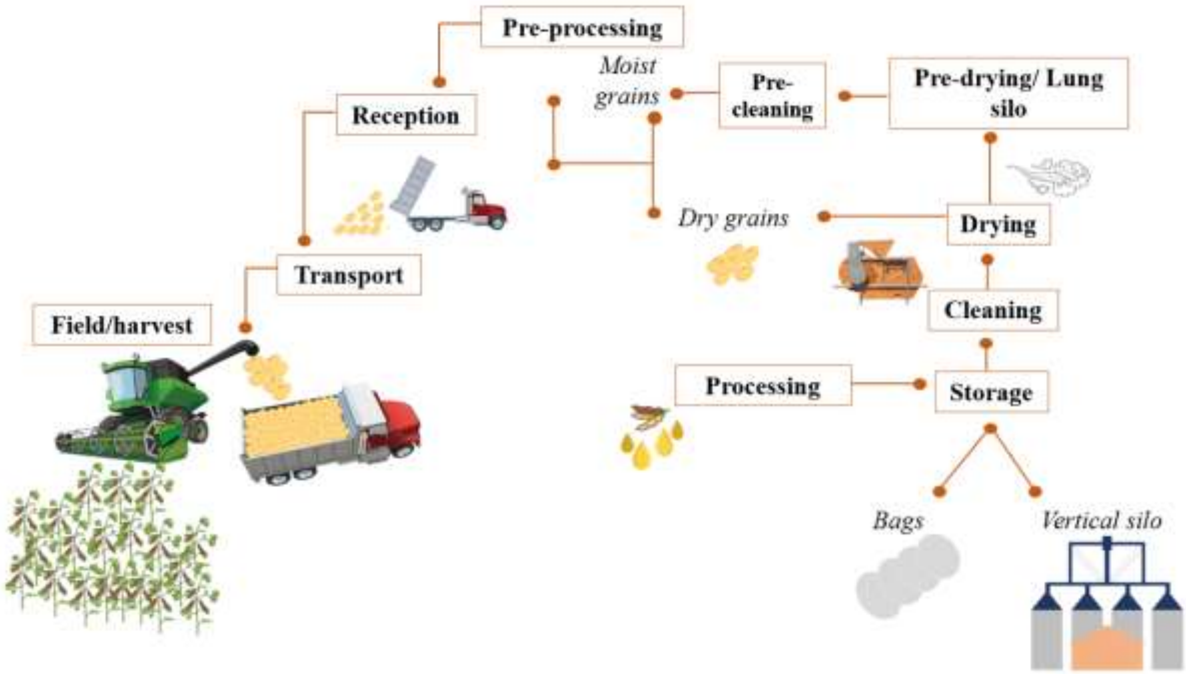

Figure 1. Structural diagram of the main processes related to post-harvest during soybean processing.

3. Drying technology

In post-harvest processes, drying is characterized as the process of reducing the grain initial moisture content to levels where the microorganisms proliferation and damage and chemical reactions of a degradative character are inhibited (Hashemi, Moosavi, Asadi-Yousefabad, Omidi, & Khaneghah, 2020).

Essentially, the ideal grain moisture content for the commercialization and storage is between 13 and 15.5%, varying according to the agricultural product type and the storage conditions and time (Coradi, Fernandes & Helmich, 2016; Martinez-Feria et al., 2019). High moisture levels drastically affect the grain physicochemical and morphological properties, such as the acidity content and the extracted oil quality (Ziegler et al., 2016a). The soybean grain drying at high temperatures causes rupture in the grain structure, favoring fungi infection and increasing the conversion of important chemical elements into undesirable products (Ferreira et al., 2019; Ziegler et al., 2016b). At high initial moisture contents and high temperatures, there is an intensified grain respiration, causing significant quality losses (Coradi et al., 2020b).

Considering the drying processes enhancement to optimize the grain moisture content reduction, conventional methods, such as natural drying, have not been widely portrayed in scientific studies. As a result, the development of automated drying systems has been an excellent alternative to antiquated alternatives (Figure 2).

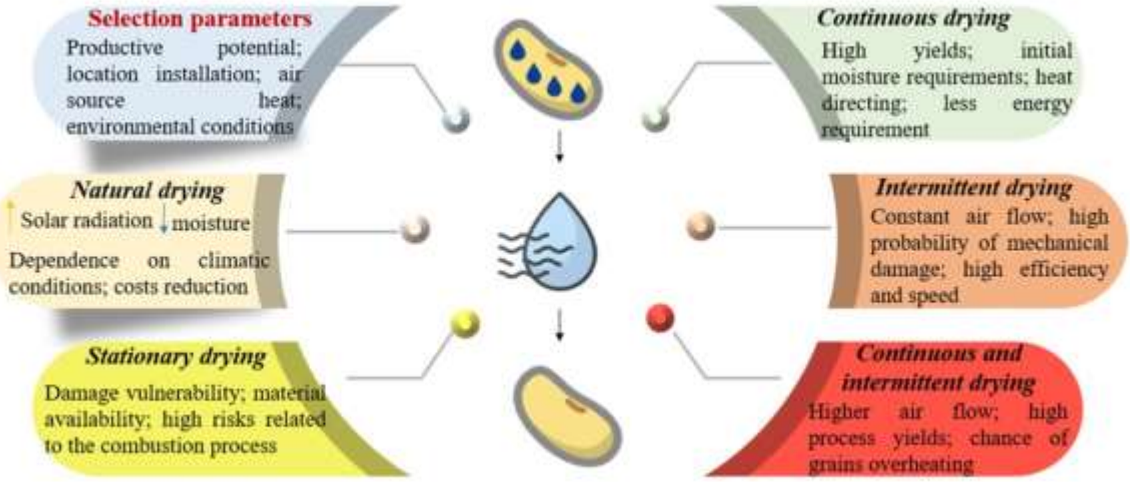

Figure 2. Variables considered for the development of the drying stage and the main types of drying applied to soybean grains.

The continuous drying process that uses natural draft air is characterized as a highly efficient and economically viable method, covering different interconnected stages (Figure 3).

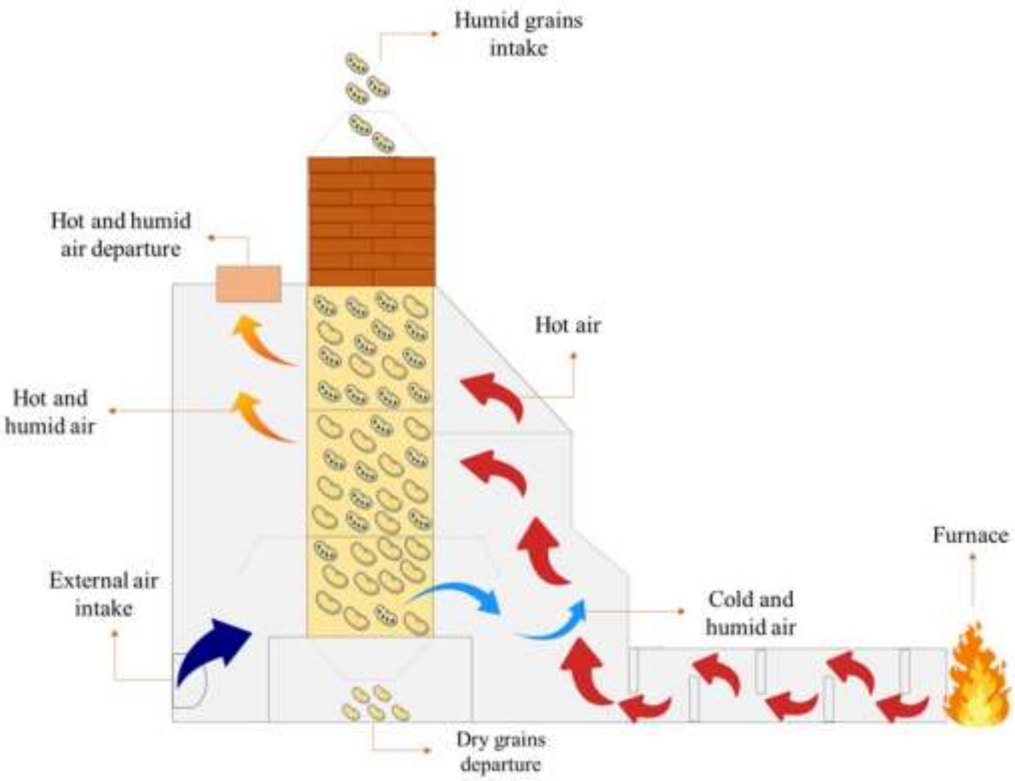

Figure 3. Operating dynamics and main flows of the continuous drying process applied to soybean grains.

The hot air, which comes from artificial heating, is directed to the drying chambers loaded with moist grains that move continuously. Subsequently, the grains are submitted to the cooling chamber (environmental temperature), in the silo lower portion, so that moisture is not reabsorbed. Since there is an increase in temperature and the grain moisture content removal, many processes consider reusing part of the hot air, especially for energy maximization and cost reduction (Stanescu & Risso, 2016).

Additionally, alternatives have been widely explored with the purpose of reducing costs and optimizing the process, mainly due to the energy expenditure and duration of the process. In this context, intermittent flow drying promotes higher grain drying process efficiency, minimizing the energy requirement and optimizing the procedure duration without grain quality loss (Defendi, Paraíso & Jorge, 2017).

Intermittent flow drying is characterized by prolonged contact between heated air and grains, without the movement of these materials (Figure 4). Furthermore, in certain periods, the grains are submitted to the equalization chamber, in which there is no contact with hot air, to redistribute the grain moisture content and to benefit from the moisture elimination during the process (Garcia, Barros, Peske & Menezes, 2004).

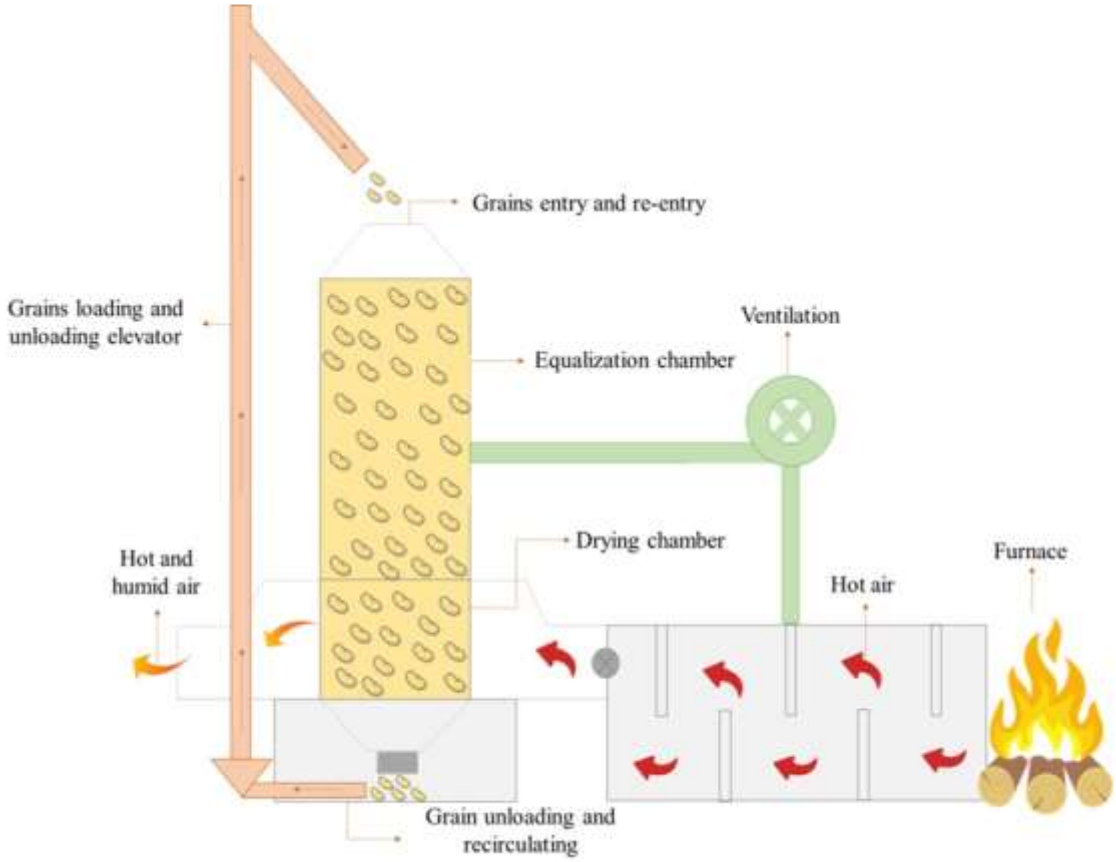

Figure 4. Operating dynamics and main flows of the intermittent drying process applied to soybean grains.

In soybean grains, the drying intermittency, combined with temperatures below 40 ºC, minimizes physical damage to the products, mainly by reducing the grain thermal and moisture stress (Jung & Yoon, 2018). Moreover, a study showed that the application of intermittence at a drying temperature of 70 ºC reduces the process energy consumption by approximately 46% (Bissaro et al., 2020). Consequently, other process variables, such as drying time, are determining factors for the process performance. A study showed that in a period of 600 minutes, the increase in intermittence caused the grain moisture content loss at 6.57% (Park & Yoon, 2019).

However, the integration and aggregation of technologies have been an excellent strategy for obtaining high yields and high-quality grains. Some studies show that to improve grain flow and quality in full-scale storage units, the combined system of using a continuous dryer, silo-dryer, intermittent, and dry aeration storage was highly efficient (Coradi, Dubal, Bilhalva, Fontoura & Teodoro, 2020d). According to Wrigley, Corke, Seetharaman & Faubion (2016) in post-harvest engineering, the combination of preservation means, intervention tools and physical methods plays an important role in grain processing.

4. Soybean drying and grain quality

The drying process comprises the gradual elimination of moisture from grains through the simultaneous transfer of heat from the air to the grains and mass transfer of water vapor to the environment (Siqueira, Resende & Chaves, 2014). Consequently, in the wet grain mass, water vapor is conducted to occupy all intercellular spaces, causing pressure in all directions (Coradi, Melo & Rocha, 2014; Coradi, Lima, Alves, Teodoro & Cândido, 2020e).

The Figure 5 shows the drying soybean grains. The water vapor flow occurs from the highest to the lowest vapor pressure, with gradual withdrawal of moisture by the heat transfer process. The use of drying air temperatures below average ambient conditions minimizes damage to the grain cellular structure. However, it may cause the grains hygroscopic balance with air before reaching the desired moisture content for storage (Hartmann Filho et al., 2016).

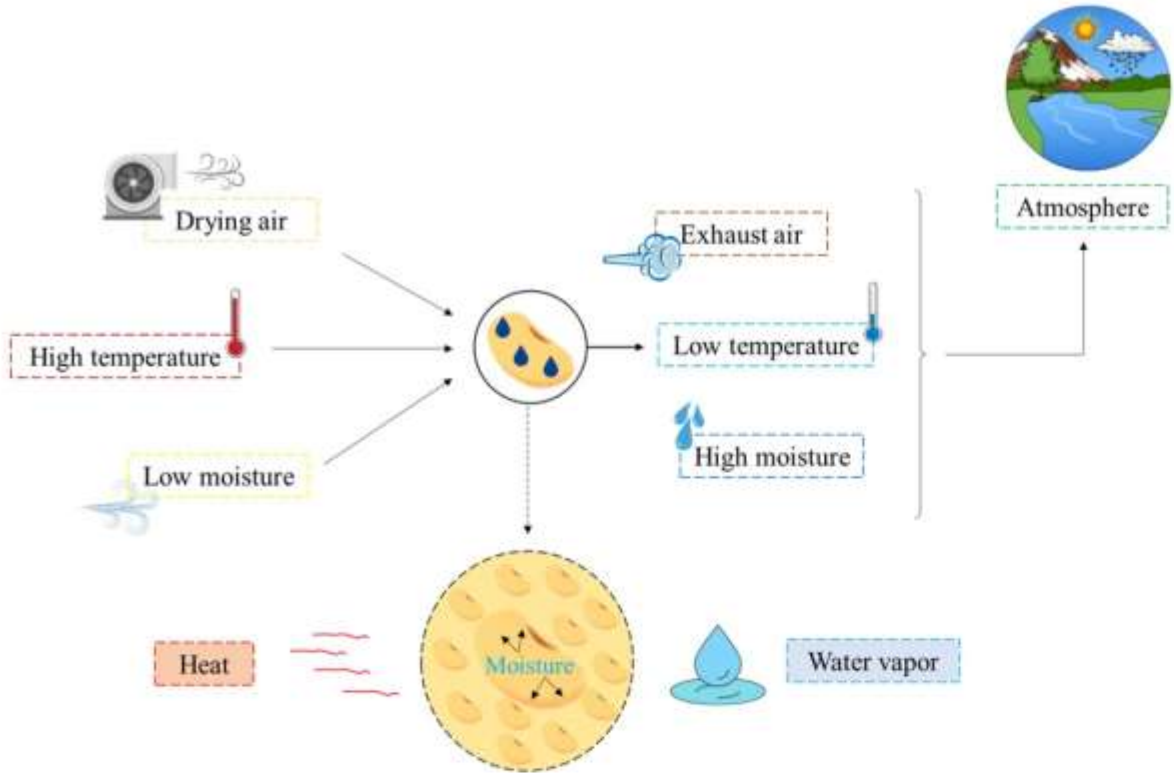

Figure 5. Representation of the performance of equilibrium moisture content during the drying process of soybean grains.

Table 1 shows the main mathematical models used to determine the hygroscopic balance of soybean grains. The knowledge regarding the moisture content characteristic curve and the equilibrium moisture content on drying will contribute to the process optimization (Gonçalves et al., 2015; Niamnuy, Nachaisin, Poomsa-Ad & Devahastin, 2012). In addition, the use of mathematical models according to grains characteristics, temperature and relative humidity, predicting the type of drying and enabling the process and costs optimization (Martinez-Feria et al., 2019).

Table 1. Mathematical models applied to the equilibrium moisture content

Model	Equation
Henderson	$U_e = \left[\frac{ln(1-a_w)}{(-aT+273.16)}\right]^{\frac{1}{b}}$
Modified Henderson	$U_e = \left[\frac{ln(1-a_w)}{-a(T+b)}\right]^{\frac{1}{c}}$
Harkins Jura	$U_e = \frac{exp(a-bT)}{c-ln(a_w)}$

Smith	$U_e = a - (bT) - cln(1 - a_w)$
Peleg	$U_e = [(K_1 a_w^{n_1}) + (K_2 a_w^{n_2})]$
Chung Pfost	$U_e = a - bln[-(T + c)ln(a_w)]$
Guggenheim Anderson de Boer (GAB)	$U_e = \frac{a \times b \times c \times a_w}{[(1 - b \times a_w) \times (1 - b \times a_w + b \times c \times a_w)]}$
Modified Halsey	$U_e = \left[\frac{exp(a - bT)}{-ln(a_w)}\right]^{\frac{1}{c}}$
Modified Oswin	$(a + bT) \times \left[\frac{a_w}{1 - a_w}\right]^{\frac{1}{c}}$
Copace	$U_e = exp[a - (bT) + (ca_w)]$
Σ-Copace	$U_e = exp[a - (bT) + c\,exp(a_w)]$
Lewicki	$U_e = A\left[\left(\frac{1}{a_w}\right) - 1\right]^{B-1}$
Sabbab	$U_e = a \times \left(\frac{a_w^b}{T^c}\right)$
Branauer, Emmet & Teller (BET)	$U_e = \left\{\frac{1}{\left[(1 - a_w) \times \left(\frac{1}{a \times b} + \frac{a - 1}{a \times b}\right)\right]}\right\}$
Kühn	$U_e = \left(\frac{K_1}{ln\ a_w}\right)^{-z} + K_2$
Modified Kühn	$U_e = K\left(\frac{1}{a_w}\right)^{-z} - B$
Oswin	$U_e = \frac{(a + b \times T)}{\left[\frac{(1 - a_w)}{a_w}\right]^{\frac{1}{c}}}$

Where: U_e: equilibrium moisture content, %; T: temperature, °C; a_w: water activity, decimal; a, b, c, z, A, B, K, K_1, K_2: equation coefficient

Table 2 presents the main mathematical models applied in the drying processes involving soybean grains. Therefore, it is important to select the drying method, mainly by defining the drying air optimum temperatures and the grain mass in the dryer movement strategy. The drying methods are classified according to the use of equipment (natural or artificial), the periodicity in the heat supply (continuous or intermittent), and the grain mass movement (stationary or continuous). Some researches aimed at simulating superheated steam drying on quality characteristics of various products are among the main innovations in the scientific literature (Shirkole, 2020). Among new techniques currently employed, cyclic drying has been reported as one of the most innovative alternatives applied to the food drying process in terms of time, energy cost, and products quality maintenance (Kouhila et al., 2020).

Table 2. Mathematical models applied to the drying process

Model	Equation
Page	$RX = exp(-k \times t^n)$
Midilli	$RX = a \times exp(-k \times t^n) + (b \times t)$
Cavalcanti Mata	$RX = a_1 \times \exp(-(k_1 \times t)^{n1}) + a_2 \times \exp(-(k_1 \times t)^{n2}) + a_3$
Henderson and Pabis	$RX = a \times exp(-k \times t)$
Two Term exponential	$RX = a \times \exp(-k_0 \times t) + b \times (-k_1 \times t)$
Modified Page	$RX = exp[-(kt^n)]$
Verma	$RX = d \times (-kt) + (1 - d)\ exp(-gt)$
Newton	$RX = exp(-kt)$
Fick	$RX = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} exp(-n^2 \times At)$
Wang and Singh	$RX = 1 + (a \times t) + (b \times t^2)$
Thompson	$t = a \times ln(RX) + b \times [ln(RX)]^2$
Logarithmic	$RX = d\ exp(-kt) + f$
Diffusion	$RX = d\ exp(-kt) + (1 - d) exp(-kft)$

Where: *RX:* water/grain ratio; *t*: drying time, h; k, k_0, k_1: constant, h^{-1}; a, a_1, a_2, a_3, b, d, f, g, n, A: equation coefficient

The drying oven with forced ventilation method is among the most used. In a study applying temperatures of 50 °C and 90 °C with an initial moisture content of 0.30 (d.b.), this technique showed that, with the temperature increase, the drying time decreases from 7 h to 2 h. Nevertheless, the temperature increase at 90 ºC reduced the volumetric contraction and the soybean grain diameter by up to 3.8 mm (Oliveira, Resende, Smaniotto, Siqueira & Neto, 2013). Finally, the effect of the number of stages of a simultaneous heat and mass transfer in a bed dryer on the quality of soybean seeds showed that increasing the number of stages (2, 3, and 4) significantly reduced the percentage of cracked seeds by up to 15% and increased vigor up to 18% (Pfeifer, Murata & Barrozo, 2010).

The interference of an inefficient drying transcends chemical and biological damages. The drying process, when performed inappropriately, can cause problems in the grain tegument color and other organoleptic characteristics. In addition, 25% moisture content and high air temperatures of up to 120 °C during the drying process influence the extracted oil content, which may increase the oil acidity content by up to 1.4 mg KOH/ g in an initial grain moisture content of 25% (Coradi, Souza & Borges, 2017).

Once the grains are directed to the industrial sector, for human consumption, color is an important parameter to verify the quality of the product during processing. In an attempt to reduce undesirable characteristics, regression models using hyperspectral imaging (HSI) have been used, confirming that medium reflectance was the best approach to the validation of the ideal color when drying the soybean grains (Huang, Wang, Zhang & Zhu, 2014). According to the physiological aspects, when the purpose is the seeds production, the management must be intense. The application of drying in soybean seeds with moisture content above 30% causes damage to the membrane and, consequently, drastically affects the physiological quality (Silva et al., 2018).

The influence of drying on soybean grains through the diffusion coefficient and activation energy showed that soybean plants with early cycle show good results when drying at temperatures of 40, 50, 60, and 70 °C (Botelho, Hoscher, Hauth & Botelho, 2018). Table 3 presents the main applications in the soybean grains drying process considering different drying types and conditions. Finally, the use of the suspension technique in systems with liposomes, containing phosphatidylcholine and phosphate, depending on the drying method (freeze dryer and spray drying) is highly promising in terms of maintaining the physicochemical properties of soybean grains, such as moisture dispersibility and hygroscopicity (Gómez-Estaca, Pérez-García, Alemán, Gómez-Guillén & Montero, 2021). Accordingly, the balance between temperature, dryer type, drying period, and technological innovation is essential to enhance the quality of grains during storage and in the processing industries. Under conditions of drying air temperatures above 40 °C, physical damage and reduced physicochemical quality are observed in soybean grains (Darvishi, Khoshtaghaza & Minaei, 2015; Garcia et al., 2004). At elevated temperatures (> 80 ºC), the oil protein and lipid content can decrease by up to 0.5% and 0.43%, respectively, and the acidity content can increase by up to 0.23 mg KOH/ g (Hartmann Filho et al., 2016).

Table 3. Scientific literature investigation applied to drying conditions for soybean grains

Drying type	Drying period	Temperature (ºC)	Initial moisture content (%)	Final moisture content (%)	Investigation	Reference
Fluidized bed	Up to 380 minutes	80-140	25	10	Damage to the physical stability of grains, such as cracking, shrinkage, and bulk density	Darvishi, Khoshtaghaza & Minaei (2015)
Natural drying	-	50 and 90	-	13	The volumetric contraction ratio and the geometric diameter of the grains decrease, intensifying with increasing temperature	Oliveira, Resende, Smaniotto, Siqueira & Neto (2013)
Intermittent drying	600-1800 seconds	25 and 35	20	-	Reduction of up to 9.8% in grains cracking	Jung & Yoon (2018)
Convection oven with forced air ventilation	-	75, 90, 105, and 120	25	19	Influence in the grain quality and electrical conductivity did not interfere in the final oil yield extracted	Coradi, Fernandes & Helmich (2016)
B.O.D. camera	-	20, 30, and 40	18	11.2, 12.8, and 14.8	The moisture content and higher temperatures intensifies the process of qualitative deterioration of stored grains	Alencar, Faroni, Peternelli, Silva & Costa (2010)
Simultaneous sliding bed dryer	-	0, 40, and 50	23	-	-	Pfeifer, Murata & Barrozo (2010)
Intermittent	-	35 and 45	60, 50, 40, 30, 22, and 12	-	A moisture content above 30% caused membrane damage, reducing the physiological grain quality and seed germination	Silva et al. (2020)
Hot air convection	-	30, 40, and 50	25	-	The activation energy decreased from 38.23 to 34.29 kJ when ozone was added to the drying air. A drying-ozonation process can be useful to improve energy during the drying steps.	Rahmanian-Koushkaki, Nourmohamadi-Moghadami, Zare, & Karimi (2017)
Horizontal fixed layer dryer with forced ventilation	-	40, 50, 60, and 70	20	11	The mineral, lipids, fiber, and ash contents were not influenced by the temperature	Siqueira et al. (2020)

					of drying. Higher drying temperatures provided lower levels of proteins	
Natural drying and hot air oven	-	35-40 and 100	80	-	Natural did not alter trypsin as it was subjected to 100 ºC	Murugkar & Jha (2010)
Infrared gas and hot air vibration drying (GFIR-HAVD)	50, 70, 130, and 150	10 and 20	-	-	High temperatures caused the degradation of isoflavones	Niamnuy, Nachaisin, Poomsa-Ad & Devahastin (2012)

4. Soybean grain storage

One of the main complications that can threaten the grain storage performance is based on the presence of insects and microorganisms. This problem can be prevented using controlled storage atmospheres, such as hermetic *bag*-type silos (Figure 6). Among the bag-type hermetic storage system advantages because it is closed, the grain mass consumes all O_2, causing the grain mass to saturate the atmosphere with CO_2 high concentrations, inhibiting the insects and fungi proliferation, and reducing grain deterioration (Rocha, Taveira, Prado & Ataíde, 2020). The entire silo atmosphere is maintained, prolonging the stored soybean grain quality (Groot, Groot, Kodde & Treuren, 2015).

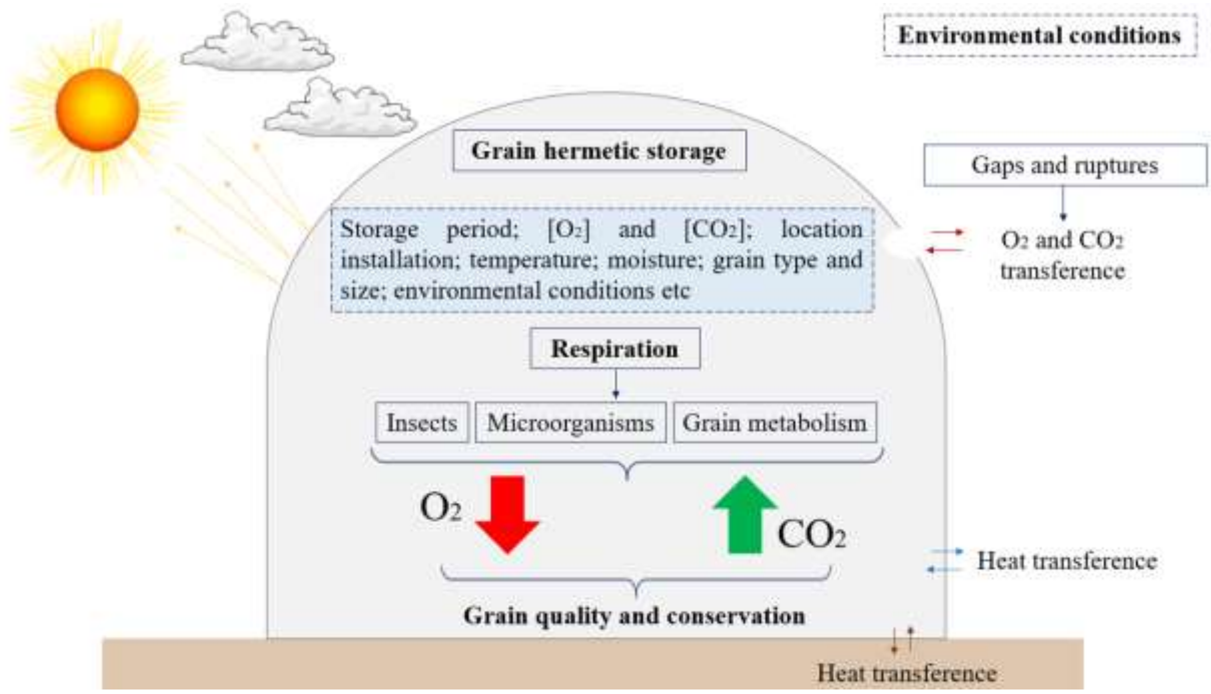

Figure 6. Cross section of a bag silo and representation of the factors and processes that are verified in the internal portion of this type of storage.

According to Ludwig et al. (2021) in hermetic storage, alterations in atmospheric composition can be achieved due to the metabolic activity of all living organisms that cause a O_2 reduction an CO_2 increase, mainly for soybean grains. This storage condition reduces deterioration, inhibiting the development of the microorganism by hypoxia with O_2 below 3% and a high concentration of CO_2 (Ochandio et al., 2017). Once the grains are under anoxylic conditions, the oxidation rate is reduced, in addition to mitigating the unfavorable oxidative process, increasing the storage product longevity (Buijs, Willems, Kodde, Groot & Bentsink, 2020). In the storage in silo vertical (Figure 7) with aeration system (Darvishi, Khoshtaghaza & Minaei, 2015).

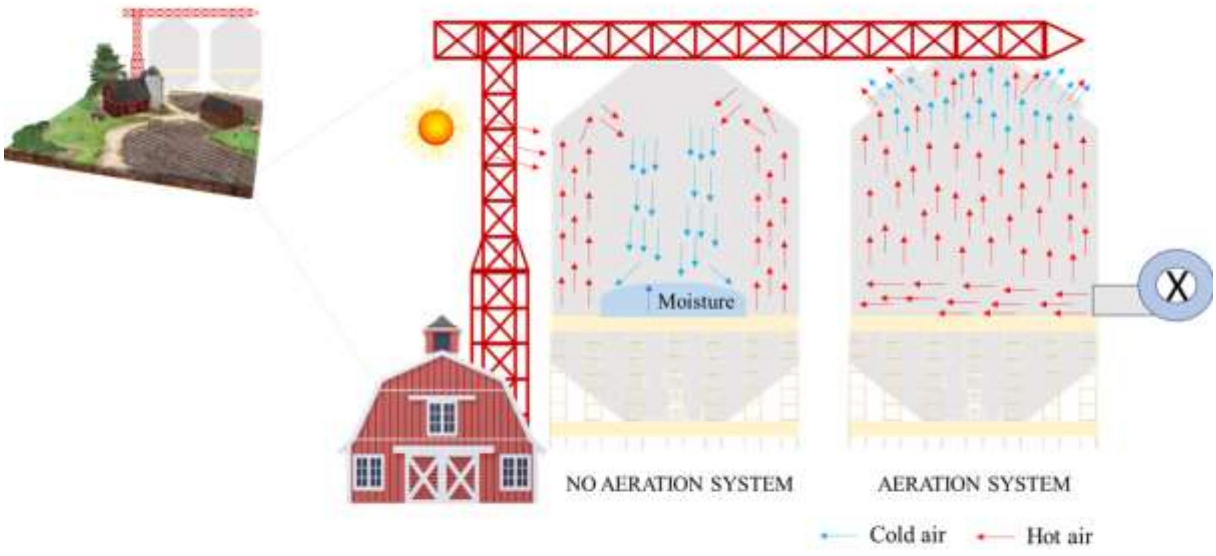

Figure 7. Representation of vertical silo and processes that occur in the presence and absence of aeration systems.

The post-harvest management assurance economic gains in the processing industries since it is largely related to the grains biochemical characteristics (carbohydrates, proteins, and lipids) maintenance (Hussain et al., 2019; Ziegler et al., 2017). Besides, the accomplishment of an adequate management provides the quality of the products in the commercialization processes assurance, reducing the physical nature (tegument break, cracks, and color loss) and biological (insects and fungi) losses, mainly in the soybean grains storage stages (Bucklin, Thompson, Montross & Abdel-Hadi, 2019; Coradi, Souza & Borges, 2017; Gão et al., 2016; Kibar, 2015; Martínez, Armesto, Gómez-Limia & Carballo, 2020; Villagómez et al., 2020).

The effects on biochemical properties occur due to oxidation reactions associated with the temperature applied during the storage process. In the grain storage stage at a temperature of 30 ºC, the occurrence of losses in oil quality is approximately 59.6% (90 days), 67% (135 days), and 76% (180 days) (Bischoff et al., 2016). The oil quality loss results directly from the lipids present in the grains degradation (Dagostin, Carpiné, Santos & Corazza, 2018; Ludwig et al., 2021). Additionally, at temperatures of 80 ºC or higher, parameters such as apparent and unit specific mass, the mass of a thousand grains, and the color of the integument are significantly changed (Botelho, Hoscher, Hauth & Botelho, 2018).

The grain mass excessive respiration, in addition to altering the physical and chemical properties, reduces germination vigor, not reaching 80% viability for the quality standard

(Marcos Filho, 2015). The moisture losses cause the hydrocarbon structures responsible for the stability and grain mass structure ruptures, and, through high cellular respiration, changes important properties such as carbohydrates, proteins, and lipids (Aguiar, Brito, Otani, Fidelis & Peluzio, 2012; Henning et al., 2010; Kim, Kwon & Bhatti, 2010; Saath, Taveira, Terenciano, Evaristo & Rosso, 2017).

Furthermore, the water activity associated with high temperatures intensifies the grain mass cellular respiration, making a conducive environment to the survival of insects, causing external humidity variation, and drastically affecting the hygroscopic balance (Freitas, Matte, Poppe, Rodrigues & Ayub, 2016; Mylona, Sulyok & Magan, 2012; Quezada, Moreno, Vazquez & Medoza, 2006). The grains moisture content is influenced by the air relative humidity around them and, therefore, they are always demanding hygroscopic balance (Oliveira, Resende, Smaniotto, Siqueira & Neto, 2013). Thus, it is extremely necessary to comprehend the adsorption and desorption isotherms, since they ensure adequate storage conditions (Ludwig et al., 2021). Table 4 reports the main storage applications for soybean grains resulting from different storage types and conditions.

In hot and humid conditions, the development of mycotoxigenic fungi is widely favored, including *Aspergillus flavus* which increases the grains stored by mycotoxins contamination risk (Bhat, Rai & Karim, 2010; Rocha, Taveira, Prado & Ataíde, 2020). The contamination intensity and speed depend on the storage environment relative humidity and on environmental factors during storage (Bazoni, Ida, Barbin & Kurozawa, 2017). Therefore, the application of fungal organic compounds as grain protectors against the action of toxin-producing fungi has shown inhibition of up to 100% of fungi *Aspergillus parasiticus* and *Aspergillus flavus* (Boukaew & Prasertsan, 2020). Moreover, hermetic storage is used in the industrialized soybean products conservation processes. Sahu & Patel (2020), analyzed the moisture sorption isotherms and alterations in the quality of extruded soybean products stored in different packaging types at temperatures of 30 ºC, 40, ºC, 50 ºC, and 60 ºC and relative humidity of 90%, observed that the product packaged in metalized polyethylene terephthalate bags maintained the best crunchiness for 90 days stored. The water vapor non-permeabilization in packaging prevented the product from remaining with good quality in relation to other packaging (low-density polyethylene bag, high-density polyethylene, and aluminum foil). In this study, the Guggenheim, Anderson, and Boer (GAB) model was considered the best to predict the range of water activity in the product, in which the sorption isotherm showed that the equilibrium moisture content was directly proportional to the moisture increase (water activity from 0.11 to 0.92).

Table 4. Scientific literature investigation applied to storage conditions for soybean grains

Storage type	Storage time (days)	Temperature (ºC)	Investigation	Reference
Horizontal metallic silo	90-180	30	Peroxidation of lipids	Bischoff et al. (2016)
-	-	80	Reduction of the apparent and unit specific density and tegument color	Botelho, Hoscher, Hauth & Botelho (2018)
Modified atmosphere	10	25	Permanence of tegument color and final weight; reduction of carbohydrates and alanine;	Makino et al. (2020)
MPET bags	5-90	30, 40, 50, and 60	No significative changes in moisture; maintenance of the crispness of extruded products stored over time	Sahu & Patel. (2020)
Hermetic plastic containers	270	25 and 35	No significative changes in physicochemical properties. At 35 °C, the color of the coat was reduced, pH reduction, and increase of acidity and fatty acids	Bazoni, Ida, Barbin, & Kurozawa (2017)
Metallic silos	-	18	Variations of 11.30% in moisture content, 32.11% of proteins, 20.62% of carbohydrates, 7.76% of fiber, 4.68% of ashes, and 23.62% of lipids	Silva et al. (2020)
Environmental and controlled atmosphere conditions	210	20, 25, and 30	Maintenance of the physiological quality under controlled atmosphere	Ludwig et al. (2021)
Big bags	0, 90, 180, 270, and 360	10, 15, and, ambient	Maintenance of the best physical and physiological quality grains. In environmental conditions, the seed mass temperatures were higher and showed greater variability than in those stored at controlled temperatures	Coradi et al. (2020b)
Environmental conditions	60	10 and 20	Influence of the moisture content and drying process at low temperatures and stored in artificially refrigerated conditions, showing better grain quality over the storage time	Coradi et al. (2020c)

The storage conditions are also fundamental for the quality of soybean forage conservation. From soybean forage stored for 120 days in 2 types of packaging (polyethylene bags and not packed but tied with rope) under three environments (roof, room, and fork storages), it was determined that the dry matter content was reduced by 24% in all storage conditions, showing a variation of 14% in the best conditions (bags and rooms) to 35% in the worst conditions (packages tied with rope and stored without roofs or forks) (Akakpo et al., 2020). Also, the use of controlled conditions with low O_2 and high CO_2 in soybean grains harvested and stored for 10 days at 25 °C under normoxia and modified atmosphere, it was established that under modified atmosphere conditions, there was a 25% contribution in the tegument color permanence and external green mass, to the detriment of grains stored in normoxia, 19% (Makino et al., 2020). These storage atmospheres are portrayed as excellent alternatives for maintaining grain quality, reducing quantitative losses in grain metabolism processes, as well as in the presence of microorganisms, insects, and pathogens (Martínez, Armesto, Gómez-Limia & Carballo, 2020).

Additionally, accelerated maturation is a good indicator to show the relation of environmental factors (temperature and relative humidity) on the soybean grains quality. Over this parameter, it is possible to observe that, during the storage period, the seed vigor is reduced (Radha, Channakeshava, Bhanuprakash, Gowda & Ramachandrappa, 2014). Correspondingly, the combination of optimal storage conditions, which support the gas ratio control (high CO_2 at the expense of low O_2), help in maintaining the grain quality.

Hermetic silos participate in the maintenance of properties such as lipid, protein content, and reduction of leached ions in soybean seeds (Silva et al., 2018). It is characterized as an alternative to the seeds and grains protection for storage companies, as well as for rural producers (Freitas, Matte, Poppe, Rodrigues & Ayub, 2016). Nevertheless, there is a necessity for accurate information about the soybean grains proper storage conditions in these types of silos (Taher, Urcola, Cendoya & Bartosik, 2019).

Investigation according to the potential application of infrared spectroscopy (IR) to evaluate the quality of the soybean grains stored in hermetic plastic containers in different conditions (25 and 35 °C) for 9 months was conducted (Bazoni, Ida, Barbin, & Kurozawa, 2017). The authors found that, at 25 °C, the physicochemical properties, such as ash (4.7%), protein (3.9%), lipids (21.9%), and carbohydrates (34.4%) were not altered. Contrarily, at 35 °C, a reduction in the tegument color (88% to 85%) was observed, in addition to an increase in free fatty acids (3.7% to 4.7%) and, consequently, the grains acidity content due to the hydrolytic degradation of fat components by the action of lipase, in which these fatty acids are liberated from the triacylglycerol structures. This scenario shows that natural maturation and storage temperature can degrade the grain physical characteristics. In addition, they cause higher levels of acidity in the grains.

Each soybean-producing region has its own characteristics of temperature and relative humidity, which require particularities regarding the measures to be adopted. The physicochemical quality of soybean grains stored in storage units at farm level, in central-western Brazil at 18 °C did not change the thousand grains color and weight (Silva et al., 2020). These authors pointed out that the value of some grains properties suffered a significant variation (11.30% moisture content, 32.11% proteins, 20.62% carbohydrates, 7.76% fibers, 4.68% ash, and 23.62% lipids) and alterations in electrical conductivity. This occurs due to the specific characteristics of the region, in which high temperatures combined with low relative humidity influence the grains equilibrium moisture content, maintaining the properties during the storage period.

Regardless of all the contribution of storage for product quality, grain storage conditions affect its basic characteristics, such as alterations in respiratory metabolism, darkening, lipids oxidation, pH decrease, free fatty acids content increase, alterations in the proteins, lipids, and isoflavones compositions (Walker, Jaime, Kagot & Probst, 2018). Therefore, considering this parameter is necessary to assess the maintenance of the quality of the final products, especially when they are directed to processing industries aimed at human and animal consumption.

5. Soybean grain processing

5.1 Biodiesel and vegetable oils production

Considering the worsening of global warming and the environmental problems resulting from this phenomenon, in recent years, there was a necessity to adopt alternative sources of sustainable energy compared to fuels originated from oil and derivatives. As a result, the immense amount of plant residues from post-harvest and industrial processes have been identified as a viable option to produce fuels with a high sustainable status and low environmental impact (Kanitkar, Sabliov, Balasubramanian, Lima & Boldor, 2011; Topi, 2020). In this context, soybean has been widely cultivated and valued as a potential feedstock to produce renewable energy. The use of these materials and the application of specific chemical reactions support obtaining biofuels with desired and biodegradable and environmentally friendly physicochemical characteristics (Colombo, Ender, Santos & Barros, 2019).

Generally, a soybean grain contains approximately 40% protein content and approximately 18–20% oil content (Sobko, Zikeli, Claupein & Gruber, 2020). In recent years, the amount of soybean oil directed to the biofuel production has been directly proportional to the grains production worldwide. This scenario is verified in the utilization of soybean oil directly aimed at the biofuels production. According to the Oil World Institute, in the 2019/20 harvest, over 50 million tons of soybean oil was conditioned to the biofuels production, representing about 26% of the total feedstocks consumed for this purpose.

The biodiesel quality is intricately associated to the grains oil extracted quality, mainly due to the stability of the compounds and the composition of the constituent fatty acids (Sinha, Haldar & Majumdar, 2015; Yao et al., 2020). However, there is a necessity to optimize several practices and steps that can significantly contribute to the biodiesel production process (Myint & El-Halwagi, 2009).

Studies have shown that the stages involving the biofuels production impact the final product quality from management and cultivation procedures developed from the plant field establishment to the processing and transportation of this material (Vunnava & Singh, 2020). Furthermore, the performance of various technologies and biochemical reactions aimed at converting vegetable oils into biodiesel are strongly affected by the grain quality and, consequently, by the external conditions to which these elements have been conducted (Mariano et al., 2014). Obtaining high-quality biofuels significantly depends on the physicochemical performance of important vegetable oils parameters, such as viscosity, moisture content, density, and ionic and acid levels, for example (Canesin et al., 2014). These characteristics performance also act directly on the techniques for processing vegetable oil extraction from soybean grains and chemical reactions aimed at modifying these oils and converting them into biodiesel, such as transesterification (Esteves, Esteves, Bungenstab, Araújo & Morgado, 2018). To obtain high-quality oil and desirable characteristics in the production process, several stages must be considered since the harvesting process to the oil storage and transportation (Figure 8).

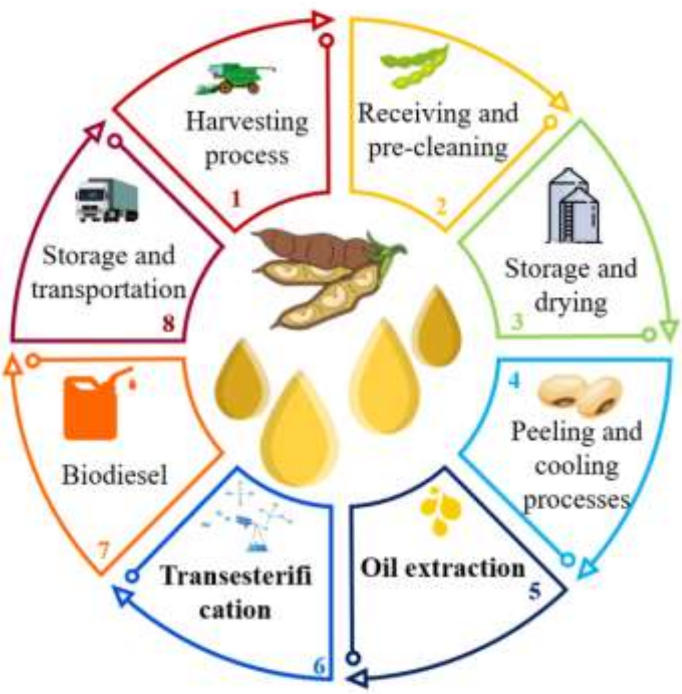

Figure 8. Diagram of the main stages of soybean processing to produce biofuels.

5.2 Soybean oil extraction procedures

The procedures adopted during the soybean post-harvest stages can directly affect the extracted oil content and quality. Studies show that the application of temperatures above 80 ºC during the drying process results in the grain physical structure disruption, affecting lecithin levels and reducing levels of protein dispersibility by up to 15% (Sangkram & Noomhorm, 2002). A study whose goal was to evaluate the grain oil content submitted to different temperatures and initial moisture content showed that temperatures of 105 ºC and initial moisture content of 25% significantly affect the grain quality (Coradi, Fernandes & Helmich, 2016). However, there were no effects on oil yields.

Besides, to produce biodiesel, soybean edible oils, and bioproducts, long periods of storage are necessary, mainly due to the demand and market value of these products. Thus, the storage period is an essential parameter for enhancing the quality of soybean grains and extracted oil (Oliveira et al., 2016). In addition, the storage process is intricately related to the grain vigor preservation and the maintenance of their chemical and nutritional properties, since the conditions of temperature, the relative air humidity, and the storage period influence the exchanges between grains and the environment (Zuchi et al., 2013). Nevertheless, the high performance of chemical and technological processes applied to the optimization of the grain oil extraction and the biodiesel synthesis is one of the determining factors for obtaining quality oils. Considering the biofuels production, the extraction stages and transesterification reactions are fundamental to obtain a high-quality product. There are different strategies to obtain biodiesel from vegetable feedstocks.

The scientific literature approaches several extraction processes, such as mechanical (pressure), solvent extraction, supercritical fluids, and microwave and ultrasound-assisted extractions. These procedures, as well as the transesterification method, the final stage for obtaining biodiesel, require grain pre-treatment, which involve the cleaning and pre-cleaning, threshing and peeling, drying, and storage processes.

The mechanical extraction or pressing process was the first method to be widely used to obtain soybean oil, through the application of high pressures and temperatures (Valladares-Diestra, Vandenberghe & Soccol, 2020). Furthermore, it is important to reduce the effect of grain enzymes, which can degrade the oil and affect the final quality (Moura et al., 2008). However, the technique extraction efficiency was significantly low, resulting in low yields and undesired characteristics, such as oil browning and deterioration due to high temperatures (Cheng & Rosentrater, 2017).

Thus, due to its application on small scales, mechanical extraction does not compensate considering the processing costs and feedstocks transportation, making it an unviable option compared to other alternatives (Cheng, Dien & Singh, 2019). Regardless of these problems, studies have shown that the temperature and pressure increases, proportionally, and the time of application of these parameters, contribute to result in maximum yields until reaching a maximum total temperature (Nde & Foncha, 2020). Temperatures above the maximum optimum temperature to enhance extraction do not result in higher productivity. Appropriately, it was verified the emergence of new methods for grain extraction oil to achieve high yields. As a result, Table 5 presents important extraction processes widely applied to soybean grains in order to obtain high-quality oil yelds.

Table 5. Scientific literature investigation applied to oil extraction methods and conditions for soybean grains

Extraction technique	Extraction conditions	Study objectives	Investigation	Reference
Solvent extraction	Hexane/ethanol in a ratio of 1.5:1–2.5:1, soaking time of 1–4 h, applied pressure of 9800–49000 kPa, duration of applied pressure of 10–30 min, and soaking temperature of 30–60 °C	Integration of soaking soybean grits in ethanol followed by pressing the soaked soybean grits	Oil increase of 20% up to 50 ºC	Sinha, Haldar & Majumdar (2015)
Solvent extraction	Ethanol in 0 and 5.98 mass% of water hydration levels, temperatures of 40, 50 and 60 °C, and	To obtain experimental data of the extraction kinetics of soybean oil and free fatty acids (FFA)	Development of the kinetics of oil extraction and minor compounds present in grains	Toda, Sawada & Rodrigues (2016)
Solvent and mechanical extractions	Ethanol and ethanol + alkyl esters mixtures (biodiesel) in temperatures of 25, 40, and 55 ºC in a solvent to soybean mass ratio of 4:1	To evaluate the kinetics and thermodynamics aspects of soybean oil extraction using (ethanol + biodiesel) mixtures in batch systems	Oil production increase and energy consumption reduction	Dagostin, Carpiné & Corazza (2015)
Solvent extraction	Soybean oil/n-hexane in an oil to hexane mass ratios of 1:1, 1:4, and 1:5 (w/w) at pressures of 0.9, 1.,1 and 1.3 bar	To investigate the separation of refined soybean oil/n-hexane mixtures using a hollow fiber ultrafiltration membrane	Increase in the oil/n-hexane mass ratio and the pressure caused an increase in the rejection and permeate total flux	Tres, Nobrega, Carvalho, Oliveira & Di Luccio (2012)
Supercritical technology	CO_2 flow rate of 1.629 L per min, temperatures of 40-50 °C, 100-300 bar, and 4 h	Supercritical CO_2 extraction of soybean oil performance	Oil extraction up to 6.59/100 g soybeans at constant CO_2 flow rate of 1.629 L per min was achieved at 50 °C, 300 bar, and 4 h	Jokic et al. (2010)
Supercritical technology	$SCCO_2$ pressure of 276 bar and a 17-g mixture of 1,2-propanediol/oil at a molar ratio of 10:1	Evaluation of soybean oil extraction with propylene glycol in supercritical carbon dioxide and analysis by NMR spectroscopy	Oil extractions increase of up to 20% with the transesterification process intensification	Vafaei, Eskin, Rempel, Jones & Scanlon (2020)
	Temperatures from 60 °C			Kanitkar, Sabliov,

Microwave-assisted extraction	to 120 °C for up to 20 min with simultaneous magnetic stirring; solvent (ethanol) to feedstock ratio of 3:1	To optimize oil extraction parameters for a batch microwave system for oil extraction	Oil yields up to 17.3% at 20 minutes of process and 120°C	Balasubramanian, Lima & Boldor (2011)
Microwave-assisted extraction	100 mL of preheated (60 ºC) soybean oil with 25 mL of 1 wt % KOH solution in methanol to soybean oil molar ratio of 6:1	Evaluation of the influence of different elements in the microwave synthesis biodiesel from soybean oil process	Biodiesel synthesis up to 99% using KOH as catalyst at 60 ºC in a reaction time of five minutes	Tesfaye & Katiyar, (2016)
Ultrasound-assisted extraction	Ultrasonic bath temperature from 30 to 60 ºC and an exposure time from 10 to 40 min	To evaluate the use of lipase from *Aspergillus niger* in the catalysis of oil hydrolysis reaction through ultrasound	An amount of free fatty acids up to 62.67 lmol/ mL in 12 h of reaction and an oil: water ratio of 1: 3 and 15% (v/ v) of enzymatic solution	Mulinari et al. (2017)

5.3 Biodiesel synthesis

The biodiesel synthesis occurs from the vegetable oil transesterification reaction through the action of organic solvents. Formed by a fatty acids methyl esters mixture, vegetable oil encounters alcohols and catalysts, causing the separation of the reaction-based products, glycerol, and pure biodiesel (González et al., 2020).

Several alcohols are used for the process, such as ethanol, butanol, and propanol. However, methanol has been widely applied, due to its physicochemical characteristics (boiling point, melting point, and density) and reduced cost (Costa et al., 2019). The soybean grain physicochemical characteristics fully affect transesterification reactions. The grain high acid content, stimulated by extreme drying and storage conditions, is related to the fatty acids concentration and the oil quality reduction, drastically affecting the reaction (Aransiola, Betiku, Layokun & Solomon, 2010). Additionally, the initial moisture content removal at temperatures up to 77 ºC resulted in a significant increase in the transesterification reaction efficiency (Haas & Scott, 2007). The process effectiveness is a consequence of the minimization of the use of reagents during the process and the facilitation of the reagent-material contact.

Many factors directly influence the transesterification reactions performance, such as the catalyst type, process conditions, and the grain fatty acids content (Singh, Fernando & Hernandez, 2007). However, there are serious problems resulting from the catalytic action in the biodiesel synthesis process. Saponification, resulting from free fatty acids activity, directly affects the catalyst concentration, as well as promoting a strong emulsion of the solutions, making it difficult to separate the glycerol (Cabral, Lorenti, Plass & Gallo, 2020). Thusly, the application of different procedures in combination with transesterification for the biodiesel synthesis has been addressed, especially those related to the optimization of the catalysts to be used in the reaction (Dagostin, Carpiné & Corazza, 2015; Lee, Seo, Kim & Lee, 2020).

One of the processes that promote increased oil yields and purity is the glycerol separation process in the transesterification reaction in supercritical technology. The use of methanol in supercritical condition (40:1 molar alcohol/ oil ratio, 35 MPa pressure, 310 ºC temperature, and 25 minutes reaction time) perpetuated the contact between the solvent and the vegetable material, significantly reducing reaction time and facilitating the removal of glycerol from the vegetable oil solution, providing an increase of up to 77% in yield (Lee, Seo, Kim & Lee, 2020). However, the application of this technique can cause high degradation of the feedstocks, resulting in the necessity of alternative strategies to repair this problem, such as the use of different catalysts and the separation of stages involving the glycerol obtaining and the vegetable oil synthesis (Silva & Oliveira, 2014). Thus, the emergence of methods such as ultrasound-assisted transesterification has been largely addressed recently.

The use of ultrasonic irradiation, using the ultrasound-assisted transesterification method (in an enzyme/ oil concentration of 15%, ethanol/ oil molar ratio of 3:1, the ultrasonic amplitude of 30%, the reaction time of 50 %, and pulse for 15 seconds), resulted in the production of oil and glycerol with a high purity, in addition to reducing the total reaction period and minimizing the use of solvents (Freitas, Matte, Poppe, Rodrigues & Ayub, 2019). The potentiation of this process occurs mainly using the best enzyme and the reaction parameters optimization, such as the presence or absence of solvent, temperature, moisture content, and conversion potential (Yu et al., 2010). Moreover, the reaction time, the intensity and frequency of the supplied irradiation waves, and the grain characteristics are fundamental to the transesterification stage efficiency (Freitas, Matte, Poppe, Rodrigues & Ayub, 2019). The use of lipase as a catalyst in the transesterification process has been promising and highly efficient for obtaining soybean oil.

The application of this catalyst cooperatively with an irradiation source promotes yields of up to 90% at temperatures of 60 ºC and a reaction time of up to 4 hours, enhancing the use of these techniques in the biodiesel synthesis (Batistella et al., 2012). High yields (>90%) were obtained in the combination of the method and different fungal lipases, generating in a process with less energy requirement, low costs, and higher conversion efficiency (Poppe, Matte, Fernandez-Lafuente, Rodrigues & Ayub, 2018).

5.4 Soybean bioproducts for food production

Considering their high nutritional status, soybean grains have been applied in a range of processes to enhance their use in different fields of food exploration. In general, soybean-based foods have high concentrations of minerals, isoflavones, proteins, sucrose, and fibers (Ibáñez, Blas, Cámara & Mateos, 2020; Yue, Abdallah & Xu, 2009). The utilization of products directly synthesized from grains and by-products potentially applied to human and animal consumption portrays the species high utilization capacity (Srivastava, Semwal, Dhiman, 2020). Figure 9 shows the main applications of soybean grains widely used in the commercial and agricultural scenario, acting as important sources of nutrients necessary for human and animal use.

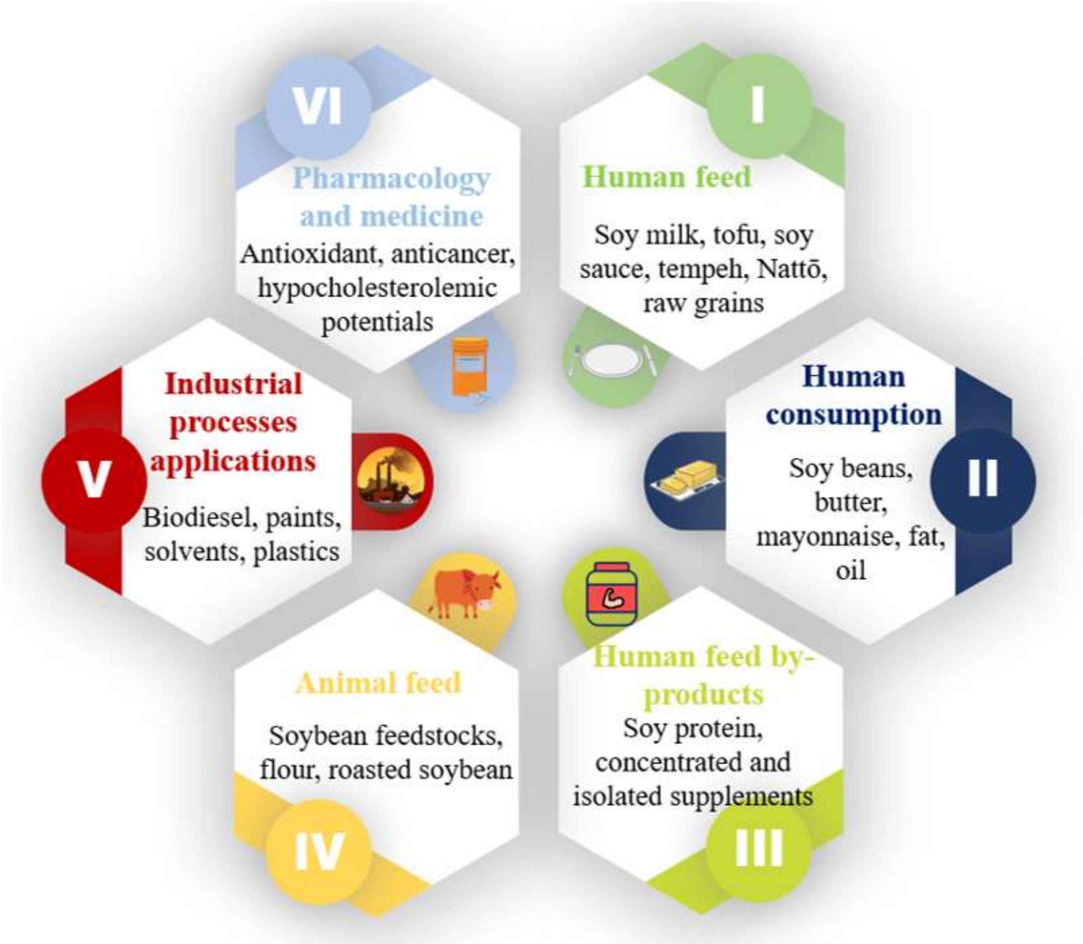

Figure 9. Main applications of soybean grains and soybean bioproducts for human and animal consumption.

Considering the dynamics and importance of the food segment in a supply chain, industries focused on food production play a fundamental role in supplying several countries. However, it is necessary to adopt production quality concepts and, mainly, the final product that is directed to the consumer (Campenhout, Maes & Claes, 2012). The literature has addressed the wide influence of edaphoclimatic factors, such as local temperature and humidity conditions and management practices in the stability and perpetuation of grain quality in the field (Campenhout, Maes & Claes, 2012). However, correct decision-making about the application of techniques and technologies in the post-harvest and subsequent grain processing is essential to avoid the proliferation of unwanted microorganisms and the products generated quality decrease (Mesterházy, Oláh & Popp, 2020).

Recently, there has been an intense development of technologies aimed at analyzing and improving the grains quality directed for human consumption. A study established a grain classification structure of a multimodal bag-of-feature model, whose main objective is to verify the visual appearance of dry soybean grains after the harvesting process (Cheng & Sun, 2015; Lin et al., 2019). According to the images, it is possible to characterize the quality of the products in the post-harvest and classification processes. The same approach was verified in the application of processes involving the characterization of images combined with a neural network and detailed computational analysis (Dai, Sun, Xiong, Cheng & Zeng, 2014; Liu et al., 2015). From the application of this strategy, it was possible to identify damaged grains and the presence of pathogens, enabling the elimination of these elements and configuring the obtaining of homogeneous samples of high physicochemical quality.

Regarding grain storage and soybean bioproducts, the relation between edaphoclimatic factors in natural stores and the storage period do not affect the bioproducts quality in up to 1 year of storage (Liu & Chang, 2012). However, grains stored for long periods (18 months) under abiotic conditions, such as temperature up to 30 ºC and relative air humidity of up to 84%, show high losses in the extracted oil and bioproducts quality (Hou & Chang, 2005). The total oil degradation can be enhanced due to an increase in oxidative reactions, caused by environmental factors, resulting in the grain functional variation and the oil quality loss (Alencar, Faroni, Peternelli, Silva & Costa, 2010). A scientific study showed that the increase in the storage period significantly affects the characteristics of proteins present in soybean meal, such as the proteins dispersibility by up to 4.2%, being characterized as a possible defeat for the final product quality (Serrano, Rebollar, Sueiro, Hermida & Mateos, 2013).

The drying process also has great effects on the oil and soybean bioproducts quality. Studies involving the drying action in the soybean meal nutritional characterization showed that the adoption of temperatures of 100 ºC negatively affects the solubility of the compounds by about 50% and the product physicochemical characteristics, reducing the functional quality (Agrahar-Murugkar & Jha, 2010). Thus, the drying step to obtain soybean meal for the poultry and ruminants feeding is essential to reduce the number of inhibitors that directly affect the product quality, providing the reach of food with high nutritional value (Erdaw, Bhuiyan & Iji, 2016). The innovation of strategies aimed at the genetic improvement to obtain high potential genotypes to be used in the vegetable oils and biodiesel synthesis has been explored (Kanai, Yamada, Hayashi, Mano & Nishimura, 2019). Accurate identification of oil contents can be carried out in advance, based on a breakdown of the metabolic status of different genotypes (Wang et al., 2019).

The development of genotypes that have reduced levels of fatty acids (<14%) that act directly on oxidative processes results in the cultivars that provide a high improvement in the properties of the synthesized oil and biodiesel (Mulinari et al., 2017; Woyann et al., 2019;

Vafaei, Eskin, Rempel, Jones & Scanlon, 2020). Thus, based on genetic factors and adverse environmental effects, it is perceived as the most suitable genotype to produce biofuels. Finally, the genetic mapping of genes strictly related to oil characteristics and fatty acid composition has proved to be an important alternative to obtain high-quality oil (Yao et al., 2020). From the identification of a locus of certain chromosomes with the verification of the RNA sequence related to the grain protein content, it is possible to identify the characteristics of stability and potential use of vegetable oil (Huang et al., 2020).

5.5 Technological perspectives for soybean bioproducts quality

Considering the great interest in soybean grain as an important source of proteins and minerals, the application of techniques and technologies that make it possible to verify and optimize the quantities and quality of the extracted oil has been investigated. Currently, the necessity to obtain products and bioproducts from soybean grains requires the adoption of different technologies and strategies that enable the maximization of the quality of these elements.

One of the main strategies employed is the microwave-assisted technique. A study was conducted with the objective of optimizing the grain roasting process by the microwave action, considering the grains exposure at different reaction times (7-11 minutes) (Efthymiopoulos, Hellier, Ladommatos, Kay & Mills-Lamptey, 2019; Tassi et al., 2019). The results showed that the maximum exposure time caused positive effects on flavor and physical properties, enhancing its application to obtain the desired product from a nutritional and technological point of view.

Besides, the microwave action was effective in reducing inhibitors that reduce its nutritional value and digestibility (Vagadia, Vanga, Singh, Gariepy & Raghavan, 2018). Microwave application at temperatures from 70 ºC to 100 ºC and reaction time from 2 to 8 minutes proved to be a highly effective method, increasing protein digestibility by up to 87% and reducing the presence of inhibitors by 1% (Tesfaye & Katiyar, 2016).

The grains drying process conducted by the method previously discussed was highly efficient at low potency rates (<0.2 W/ g), not affecting the grains stability and quality (Toda, Sawada & Rodrigues, 2016; Wang et al., 2017). For the soybean processing and baking without digestibility and food nutritional value losses, the use of microwave was the most efficient when compared to conventional methods and under pressure (Kaushik, Satya & Naik, 2010).

The infrared drying technique has been another technology widely used for grain processing. The strong and direct absorption of infrared by the materials promotes the heating with higher speed, energy gain, and high quality (Rahmanian-Koushkaki et al., 2017). The application of infrared waves enabled high efficiency in the bleaching and drying process of Edamame, highly commercialized and consumed in Asia (Lara et al., 2019). Intensities of up to 11.06 kW/ m^2 and exposure time of up to 120 seconds enhanced the process efficiency, characterizing it as an innovative strategy.

Finally, along with this method, the application of infrared waves by the physicochemical method Fourier-Transform Infrared Spectroscopy (FTIR), which determines the compounds present in the grains under different wavelengths, is effective to verify the soybean grain biochemical characterization. The determination of the grain quality and biochemical properties (proteins, fatty acids, carbohydrates, and starches concentrations) at wavelengths from 4000 to 600 cm^{-1} was highly effective in investigating the grain biochemical potential (Larios et al., 2020).

7. Final contextualization, challenges, future perspective, and conclusions

The optimization of a food supply chain that results in minimizing waste and acting in a sustainable mode is one of the main objectives of an integrated agricultural system. Considering that one-third of the total food produced in the world is lost in the processes that involve post-harvest systematization, there is a necessity to develop strategies and solutions that surround the different stages of the productive supply chain.

The quality losses of grains and vegetable oils portrayed in the drying, storage, and processing stages feed a comprehension of serious economic consequences and the importance of appropriate and compatible management in these stages. The influence of biotic and abiotic factors in these processes causes important morph physiological changes that can threaten the whole grain processing and unbalance the performance and efficiency of productive management.

This study enabled to comprise the dynamics of the soybean supply chain, from post-harvest procedures to industrial processing to produce foods of human and animal interest, vegetable oil, and biofuels synthesis. The adoption of encouraging strategies to provide production gains indicates the growing interest in establishing appropriate logistics during the grain drying, storage, and processing stages to maintain the quality of the final product.

The correct systematic management of the soybean production chain promotes efficiency in a livelihood practiced by countless rural producers. Accordingly, this study provided adequate information on management practices to reduce losses in soybean post-harvest logistics and strengthen the production chain.

In conclusion, post-harvest quanti-qualitative losses of grains bring an imbalance in grain productive sector, and the variation of moisture content of grain mass and temperature and relative humidity of their intergranular air may influence their storage ecosystem. To reduce grain losses during storage stage, it is essential that crushed grains are uniform in quality and go through cleaning and drying processes. The heterogeneity of harvested grain lots from the beginning to the end of harvesting period hinders the capacities of dryers. Therefore, it is necessary to closely monitor and manage moisture content in grain mass and their drying air temperature to ensure process optimization of energy consumption and grain quality. An alternative for this could be the adoption of grain storage distribution units and drying technologies on a regional scale. Managing soybean grain in silo-dryer for drying and storage, and continuous dryer + aerator-silo for storage is an alternative that ensures low losses and high grain quality and improves protein and crude oil conten, for a much better.

8. References

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CHAPTER 2

(Paper submitted to Revista de Engenharia Agrícola)

Drying and storage technologies minimize quality losses in soybeans in the south Brazil regions

Abstract: This study had objective to evaluate, in real production scale, the management of batches of harvested soybean grains in storage units, which are submitted for different technological processes of drying. Study regions were separated in micro-regions based on structure and static storage capacity. For each micro-region (West, East, North, South, Central), dry soybeans in continuous dryer-CD1, continuous dryer + silo-dryer-CDSD2, continuous dryer + aerator-silo-CDAS3. Grain quality losses in function of drying management ranged from 0.23 to 3.26% in crude protein, and 0.15 to 3.05% in crude oil. In regions with large scale soybean production, the adoption of storage unit structures at farm level ranging from 11 to 19 km, with high drying technology in partial continuous grain flow and final stationary drying in a silo-dryer or silo-aerator is the best alternative for a productive-sustainable system. Managing CDSD2 and CDAS3 soybean drying is an alternative that ensures low losses and high grain quality and improves protein and crude oil content. In conclusion the CDSD2 and CDAS3 drying systems reduced crude protein and oil content losses by 94% and 95% for a much better sustainable postharvest system.

Keywords: grain conservation, grain quality, food security, soybean postharvest, soybean processing.

1. Introduction

In Brazil, the area of grain production has an average increase of 3.5% yearly, and the productivity has increased at approximately 27.7% with an estimated average production of 350 million tons of grain (Conab, 2023). Among the largest grain producing regions, midwest and south regions have been highlighted and the main crops produced are soybeans, corn, rice, and cotton. Soybean is one of the main agricultural crops produced, standing out with approximately 40% and 20% of crude protein and crude oil, respectively, and are intended mainly for human consumption and animal feed. However, the expansion of soybean production in Brazil brought new challenges, especially in the postharvest stages, causing a significant deficit in static storage capacity in relation to total grain production, and these challenges are directly reflected on the logistics, quality, and marketing prices of the products.

Postharvest quanti-qualitative losses of grains bring an imbalance in grain productive sector, and the variation of moisture content of grain mass and temperature and relative humidity of their intergranular air may influence their storage ecosystem, thereby, increasing the respiratory rate of the grain mass, causing deterioration of the grains, reducing the percentage of their dry matter, and causing contamination by insects, pests, fungi, and mycotoxin production (Ng'ang'a et al., 2016; Babu et al., 2018; Nyabako et al., 2020). To reduce grain losses during storage stage, it is essential that crushed grains are uniform in quality and go through cleaning and drying processes. Fundamentally, the aim of drying is reducing the moisture content of grains for optimum storage conditions, reducing water activity to a level where microbial growth and rate of deterioration are slowed, however, thermal drying process cannot be severe (Opoku et al., 2018; Raza et al., 2019). Besides the removal of moisture, drying may interfere with the physical-chemical structure of grains, promoting breakdown in cellular tissues and accelerating deterioration process of the grains (Wang et al., 2015; Coradi et al., 2017).

The heterogeneity of harvested grain lots from the beginning to the end of harvesting period hinders the capacities of dryers. Therefore, it is necessary to closely monitor and manage moisture content in grain mass and their drying air temperature to ensure process optimization of energy consumption and grain quality (Li et al., 2007; Bowser et al., 2011). Currently, the energy used in drying comes from natural sources. Due to growing environmental concerns, there is a requirement to further reduce energy consumption in the food sector, which will result in decoupling food prices. Leveraging on renewable energy is a desirable means of drying agricultural products and concurrently associating them with current drying technologies will also improve their efficiency vastly, exploring operational drying conditions, improving temperature and air flow control (Rabha et al., 2017). An alternative for this could be the adoption of grain storage distribution units and drying technologies on a regional scale. Hence, the objective of this work was to evaluate, on a real scale of production, the quanti-qualitative losses of soybeans influenced by the region production, structure, static storage capacity, and drying technologies.

2. Material and Methods

In the first stage of this study, the structures and static capacity of grain storage were evaluated. Then, a survey of the grain storage units and the logistics of production flow was performed on a regional production basis in Southern Brazil, specifically, the municipality of Cachoeira do Sul, which is considered the second largest grain producer in the state of Rio Grande do Sul. The study region was separated into five micro-regions (South, West, East, North, and Central) based on structure and static storage capacity, temperature and relative humidity of ambient air, and moisture content of grain harvest (Figure 1).

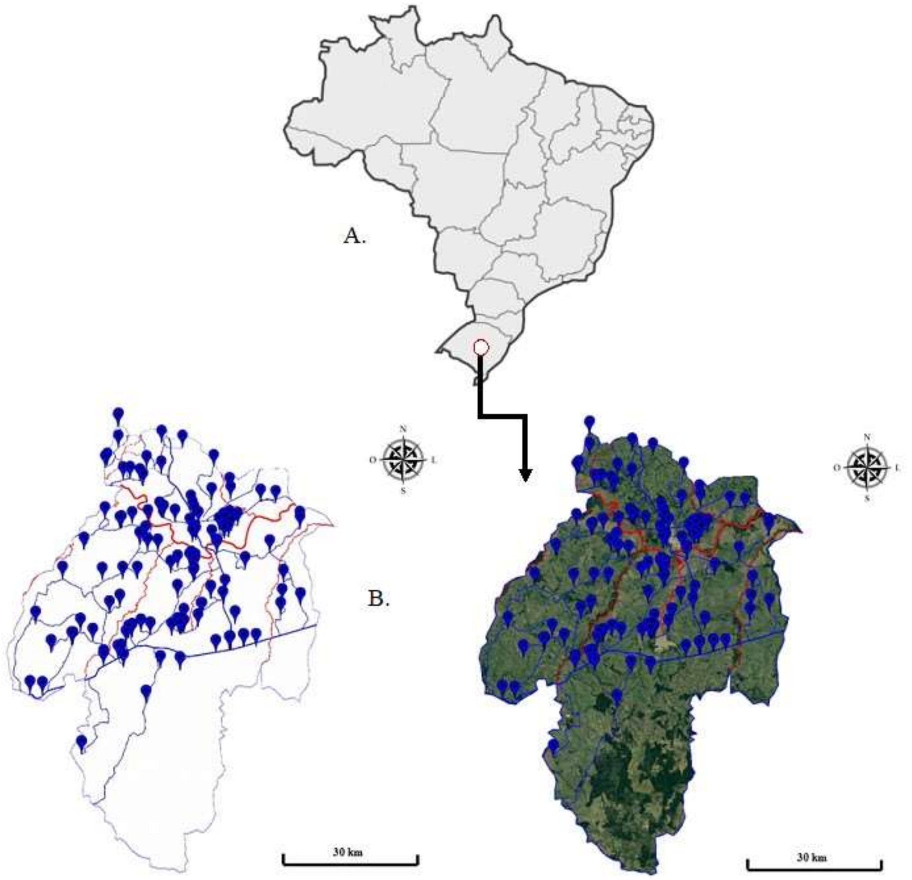

Figure 1. Map of Brazil, state of Rio Grande do Sul (A), location of grain storage units in the municipality of Cachoeira do Sul-RS, Brazil (B).

The inventory volumes and characteristics of storage structures on the experimental area were different in the first and second half of the year. In the first half of the year, grains were harvested the most. During this period, storage in large structures of bulk warehouses for commercialization was predominant (Figures 2A-B). In both storage systems, stocks at farms, service providers, and industries were balanced (Figures 3A-B). In the second half of the year, storage system in vertical silos was predominant, followed by storage in bulk warehouses and conventional bulk warehouses, for long-term storage.

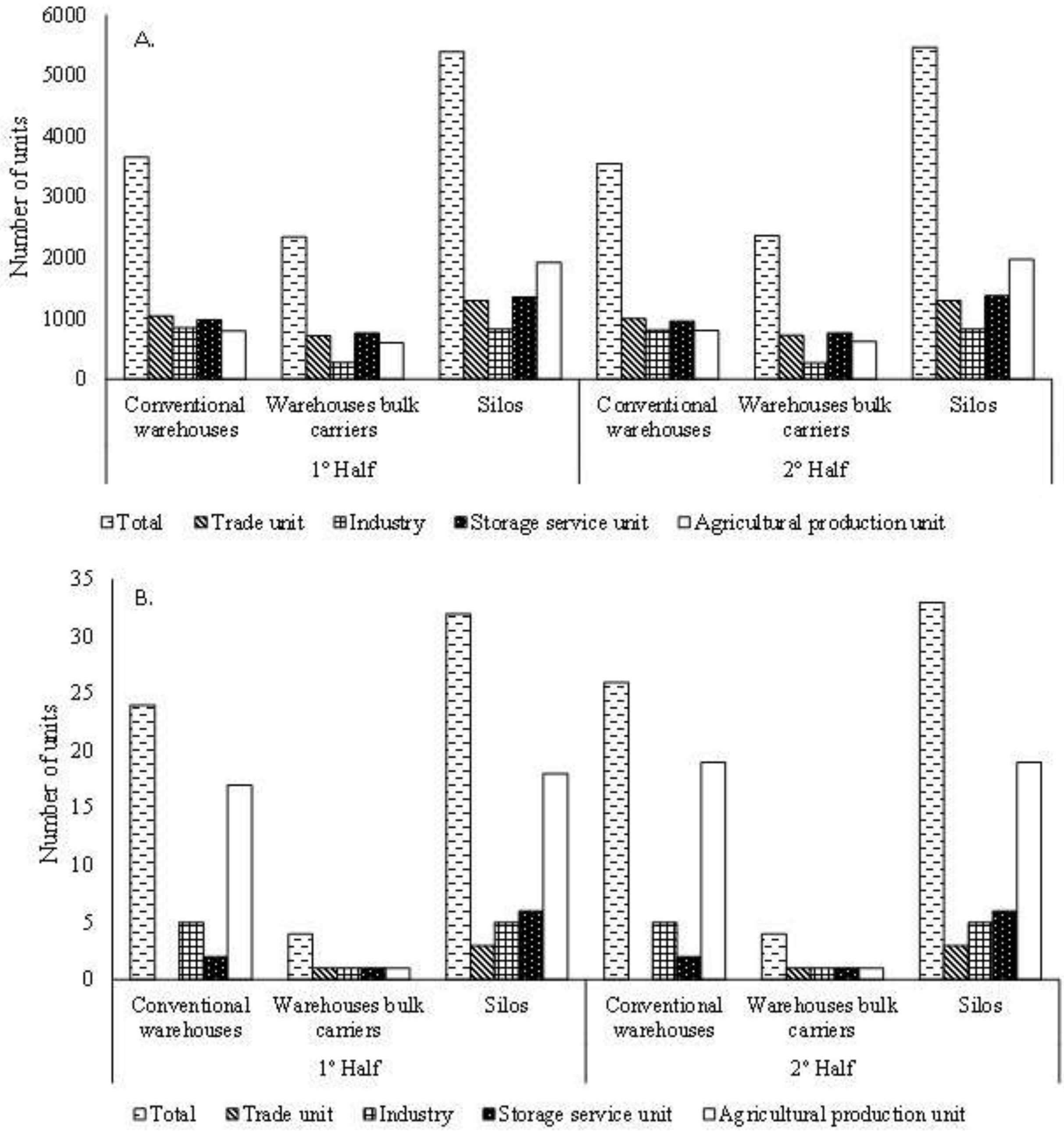

Figure 2. Number of grain storage units in operation in Brazil (A). Number of grain storage units in Cachoeira do Sul / RS (B).

In the northern region, grain storage units were located at an average distance of 19.6 km from main highways, ranging from 0 km to 47.4 km; in the west region, the storage units were located at an average distance of 11.7 km, ranging from 0 km to 27.3 km; in the south, the units were located at an average distance of 5.15 km, ranging from the shortest distance of 12.8 km to the longest distance of 23.1 km; in the east, the units were located at an average distance of 11.3 km, ranging from 0 km to 23.5 km; and in the central region, the units were located at an average distance of 15.2 km, ranging from 0 km to 31.9 km.

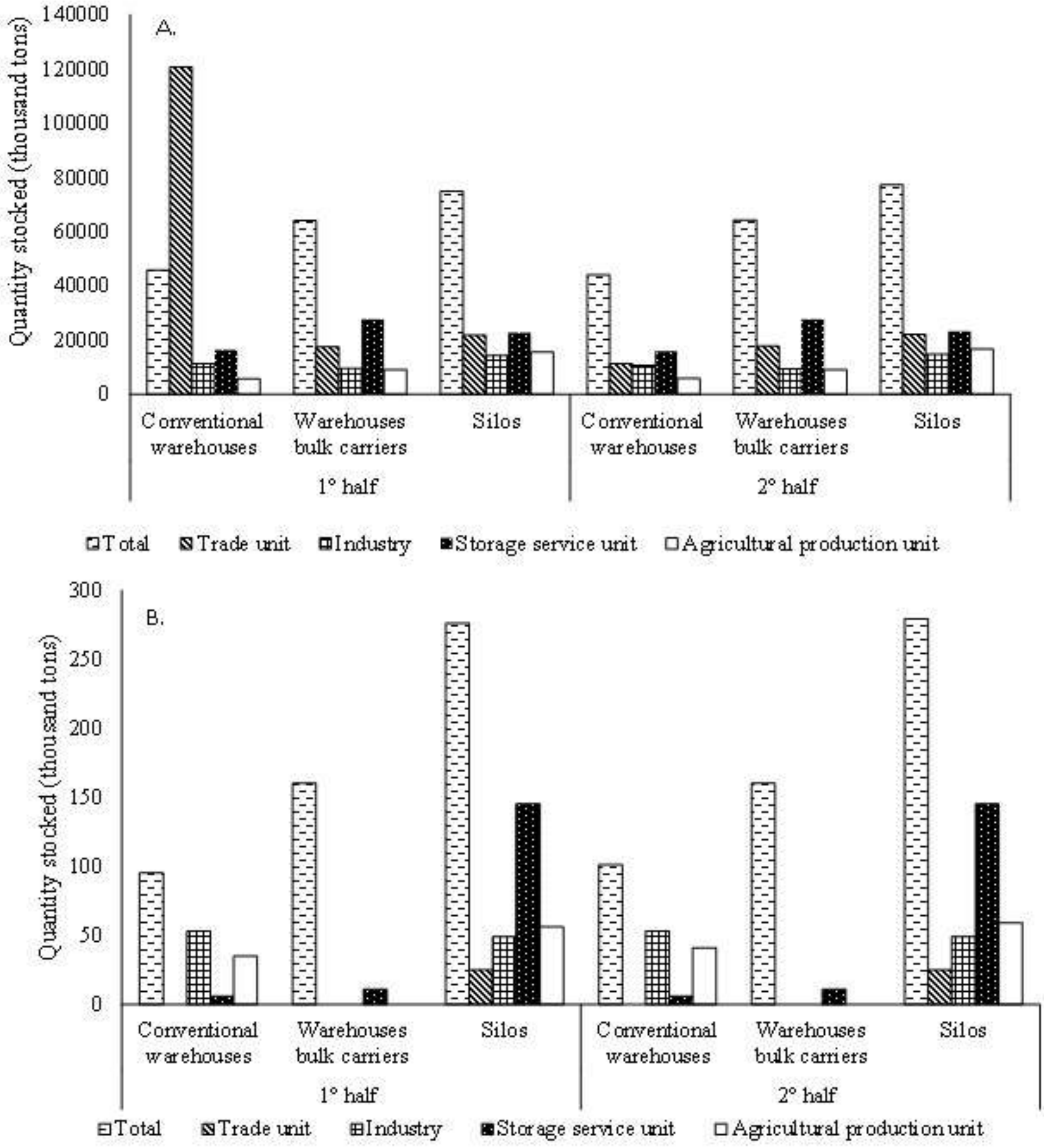

Figure 3. Static grain storage capacity in Brazil (A). Static grain storage capacity in Cachoeira do Sul / RS (B).

The grain storage units evaluated consisted of receiving structures with manual and pneumatic grain extractors with truck unloading manually or with hydraulic plants; pre-cleaning and cleaning systems composed of air machines and sieves, flow drying equipment for grain, and air movement in mixed flows; and stationary dryers (silos-dryers). Storage was carried out in elevated metal silos and horizontal bulk silos with an aeration and dry-aeration system. For each micro-region (West, East, North, South, Central) the drying technologies in the storage units were evaluated (dry soybeans in continuous dryer-CD1, continuous dryer + silo-dryer-CDSD2, continuous dryer + aerator-silo-CDAS3) (Figure 4). Average ambient air conditions varied from 55 to 70% relative humidity and 20 to 31 °C temperature during the period. The soybeans were harvested with moisture contents between 17 and 20%. When drying in CD1, the drying air temperature varied from 80 to 95 °C. When drying in CDSD2, the temperature of the drying air used varied from 80 to 95 °C until the moisture content reached 16% and after in the silo-dryer, the temperature of the dehumidified ambient air (50-60% RH) was used to complete drying. In CDSD3 drying, the drying air temperature was 80 to 95 °C until the moisture content reached 14% and then the grains were dried with natural air aeration until 12%.

Grain samples were collected and sent to a quality control room where technicians determined their moisture content and quality. During grain drying, the air temperature was monitored using a thermocouple sensor installed in the dryer itself and positioned in the transition space of the drying chamber (air-grain mixture). The temperature of grain mass was measured during drying; samples were collected at the exit of the dryer with the aid of a container. Temperature and relative humidity sensors were used to monitor the ambient air temperature, drying air, and exhaust air. Samples were placed next to an iodine thermometer to obtain the temperature. Paddle anemometers were used to measure air velocity at the entry and exit of drying systems.

To evaluate grain quality, an encouraging strategy is the indirect measurement of moisture content of grain samples during drying, correlating with the electrical capacitance of the moisture content. Electrical conductivity test was performed on soybeans. Four replicates of fifty grains were used for each treatment. The grains were weighed on a digital scale to two decimal places, placed in plastic container (200 mL), and then, 75 mL of deionized water was added to each container (Parmar et al., 2018). The cups were placed in germinator previously set at 25 °C for 24 hours. Subsequently, the containers were removed and gently shook. To conduct the tests, an AK51 electric conductivity meter was incorporated with automatic calibration and automatic temperature compensation and used. Results were expressed in µS cm^{-1} g^{-1} (Brazil, 2007).

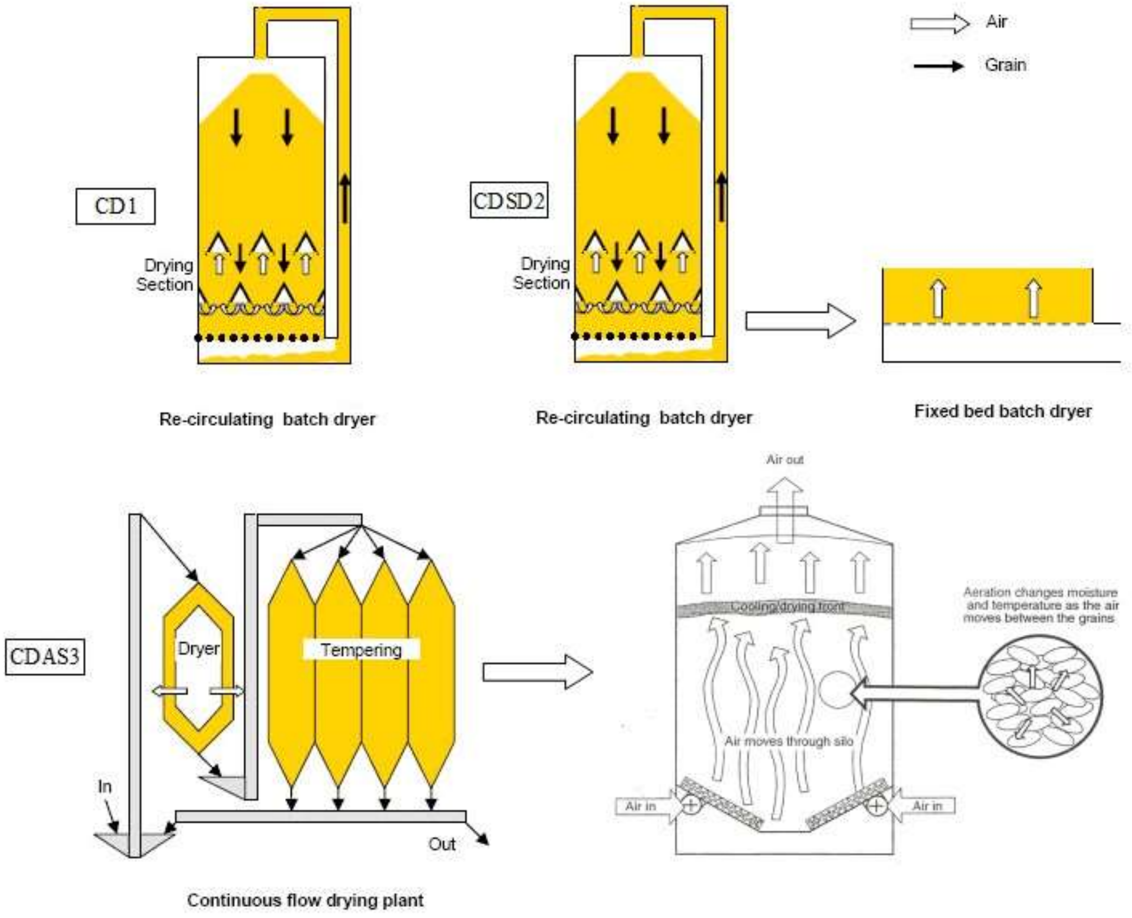

Figure 4. CD1 - dry soybeans in continuous dryer, CDSD2 - dry soybeans in continuous dryer + silo-dryer, CDAS3 - dry soybeans in continuous dryer + aerator-silo.

To determine the percentage of dry matter (DM) of soybean samples, the samples were previously ground to fine size after placing them in a drying oven at 105 ºC for 8 h (AOAC, 1984). The percentage of dry matter of the sample was calculated from the difference between the initial and final weight. Protein content of the soybean sample was determined using the Kjeldahl method (AOAC, 1997). For determination of Nitrogen (N) content, 0.20 g of sample was measured and placed in a digester block together with a catalyst and sulfuric acid at a temperature of 300 °C. After digestion, 10 mL of distilled water and 5 mL of ammonium borate was added for distillation. After distillation, titration with hydrochloric acid was performed. The process was repeated twice for each sample. For the conversion of N values to crude protein (CP), the correction factor of 6.25 was used, considering 16% nitrogen (100/16 = 6.25).

Lipid contents (ether extract - EE) was determined according to AOCS (2005), using ANKOM XT15 equipment and ANKOM XT4 filter bags. Petroleum ether was used as the solvent for extraction at a temperature of 90 ºC for 60 minutes. After extraction, the beakers were placed in an oven until all the solvent had evaporated. The beakers were then removed from the oven and placed in a desiccator until they reached a constant temperature for weighing. The data obtained were analyzed using analysis of variance, and the resulting means separated using Tukey test at 5% probability using Sisvar 5.6 software.

3. Results and Discussion

Grain storage distribution units in the study region and the access roads to the main highways for the outflow of grain production satisfactorily met the regional demand. The grain storage units are located, mainly, in the central part of the region, owing to their proximity to main roads, which connect other regions. In the central region, 60% of the soybeans were dried in continuous dryer (CD1), 10% in continuous dryer + silo-dryer (CDSD2), and 30% in continuous dryer + aerator-silo (CDAS3) storage units. In the southern region, 100% of the drying systems were composed of CD1. In the northern region, 35%, 35%, and 30% of the storage units were composed of CD1, CDSD2, and CDAS3 drying systems, respectively. In the western region, 30%, 30%, and 40% of the drying systems were composed of CD1, CDSD2, and CDAS3, respectively. In the eastern region, the drying systems were composed of 30% CD1, 20% CDSD2, and 50% CDAS3. The soybean lots were harvested and submitted for drying management.

The drying technology influenced the time to reduce the moisture content and the temperature of the grain mass. The CD1 dry soybean took 90 min to reduce the moisture content from 17% to 11.0%, causing an increase in the temperature of the grain mass by an average of 36 to 41 °C. While, in the soybean batches dried in CDSD2 and CDAS3, the drying time was 60 min, remaining with the same variations in the reduction of moisture contents and increases in the grain mass temperature of the CD1.

The removal of moisture from products through drying results from the difference between the vapor pressure of the grain and that of the air, creating a gradient of vapor tension. The moisture is gradually transferred from the interior of the grain to the periphery, owing to capillary movements, moisture diffusion, and vapor pressure gradients (Mayor and Sereno, 2004). Thus, the drying processes and technology layout of the storage units in the regions affected the quality of soybeans (Table 1). The drying carried out with CDSD2-continuous dryer + silo-dryer, CDAS3-continuous dryer + aerator-silo were more suitable for quality of grains; however, in the central region, where the drying systems used were composed of mass monitoring technologies, grain and drying air minimized the effects of dryer types and distribution of storage units.

Some researchers observed a linear reduction of apparent specific mass and unit-specific mass of soybean with increased drying temperature. The increase in storage units, based on region, reduced the volume of dry grains per unit, contributing to a low flow of grain lots from the crop to the drying systems, making it possible to use silo-dryer and drying equipment with slow drying rate. In addition, the maintenance of moisture contents of stored grains when the grains were subjected to drying more evenly, reducing the losses of dry matter and the apparent specific mass of grains (Botelho et al., 2015).

However, improper handling of grain or drying system can cause serious damage to grains. Coradi et al. (2017) described how drying soybeans with moisture content above 19% and air temperature at 120 °C significantly increased the acidity and content of crude oil and protein compared to drying at lower temperatures such as 75, 90, and 105 °C. Others studies evaluated soybeans with moisture content of 23% (w.b.), having subjected them to drying at temperatures of 40, 50, 60, 70, and 80 ºC until the moisture content was 12.5 ± 0.7% (w.b.). The authors concluded that the quality of soybean and crude oil decreases as the drying air temperature increases (Coradi et al., 2020).

The study revealed that when evaporated moisture mass in a drying process is increasingly smaller, mass of dried product and drying yield was increasingly lower. Moreover, the lower the final moisture content of grains, the higher the energy that the drying process consumed for a higher fuel mass flow and higher energy efficiency of the dryer. Results obtained from the current study are favorable for a sustainable system, considering the increase in the use of heat sources based on sustainable biomass. This study presents a viable option for grain-producing regions experiencing high energy costs, reducing greenhouse gas and carbon emissions associated with the use of fossil fuels (Kusnandar et al., 2019).

According to the results shown in Table 1, there are significant differences between drying technologies in terms of developing more sustainable systems. Significant losses in grain quality were observed (0.23 to 3.26% crude protein and 0.15 to 3.05% crude oil) in drying management. Similarly, losses of energy, from firewood used, during drying were from 2.5 to 16.4%. The difference between vapor pressure of grain and air resulted in loss of moisture during drying process (Devahastin and Pitaksuriyarat, 2006). Drying of grain occurs when there is a gradient of vapor tension between grain and air, gradually transferring moisture from the interior of grain to their periphery owing to capillary movements, moisture diffusion, and vapor pressure gradients (Darvishi et al., 2015). This means that the warmer the air, the more moisture is retained, and the better the grain surface dries out (Taşeri et al., 2018). According to these concepts, drying process may be fast or slow depending on the drying technology system and energy use. Regarding energy utilization and grain quality, this study reveals a predominant continuous grain flow and fast drying (Shapiro-Garza et al., 2020).

With regards to operational aspects of production, making postharvest systems more sustainable plays a significant role in reducing losses. Considering the yield and thermal utilization of dryers, proper use of different technologies allows drying of agricultural products in a sustainable way, ensuring the quality of agricultural products, and reducing losses in physical and chemical characteristics (Stathers et al., 2020).

Table 1. Physical and physicochemical quality of soybean grain lots handled in the drying

Microrregions	Analysis	Drying systems		
		CD1	CDSD2	CDAS3
Central Region	*M* (%)	12.31 $^{\pm 0.56}$ A	12.85 $^{\pm 0.47}$ A	12.20 $^{\pm 0.51}$ A
	DM (%)	86.69 $^{\pm 1.38}$ A	84.15 $^{\pm 1.43}$ B	83.80 $^{\pm 1.56}$ C
	CP (%)	42.64 $^{\pm 0.85}$ A	42.02 $^{\pm 0.75}$ A	39.61 $^{\pm 0.88}$ B
	EE (%)	23.41 $^{\pm 1.10}$ A	23.52 $^{\pm 1.08}$ A	23.34 $^{\pm 1.06}$ A
	ρ_{un} (kg m^{-3})	955.20 $^{\pm 10.16}$ C	965.20 $^{\pm 13.71}$ B	971.64 $^{\pm 9.23}$ A
	ρ_{ap} (kg m^{-3})	643.06 $^{\pm 7.32}$ B	633.45 $^{\pm 8.67}$ C	650.05 $^{\pm 8.32}$ A
	ξ (%)	32.67 $^{\pm 3.21}$ A	34.42 $^{\pm 2.45}$ A	33.11 $^{\pm 2.89}$ A
	EC (µS cm^{-1} g^{-1})	133.45 $^{\pm 13.52}$ A	120.67 $^{\pm 15.68}$ B	51.78 $^{\pm 5.32}$ C
South Region	*M* (%)	12.18 $^{\pm 0.66}$ A	12.24 $^{\pm 0.59}$ A	12.67 $^{\pm 0.61}$ A
	DM (%)	83.19 $^{\pm 1.62}$ B	84.65 $^{\pm 1.81}$ A	84.31 $^{\pm 1.97}$ A
	CP (%)	41.86 $^{\pm 0.97}$ B	42.66 $^{\pm 0.82}$ A	42.15 $^{\pm 0.82}$ A
	EE (%)	21.01 $^{\pm 1.18}$ B	21.12 $^{\pm 1.26}$ B	22.24 $^{\pm 1.43}$ A
	ρ_{un} (kg m^{-3})	920.20 $^{\pm 12.47}$ A	918.20 $^{\pm 13.51}$ B	914.14 $^{\pm 15.92}$ C
	ρ_{ap} (kg m^{-3})	618.36 $^{\pm 9.19}$ A	618.35 $^{\pm 10.51}$ A	615.15 $^{\pm 10.63}$ A
	ξ (%)	31.27 $^{\pm 4.19}$ A	31.22 $^{\pm 5.65}$ A	31.22 $^{\pm 7.24}$ A
	EC (µS cm^{-1} g^{-1})	155.25 $^{\pm 17.06}$ A	136.67 $^{\pm 14.00}$ B	67.78 $^{\pm 17.45}$ C

North Region	*M* (%)	12.62 $^{\pm 0.61}$ A	12.16 $^{\pm 0.59}$ A	12.51 $^{\pm 0.61}$ A
	DM (%)	86.19 $^{\pm 1.50}$ A	83.65 $^{\pm 1.81}$ B	83.3 $^{\pm 1.97}$ B
	CP (%)	42.38 $^{\pm 0.91}$ A	41.76 $^{\pm 0.82}$ B	39.35 $^{\pm 0.82}$ C
	EE (%)	22.81 $^{\pm 1.14}$ A	22.92 $^{\pm 1.26}$ A	22.74 $^{\pm 1.43}$ A
	ρ_{un} (kg m^{-3})	928.2 $^{\pm 11.32}$ C	938.2 $^{\pm 13.51}$ B	944.64 $^{\pm 15.92}$ A
	ρ_{ap} (kg m^{-3})	628.06 $^{\pm 8.26}$ B	618.45 $^{\pm 10.51}$ C	635.05 $^{\pm 10.63}$ A
	ξ (%)	32.77 $^{\pm 3.70}$ C	34.52 $^{\pm 5.65}$ A	33.21 $^{\pm 7.24}$ B
	EC (µS cm^{-1} g^{-1})	149.45 $^{\pm 15.29}$	136.67 $^{\pm 14.00}$	67.78 $^{\pm 17.45}$
Eastern Region	*M* (%)	12.45 $^{\pm 0.71}$ A	12.99 $^{\pm 0.71}$ A	12.34 $^{\pm 0.55}$ A
	DM (%)	86.39 $^{\pm 1.74}$ A	83.85 $^{\pm 2.07}$ B	83.5 $^{\pm 1.84}$ B
	CP (%)	42.42 $^{\pm 1.03}$ A	41.8 $^{\pm 0.96}$ B	39.39 $^{\pm 0.75}$ C
	EE (%)	22.91 $^{\pm 1.22}$ A	23.02 $^{\pm 1.32}$ A	22.84 $^{\pm 1.40}$ A
	ρ_{un} (kg m^{-3})	930.2 $^{\pm 13.63}$ C	940.2 $^{\pm 15.89}$ B	946.64 $^{\pm 14.73}$ A
	ρ_{ap} (kg m^{-3})	635.06 $^{\pm 10.13}$ B	625.45 $^{\pm 12.47}$ C	642.05 $^{\pm 9.65}$ A
	ξ (%)	32.78 $^{\pm 4.68}$ C	34.53 $^{\pm 6.43}$ A	33.22 $^{\pm 6.85}$ B
	EC (µS cm^{-1} g^{-1})	143.45 $^{\pm 18.83}$ A	130.67 $^{\pm 18.56}$ B	61.78 $^{\pm 15.17}$ C
West Region	*M* (%)	12.11 $^{\pm 0.69}$ A	12.34 $^{\pm 0.68}$ A	12.03 $^{\pm 0.67}$ A
	DM (%)	84.99 $^{\pm 1.68}$ A	84.79 $^{\pm 2.01}$ A	84.00 $^{\pm 2.10}$ A
	CP (%)	41.52 $^{\pm 1.00}$ A	41.18 $^{\pm 0.93}$ A	41.52 $^{\pm 0.89}$ A
	EE (%)	20.85 $^{\pm 1.20}$ A	20.69 $^{\pm 1.31}$ A	20.85 $^{\pm 1.46}$ A
	ρ_{un} (kg m^{-3})	916.8 $^{\pm 13.05}$ A	913.4 $^{\pm 15.30}$ B	916.8 $^{\pm 17.11}$ A
	ρ_{ap} (kg m^{-3})	614.15 $^{\pm 9.66}$ A	609.94 $^{\pm 11.98}$ B	614.15 $^{\pm 11.61}$ A
	ξ (%)	31.13 $^{\pm 4.44}$ A	30.99 $^{\pm 6.24}$ A	31.13 $^{\pm 7.63}$ A
	EC (µS cm^{-1} g^{-1})	163.25 $^{\pm 17.95}$ B	171.25 $^{\pm 17.42}$ A	163.25 $^{\pm 19.73}$ B

M - moisture content, *DM* - dry matter, *CP* - crude protein, *EE* - ethereal extract, ρ_{un}- specific unit mass, ρ_{ap} - apparent specific mass, ξ - porosity, *EC* - electrical conductivity. CD1-dry soybeans in continuous dryer, CDSD2-continuous dryer + silo-dryer, CDAS3-continuous dryer + aerator-silo-CDAS3. Averages followed by the same letter in the line do not differ from each other at 5% probability.

Thus, it is estimated that the real values of postharvest quanti-qualitative losses are obtained within the productive context of a region with appropriate local characteristics, in which drying technologies and grain flows are factors that delineate the parameters of a model for control and management of soybeans during postharvest, with the lowest percentages of possible losses (Bakhtavar et al., 2019). In the regional context, it was observed that static storage capacity of the evaluated region met the production of grains, owing to the predominant use of storage service provider units. Over the years, there have been results similar to and that corroborate the results of the current study. Analyzing the storage capacity in the regions, the Brazil has always had a deficit in storage structures and that the surpluses observed in recent years was due to reduction in production, owing to observed climatic adversities and not an increase in static storage capacity (Bakhtavar and Afzal, 2020).

In recent years, static capacity in Brazil has not maintained pace with crop increase. Therefore, there are space in critical regions to better adapt and expand storage, as a means of helping producers retain their production, so as to keep up with the best seasons and even avoid major congestion in ports, warehouses, and silos. These same researchers warned against the mistake that could be made when issues of static storage capacity are simply confronted based on production, because, in practice, harvests do not commensurate storage capacities and entire products are not harvested simultaneously. Similarly, not all harvested crops are stored; some could be exported or readily sold to consumer in the market. In addition, price quotations also determine the dynamics of marketing and storage. Thus, a universal parameter was proposed to deal with inventory turnover and would serve as an indicator of technical and economic viability of dynamic capacity (Medeiros et al., 2020).

Mourtzinis et al. (2019) analyzed the relationship between production and storage capacity of agricultural products, in dynamic perspectives of the regions. The average production from 2005 to 2008 harvests was calculated to generate the dynamic storage availability index and suggest a critical situation for most of the surveyed micro-regions. For a more complete analysis, it would also be necessary for the National Register of Storage Units to include those units owned by rural producers, which do not have the National Register of Legal Entities but have significant storage capacity (Amjad et al., 2015).

Rocha et al. (2019) analyzed the possibility of logistical gains through storage of grain from soybean market by producers in the region of Sorriso, state of Mato Grosso, at different periods, during the years 2009, 2010, and 2011. Their results indicate that storage strategy should be evaluated. Parmar et al. (2018) studied the storage infrastructure and grain flow. Among the results obtained, the author identified a shortage of 41.85% in storage capacity, which is equivalent to over 20 million tons. He also found that the current logistics employed are inefficient and do not integrate postharvest with product distribution. The author suggested storage at farm level as an alternative to reducing losses and adding value to product.

In regions with large-scale soybean production, the adoption of storage unit structures at farm level ranging from 11 to 19 km; depending on the volume of grains, with high drying technology, in partial continuous grain flow, and final stationary drying in a silo-dryer or silo-aerator; is the best alternative for a productive-sustainable system in soybean and energy quality, reducing losses by increasing the potential of resources applied during postharvest. Managing CDSD2 and CDAS3 soybean drying is an alternative that ensures low losses and high grain quality and improves protein and crude oil content; therefore, energy impacts is reduced and efficiency of the drying system is increased.

4. Conclusions

This study concludes that CDSD2 and CDAS3 drying system reduces the physical, crude protein and oil content losses until 95%. In conclusion, postharvest quanti-qualitative losses of grains bring an imbalance in grain productive sector, and the variation of moisture content of grain mass and temperature and relative humidity of their intergranular air may influence their storage ecosystem. To reduce grain losses during storage stage, it is essential that crushed grains are uniform in quality and go through cleaning and drying processes. The heterogeneity of harvested grain lots from the beginning to the end of harvesting period hinders the capacities of dryers. Therefore, it is necessary to closely monitor and manage moisture content in grain mass and their drying air temperature to ensure process optimization.

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CHAPTER 3

(Paper published on the Scientific Reports)

Mathematical modeling and multivariate analysis applied earliest soybean harvest associated drying and storage conditions and influences on physicochemical grain quality

Abstract: Anticipating the harvest period of soybean crops can impact on the post-harvest processes. This study aimed to evaluate early soybean harvest associated drying and storage conditions on the physicochemical soybean quality using of mathematical modeling and multivariate analysis. The soybeans were harvested with a moisture content of 18 and 23% (d.b.) and subjected to drying in a continuous dryer at 80, 100, and 120 °C. The drying kinetics and volumetric shrinkage modeling were evaluated. Posteriorly, the soybean was stored at different packages and temperatures for 8 months to evaluate the physicochemical properties. After standardizing the variables, the data were submitted to cluster analysis. For this, we use Euclidean distance and Ward's hierarchical method. Then defining the groups, we constructed a graph containing the dispersion of the values of the variables and their respective Pearson correlations for each group. The mathematical models proved suitable to describe the drying kinetics. Besides, the effective diffusivity obtained was 4.9 x 10^{-10} m^2 s^{-1} promoting a volumetric shrinkage of the grains and influencing the reduction of physicochemical quality. It was observed that soybean harvested at 23% moisture, dried at 80 ºC, and stored at a temperature below 23 ºC maintained its oil content (25.89%), crude protein (35.69%), and lipid acidity (5.54 mL). In addition, it is to note that these correlations' magnitude was substantially more remarkable for the treatments allocated to the G2 group. Furthermore, the electrical conductivity was negatively correlated with all the physicochemical variables evaluated. Besides this, the correlation between crude protein and oil yield was positive and of high magnitude, regardless of the group formed. In conclusion, the early harvest of soybeans reduced losses in the field and increased the grain flow on the storage units. The low-temperature drying and the use of packaging technology close to environmental temperatures conserved the grain quality.

Keywords: postharvest technology; pre-processing of soybean; soybean conservation; industrial processing.

1. Introduction

Soybean accounts for approximately 90% of vegetable oil production and more than 80% of biodiesel production[1]. To store and sell soybeans, moisture content should not exceed 14%, which can be reduced to 12%, improving the quality of storage[2]. However, soybean drying when it is not properly controlled and handled can cause physical and latent damage, which may be aggravated in the following stages of storage[3,4,5,6].

The anticipation of the soybean harvest period can impact the post-harvest processes. Thus, early harvesting of soybeans with higher moisture content can reduce adverse effects of weather and climate conditions. In addition, the completion of the harvest period will be possible to manage the soybean batches to improve post-harvest operations and reduce losses in these stages.

It should be noted that on the drying of the grain there are simultaneous heat and mass transfer. Thus, the water is moving in the grains by the liquid diffusion process at drying temperature below 100 °C. In this case, the vaporization of the water takes place on the grain surface. However, when the temperature of the air-drying is above 100 °C, there is usually a vapor diffusion process[7,8,9]. The drying provides water loss, which may cause damage to the cellular structure of the product; this leads to changes in shape and a decrease in its dimensions[10,11,12]. However, the shrinkage of plant products during drying is not only linked to water content; it depends also on the drying conditions, shape, and size of the product.

The understanding of the heat and mass transfer process in the drying process implies the decision-making of dryer projects and in the grain mass management during the drying operation[13]. The air temperature and product flow must be monitored during drying, as the variation of these parameters will interfere with the drying time and how the water diffusivity and vaporization of the grains can change the physical and chemical characteristics of the grains, reducing their quality[14,15,16].

Under conditions of drying air temperatures above 40 °C, physical damage and reduced physicochemical quality are observed in soybean. At elevated temperatures (> 80 ºC), the protein and lipid content can decrease by up to 0.5% and 0.43%, respectively, and the acidity content can increase by up to 0.23 mg KOH/g. The use of mathematical modeling of drying is an alternative to verify which are the best operating conditions and viability of the drying system[17,18,19,20,21].

Soybean production takes place at specific times of the year, depending on the region. Therefore, for the processing industries to operate all year round, soybeans must be properly stored to supply industrial demand. The storage environment determines the activity of all biotic components in the system, which leads to safe storage or product loss[22,23,24]. During storage, changes also occur in the physicochemical and technological properties of soybean. The changes are related to the storage time, associated with the temperature and moisture content of the soybean. In addition to the effects caused by the storage conditions, some changes in the soybean may also come from the harvest period and drying conditions used, worsening in storage.

To minimize the effects of drying and storage operations, it is suggested to manage the soybean batches after harvest. As a hypothesis, soybeans harvested in advance, with moisture contents close to 23% (d.b.) would not compromise the flow of batches in the storage units. Thus, drying can be carried out slowly, with a temperature below 100 ºC, which would help in the conservation of soybeans during storage at a temperature below 23 ºC. The anticipation of the harvest it could be increasing the time for crop rotation in the field, reduce investments with drying and storage structures.

Multivariate analysis has been applied in several studies in the area of drying and grain storage when there is greater experimental complexity[2,6,9]. Due to a large number of treatments in researches in this area, the analysis of principal components and correlations allow verifying the interrelationship of these treatments with the variables evaluated clearly, making it possible to better explore these results. Depending on the experimental conditions involved in this study, it is suggested to apply the technique to verify the groupings of factors and correlations of quantifiable and qualitative variables for a better conclusion. The objective of the study was to evaluate early soybean harvest associated with drying and storage conditions on the physicochemical properties quality using mathematical modeling and multivariate analysis.

2. Material and Methods

2.1 Material

Soybean (*Glycine max* L.) of the cultivar BRS 7570 IPRO with an average cycle of 109 days was cultivated at a density of 360 to 380 thousand plants per hectare, in a high fertility soil, reaching a productivity of 4920 kg per hectare. Soybeans were harvested with 23% (d.b.) and 18% (d.b.) moisture content.

2.2 Drying conditions

The soybean was subjected to drying in a continuous dryer (Figure 1), commercial convectional model dryer-KW-Khronos, capacity 60 t h^{-1} (Kepler Weber, Panambi, Brazil), at 80, 100, and 120 °C. We consider thin layer drying due to the high airflow (238 m^3/h) that occupies a large part of the drying chamber and crosses a thin layer of grains in downward movement. The dryer has a specific point in the drying chamber for the passage of heated air, where measurements and sampling of the grains were carried out.

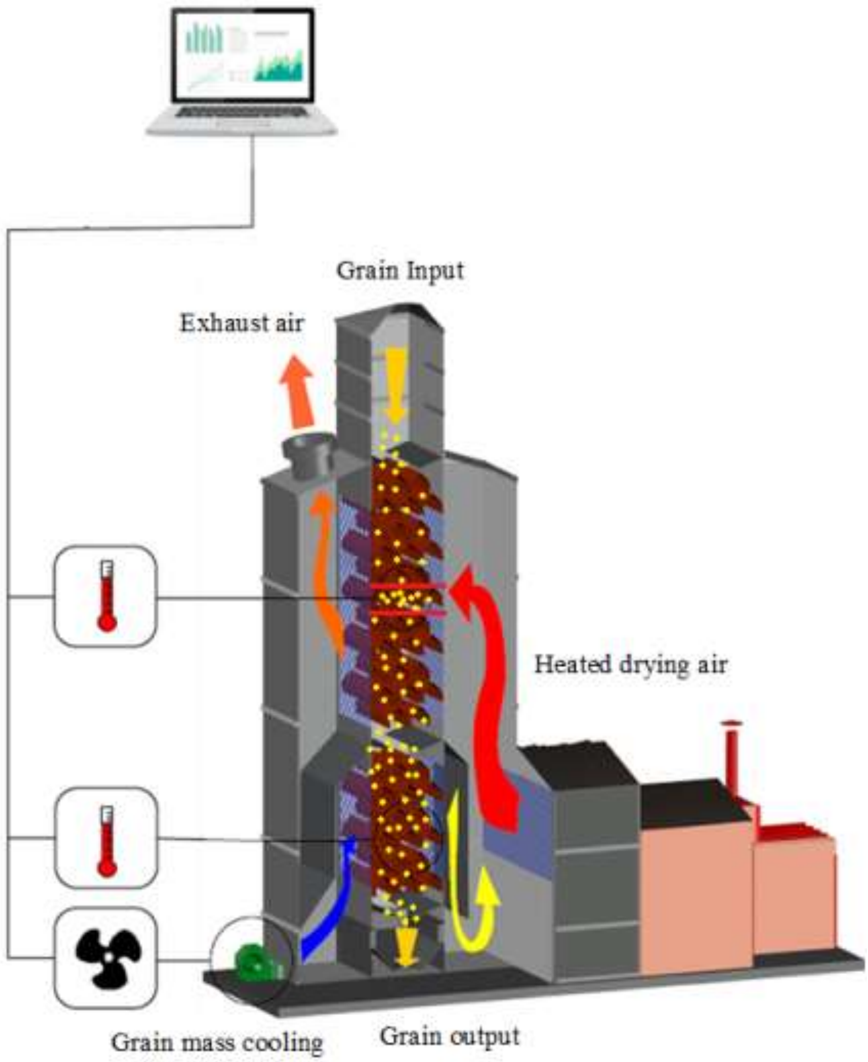

Figure 1. Schema of the dryer system.

Three tests were performed for each initial moisture content grain harvested (18 and 23%) and drying air temperature (80, 100, and 120 °C) for three repetitions. During drying, soybean samples were collected at 15 min intervals to determine the moisture content and volumetric shrinkage. In total was collected 102 samples of 2 kg were at the exit of the drying chamber on the bucket elevator belt. Drying was carried out until the grains reached moisture contents of 11% (d.b.). At the end of the drying, a sample of each repetition (a total of 18 samples) was collected to determine the physicochemical grain quality.

The moisture contents were measured by the indirect method of electrical capacitance using the G650i model equipment (Gehaka, São Paulo, Brazil) calibrated by drying oven method TE-394/2-MP model (Tecnal, Piracicaba, SP, Brazil), with convective heated air at 105 ± 1°C for 24 h and forced ventilation with air. Then, the sample was sent to a desiccator with silica for cooling, for 5 min. The moisture content was calculated by the initial and final difference of the sample weight using a digital balance, model B13200H (Shimadzu, Kyoto, Japan), in three replications25. We also measured the temperature and relative humidity of the ambient. The temperature and relative humidity were checked with studio monitors with the aid of a psychrometer, model PY-5080 (Instrufiber, São Paulo, Brazil).

The volume (Vg) of the fifty grains was determined at each sampling performed during the drying process with the aid of a caliper, according to the expression (1)26. The unitary volumetric shrinkage (Ψg) during the drying of the product was determined by the ratio between the final and initial volumes of the grain for each moisture content.

$$Vg = \frac{\pi abc}{6} \quad (1)$$

where,

a: major axis of the grain (mm)

b: mean axis of the seed (mm)

c: minor axis of the seed (mm)

The experimental unit shrinkage, expressed by the following mathematical models have been adjusted[26,33]:

Models references	Models	
Bala and Woods	$\Psi_g = a\{1\text{-exp}[b(\overline{X} - X_0)]\}$	(2)
Lang and Sokhansanj	$\Psi_g = a+ß_1(\overline{X} - X_0)$	(3)
Rahman	$\Psi_g = a+ß_2(\overline{X} - X_0)$	(4)
Corrêa	$\Psi_g = 1/[a+b\exp(\overline{X})]$	(5)
Line	$\Psi_g = a+b\overline{X}$	(6)
Exponential	$\Psi_g = a\exp(b\overline{X})$	(7)

where,

Ψ_g: unit volume shrinkage (d.b.)

$\overline{X}$: moisture content of the product (d.b.)

X_0: initial moisture content of the product (d.b.)

$ß_1$: $a + b(UR) + c(T)$

a, *b*: parameters that depend on the product

T: air temperature (ºC)

$ß_2$: volumetric coefficient, dimensionless contraction.

The drying curves were fitted to the experimental data using thirteen different semi-empirical and empirical equations[4,10,11,19,20,27,28,30], discriminated below:

Models	Models references	
$MR = \exp(-kt)$	Newton	(8)
$MR = \exp(-kt^n)$	Page	(9)
$MR = \exp(-(kt)^n)$	Page Modified	(10)
$MR = a\exp(-kt)$	Henderson & Pabis	(11)
$MR = a\exp(-kt) + c$	Logarithmic	(12)
$MR = a\exp(-k_o t) + b\exp(-k_1 t)$	Two Terms	(13)
$MR = a\exp(-\kappa\tau) + (1-a)\exp(-kat)$	Two Exponential Terms	(14)
$MR = 1 + at + bt^2$	Wang & Singh	(15)
$MR = a\exp(-kt) + b\exp(-k_0 t) + c\exp(-k_1 t)$	Henderson & Pabis	(16)
$MR = a\exp(-kt^n) + bt$	Midilli	(17)
$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	Diffusion approximation	(18)

where,

MR: moisture ratio (dimensionless)

t: drying time (h)

k, k_o, k_1: drying constant (h^{-1})

a, *b*, *c*, *n*: model coefficients

For determining the ratios of moisture during drying under different conditions, the following expression was used (equation 19)[4,10,19,27]:

$$MR = \frac{\overline{X} - X_e}{X_0 - X_e} \qquad (19)$$

where,

X_e: equilibrium moisture content of the product (d.b.)

In thin-layer drying of agricultural products, analysis of the dehydration process that takes place in the falling rate period is calculated using a simple diffusion model based on Fick's second law. Evaluation of the moisture diffusion mechanism in spherical bodies can be represented by the following equation 20[27,33]:

$$\frac{\partial X}{\partial t} = \frac{D}{r^2}\left[\frac{\partial}{\partial r}\left(r^2\frac{\partial X}{\partial r}\right)\right] \tag{20}$$

where,

X: moisture content (kg_{water}/kg_{DS})

t: time (s)

D: diffusivity ($m^2\ s^{-1}$)

r: radius coordinate (m)

The method of slopes was used for the estimation of effective moisture diffusivity of soybean kernels at corresponding moisture content under different drying conditions. The uniform moisture content was assumed as the initial condition (Equation 21). Due to the geometry, the asymmetry boundary condition was defined (Equation 22). Finally, the second boundary condition was the neglect of external resistance (Equation 23)[27,33]:

$$X(r,0) = X_0 \tag{21}$$

$$\frac{\partial X}{\partial r}(0,t) = 0 \tag{22}$$

$$X(R,t) = X_e \tag{23}$$

A sphere with initial moisture content, which is subjected to the drying process in the open air, under constant conditions, can be described by Fick's theory, having the following analytical solution (Equation 24)[28,30]:

$$MR = \frac{\overline{X} - X_e}{X_0 - X_e} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(\frac{-Dn^2\pi^2 t}{R^2}\right) \tag{24}$$

where,

R: sphere radius (m)

It is usual to consider the value of the diffusion coefficient constant or linearly. This relationship has been expressed by the Arrhenius model (Equation 25)[20]:

$$D = A\exp\left(-\frac{E}{RT}\right) \tag{25}$$

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)

2.3 Storage conditions

Soybeans harvested at different moisture content (18 and 23%) and dried at different temperatures (80, 100, and 120 °C) were stored in paper and plastic raffia-polyethylene bags at 15, 23, and 30 °C in climatic chambers for 0, 4, and 8 months. Three repetitions per treatment were performed. A total of 432 soybean samples were collected and submitted to physicochemical quality assessments.

2.4 Physicochemical quality of soybeans

The moisture content, oil content, acid index, and crude protein content (% d.b.) were determined according to AOAC[25]. The electrical conductivity test was conducted in soybean, according to Vieira & Krzyzanowski[29].

2.5 Statistical analysis

To adjust the mathematical models of analysis of soybean drying, nonlinear regression was performed, through the Quasi-Newton method, using the computer program Statistica 7.0®. To check the degree of fit of each model, the significance of the regression coefficient by t-test was considered, adopting the 1 and 5% level of probability, the magnitude of the coefficient of determination (R^2), the mean relative error values (P), the average estimated error (SE), and verified the behavior of the distribution of residuals. The relative average error and the average error estimated for each model were calculated according to the following expressions, respectively:

$$P = \frac{100}{n} \sum \frac{|Y - \hat{Y}|}{Y} \tag{26}$$

$$SE = \sqrt{\frac{\sum (Y - \hat{Y})^2}{GLR}} \tag{27}$$

where,

Y: experimentally observed value

$\hat{Y}$: value calculated by the model

n: number of experimental observations

GLR: degrees of freedom of the model

The data for physicochemical quality were analyzed by analysis of variance, Tukey's test at 1 and 5% probabilities, and linear regression. After standardizing the variables, the data were submitted to cluster analysis. For this, we use Euclidean distance and Ward's hierarchical method. After defining the groups, we constructed a graph containing the dispersion of the values of the variables and their respective Pearson correlations for each group. These analyzes were performed with the "ggfortify" and "GGally" packages from software R (Table S1).

Table S1. Experimental design and clusters of drying and storage conditions

Initial drying moisture content (%)	Drying air temperature (°C)	Packaging	Storage temperature (°C)	Storage time (months)	Treatments	Clusters
18	Mixed	Permeable	23	4	C23	G1
18	Mixed	Permeable	15	4	C26	G1
18	Mixed	Impermeable	23	4	C32	G1
18	Mixed	Impermeable	15	4	C35	G1
18	100	Permeable	30	4	C38	G1
18	100	Permeable	23	4	C41	G1
18	100	Permeable	15	4	C44	G1
18	100	Impermeable	30	4	C47	G1
18	100	Impermeable	23	4	C50	G1
18	100	Impermeable	15	4	C53	G1
18	120	Permeable	30	4	C56	G1
18	120	Permeable	23	4	C59	G1
18	120	Permeable	15	4	C62	G1
18	120	Impermeable	30	4	C65	G1
18	120	Impermeable	15	4	C68	G1
23	Mixed	Permeable	23	4	C95	G1
23	Mixed	Permeable	15	4	C98	G1
23	Mixed	Impermeable	23	4	C104	G1
23	Mixed	Impermeable	15	4	C107	G1
23	100	Permeable	30	4	C110	G1
23	100	Permeable	23	4	C113	G1
23	100	Permeable	15	4	C116	G1
23	100	Impermeable	30	4	C119	G1
23	100	Impermeable	23	4	C122	G1
23	100	Impermeable	15	4	C125	G1
23	120	Permeable	30	4	C128	G1
23	120	Permeable	23	4	C131	G1
23	120	Permeable	15	4	C134	G1
23	120	Impermeable	30	4	C137	G1
23	120	Impermeable	23	4	C140	G1
18	Mixed	Permeable	30	8	C21	G1
18	Mixed	Permeable	23	8	C24	G1
18	Mixed	Permeable	15	8	C27	G1
18	Mixed	Impermeable	30	8	C30	G1
18	Mixed	Impermeable	23	8	C33	G1
18	Mixed	Impermeable	15	8	C36	G1
18	100	Permeable	30	8	C39	G1
18	100	Permeable	23	8	C42	G1
18	100	Permeable	15	8	C45	G1
18	100	Impermeable	30	8	C48	G1

18	100	Impermeable	23	8	C51	G1
18	120	Permeable	30	8	C57	G1
18	120	Permeable	23	8	C60	G1
18	120	Permeable	15	8	C63	G1
18	120	Impermeable	30	8	C66	G1
18	120	Impermeable	23	8	C69	G1
18	120	Impermeable	15	8	C72	G1
25	Mixed	Permeable	30	8	C93	G1
25	Mixed	Permeable	23	8	C96	G1
25	Mixed	Permeable	15	8	C99	G1
25	Mixed	Impermeable	30	8	C102	G1
25	Mixed	Impermeable	23	8	C105	G1
25	Mixed	Impermeable	15	8	C108	G1
23	100	Permeable	30	8	C111	G1
23	100	Permeable	23	8	C114	G1
23	100	Permeable	15	8	C117	G1
23	100	Impermeable	30	8	C120	G1
23	100	Impermeable	23	8	C123	G1
23	120	Permeable	30	8	C129	G1
23	120	Permeable	23	8	C132	G1
23	120	Permeable	15	8	C135	G1
23	120	Impermeable	30	8	C138	G1
23	120	Impermeable	23	8	C141	G1
23	120	Impermeable	15	8	C144	G1
18	Mixed	Permeable	30	0	C19	G2
18	Mixed	Permeable	23	0	C22	G2
18	Mixed	Permeable	15	0	C25	G2
18	Mixed	Impermeable	30	0	C28	G2
18	Mixed	Impermeable	23	0	C31	G2
18	Mixed	Impermeable	15	0	C34	G2
18	100	Permeable	23	0	C40	G2
18	100	Permeable	15	0	C43	G2
18	100	Impermeable	30	0	C46	G2
18	100	Impermeable	23	0	C49	G2
18	100	Impermeable	15	0	C52	G2
18	120	Permeable	30	0	C55	G2
18	120	Permeable	23	0	C58	G2
18	120	Permeable	15	0	C61	G2
18	120	Impermeable	30	0	C64	G2
18	120	Impermeable	23	0	C67	G2
18	120	Impermeable	15	0	C70	G2
23	Mixed	Permeable	30	0	C91	G2
23	Mixed	Permeable	23	0	C94	G2
23	Mixed	Permeable	15	0	C97	G2
23	Mixed	Impermeable	30	0	C100	G2
23	Mixed	Impermeable	23	0	C103	G2
23	Mixed	Impermeable	15	0	C106	G2
23	100	Permeable	23	0	C112	G2
23	100	Permeable	15	0	C115	G2
23	100	Impermeable	30	0	C118	G2
23	100	Impermeable	23	0	C121	G2
23	100	Impermeable	15	0	C124	G2
23	120	Permeable	30	0	C127	G2
23	120	Permeable	23	0	C130	G2
23	120	Permeable	15	0	C133	G2
23	120	Impermeable	30	0	C136	G2
23	120	Impermeable	23	0	C139	G2
23	120	Impermeable	15	0	C142	G2
18	80	Permeable	30	0	C1	G3
18	80	Permeable	23	0	C4	G3

18	80	Permeable	15	0	C7	G3
18	80	Impermeable	30	0	C10	G3
18	80	Impermeable	23	0	C13	G3
18	80	Impermeable	15	0	C16	G3
23	80	Permeable	30	0	C73	G3
23	80	Permeable	23	0	C76	G3
23	80	Permeable	15	0	C79	G3
23	80	Impermeable	30	0	C82	G3
23	80	Impermeable	23	0	C85	G3
23	80	Impermeable	15	0	C88	G3
18	80	Permeable	30	4	C2	G3
18	80	Permeable	23	4	C5	G3
18	80	Permeable	15	4	C8	G3
18	80	Impermeable	30	4	C11	G3
18	80	Impermeable	23	4	C14	G3
18	80	Impermeable	15	4	C17	G3
23	80	Permeable	30	4	C74	G3
23	80	Permeable	23	4	C77	G3
23	80	Permeable	15	4	C80	G3
23	80	Impermeable	30	4	C83	G3
23	80	Impermeable	23	4	C86	G3
23	80	Impermeable	15	4	C89	G3
18	80	Permeable	15	8	C9	G3
18	80	Impermeable	23	8	C15	G3
18	80	Impermeable	15	8	C18	G3
23	80	Permeable	15	8	C81	G3
23	80	Impermeable	23	8	C87	G3
23	80	Impermeable	15	8	C90	G3
18	100	Permeable	30	0	C37	G4
23	100	Permeable	30	0	C109	G4
18	Mixed	Permeable	30	4	C20	G4
18	Mixed	Impermeable	30	4	C29	G4
18	120	Impermeable	15	4	C71	G4
23	Mixed	Permeable	30	4	C92	G4
23	Mixed	Impermeable	30	4	C101	G4
23	120	Impermeable	15	4	C143	G4
18	80	Permeable	30	8	C3	G4
18	80	Permeable	23	8	C6	G4
18	80	Impermeable	30	8	C12	G4
18	100	Impermeable	15	8	C54	G4
23	80	Permeable	30	8	C75	G4
23	80	Permeable	23	8	C78	G4
23	80	Impermeable	30	8	C84	G4
23	100	Impermeable	15	8	C126	G4

Permeable – Paper bags, Impermeable - Plastic raffia - polyethylene bags, Mixed – dried grains at 80, 100 and 120 °C and mixed for storage.

3. Results and Discussion

3.1 Drying kinetics and quality of soybeans on the drying

In the results obtained (Figure 2A), the drying curves at different temperatures describe a logical behavior and values. It was observed that the increase in the drying air temperature to lower the initial moisture content of the soybean reduced the drying time. However, at the end of the process, the grains reached the same moisture ratio. Soybeans with initial moisture contents of 23% (d.b.) and drying at 80 °C completed the drying process in a higher time of 2.6 h, while soybean with initial moisture contents of 18% (d.b.) subjected at 120 °C took 0.7 h to complete the process. The other conditions evaluated varied the drying time from 0.8 to 2.0 h. During the drying period, the ambient air temperature varied between 22 and 26 °C and the relative humidity between 50 and 65%. Regardless of the initial moisture contents, in the final third of drying with an air temperature above 100 °C there was an increase in the temperature of the grain mass to 45 °C, while in the drying at 80 °C and from the middle of the process, the soybean remained with a mass temperature between 36 and 38 °C.

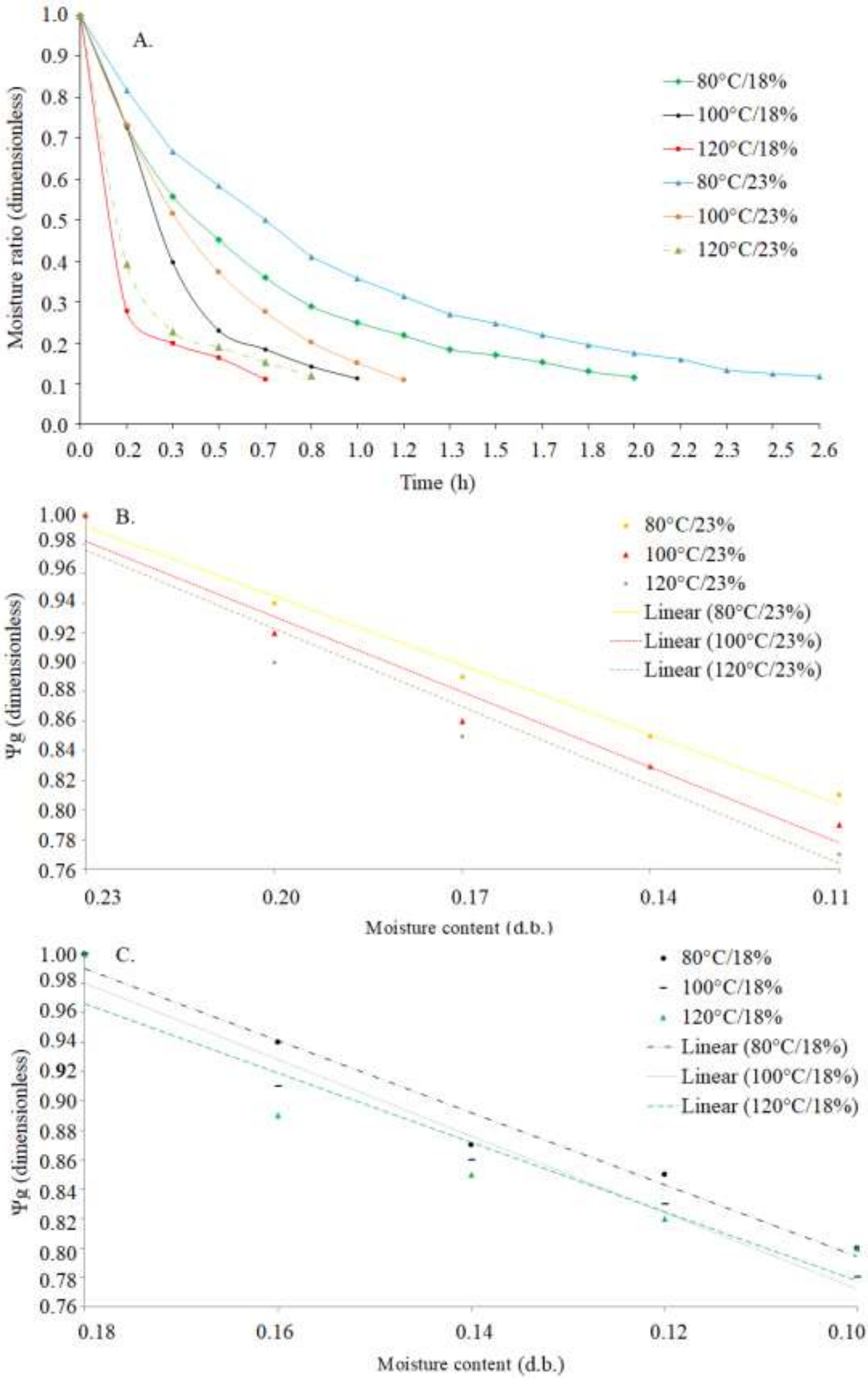

Figure 2. Moisture content adjusted by the Wang & Singh model (A), volumetric shrinkage of soybeans in the drying using the model of Rahman, at initial moisture content of 23% (d.b.) (B) and 18% (d.b.) (C).

The coefficients of the adjusted models analyzed during the drying of soybean are shown in Tables 1 and 3. The coefficients of determination R^2 indicated a satisfactory representation of the phenomenon under study (

Table2 and 4). Among all tested models, Wang and Singh's model showed the lower values of the mean relative error (P), average estimated error (SE), and distribution of residues for the temperature of the air drying 80, 100, and 120 °C (

Table2 and 3).

Table 1. Parameters obtained from models fitted to the data for drying of soybean grains for 23% (d.b.) of initial moisture content

Mathematical models					
	T (°C)	*k*			
	80	0.463600			
Newton	100	0.662870			
	120	7.602332			
	T (°C)	*k*	*n*		
	80	0.293530	1.617070		
Page	100	0.388050	1.302200		
	120	0.499964	0.000125		
	T (°C)	*k*	*n*		
	80	0.468590	1.617070		
Page Modified	100	0.665160	1.302200		
	120	0.046526	0.000017		
	T (°C)	*a*	*k*		
	80	1.064980	0.488950		
Henderson & Pabis	100	1.047710	0.699440		
	120	0.989430	7.531181		
	T (°C)	*a*	*k*	*c*	
	80	11.16890	0.024820	-10.189600	
Logarithmic	100	2.704230	0.157990	-1.732700	
	120	0.930360	9.952775	0.067291	
	T (°C)	*a*	k_0	*b*	k_1
	80	0.532496	0.498886	0.532496	0.498860
Two Terms	100	0.523857	0.699442	0.523557	0.699442
	120	0.494720	7.531181	0.494720	7.531181
	T (°C)	*a*	*k*		
Two Exponential Terms	80	1.938070	0.726790		
	100	1.796970	0.955320		
	120	0.317576	17.99533		
	T (°C)	*a*	*b*		
	80	-0.284900	0.002680		
Wang & Singh	100	-0.462100	0.039562		
	120	-4.089220	4.080789		

	T (°C)	*a*	*k*	*b*	k_0	*c*	k_1
Henderson & Pabis Modified	80	0.354997	0.498886	0.354997	0.198886	0.354997	0.498886
	100	0.349238	0.699442	0.349238	0.699442	0.349238	0.699442
	120	0.329811	7.531181	0.329811	7.531181	0.329811	7.531181
	T (°C)	*a*	*k*	*n*	*b*		
Midilli	80	0.990558	0.023506	0.000019	-0.264911		
	100	1.003716	0.175032	0.519332	-0.268476		
	120	0.771639	0.626056	0.000218	-0.684975		
	T (°C)	*a*	*k*	*b*			
Diffusion approximation	80	0.541710	0.464301	1.000000			
	100	0.528730	0.662866	0.999900			
	120	0.409782	9.255399	55.000000			

Table 2. Coefficient of determination (R^2), mean relative error (P), estimated values of average error (SE) drying of soybean grains due to different temperatures for 23% (d.b.) of initial moisture content

Mathematical models	80 ^{0}C	100 ^{0}C	120 ^{0}C
		R^2 (%)	
Newton	95.17	97.70	98.67
Page	98.12	98.76	94.15
Page Modified	98.12	98.76	76.57
Henderson & Pabis	95.55	97.92	98.68
Logarithmic	99.37	99.68	99.27
Two Terms	95.57	97.92	98.68
Two Exponential Terms	97.50	98.69	99.14
Wang & Singh	99.32	99.59	99.04
Henderson & Pabis Modified	95.57	97.92	98.68
Midilli	99.36	97.78	95.14
Diffusion approximation	95.19	97.70	99.73
		SE	
Newton	0.0890	0.0626	0.06488
Page	0.0594	0.0477	0.56505
Page Modified	0.0594	0.0477	0.29748
Henderson & Pabis	0.0911	0.0603	0.07467
Logarithmic	0.0347	0.0603	0.05569
Two Terms	0.0948	0.0648	0.12933
Two Exponential Terms	0.0689	0.0603	0.06035
Wang & Singh	0.0321	0.0204	0.01717
Henderson & Pabis Modified	0.1002	0.0705	0.12933
Midilli	0.0345	0.0214	0.24655
Diffusion approximation	0.0974	0.0670	0.04121
		P (%)	
Newton	6.85	0.24	2.79
Page	5.98	7.16	5.60
Page Modified	5.98	6.16	8.41
Henderson & Pabis	5.85	4.82	4.11
Logarithmic	1.74	4.82	1.47
Two Terms	6.55	4.82	4.11
Two Exponential Terms	4.97	4.82	6.11
Wang & Singh	3.01	3.45	2.52
Henderson & Pabis Modified	6.55	4.82	4.11
Midilli	1.34	0.27	4.64
Diffusion approximation	7.39	6.24	7.35
		Distribution residue	

Newton	T	T	T
Page	T	T	A
Page Modified	T	T	A
Henderson & Pabis	T	T	A
Logarithmic	A	A	A
Two Terms	T	T	A
Two Exponential Terms	T	A	A
Wang & Singh	A	A	A
Henderson & Pabis Modified	T	T	A
Midilli	A	A	A
Diffusion approximation	T	T	A

Table 3. Parameters obtained from models fitted to the data for drying of soybean grains for 18% (d.b.) of initial moisture content

Mathematical models							
	T (^{0}C)	*k*					
	80	0.971060					
Newton	100	5.889470					
	120	5.786360					
	T (^{0}C)	*k*	*n*				
	80	0.974770	0.976759				
Page	100	0.620970	0.000086				
	120	0.672511	0.000004				
	T (^{0}C)	*k*	*n*				
	80	0.974180	0.976759				
Page Modified	100	0.044058	0.000038				
	120	0.044463	0.000079				
	T (^{0}C)	*a*	*k*				
	80	0.955030	0.924030				
Henderson & Pabis	100	0.970820	5.691402				
	120	1.001650	5.793869				
	T (^{0}C)	*a*	*k*	*c*			
	80	1.430271	0.405995	-0.534078			
Logarithmic	100	0.912190	8.981745	0.081508			
	120	1.071784	4.830920	-0.076094			
	T (^{0}C)	*a*	k_0	*b*	k_1		
	80	0.477517	0.924032	0.477517	0.924032		
Two Terms	100	0.485410	5.691402	0.485410	5.691402		
	120	0.500825	5.753869	0.500825	5.793869		
	T (^{0}C)	*a*	*k*				
Two Exponential Terms	80	1.390710	1.090440				
	100	0.291287	14.96863				
	120	1.481680	6.748937				
	T (^{0}C)	*a*	*b*				
	80	-0.718800	0.132126				
Wang & Singh	100	-2.820600	1.925448				
	120	-4.050820	4.181176				
	T (^{0}C)	*a*	*k*	*b*	k_0	*c*	k_1
	80	0.318345	0.924032	0.318345	0.924032	0.318345	0.924032
Henderson & Pabis Modified	100	0.323610	5.691402	0.323610	5.691402	0.323610	5.691402
	120	0.333883	5.793869	0.333883	5.793869	0.333883	5.793869
	T (^{0}C)	*a*	*k*	*n*	*b*		
	80	0.945430	0.190295	0.000044	-0.34510		
Midilli	100	0.785988	0.511196	0.000012	0.610212		
	120	1.000000	1.329180	0.373421	0.716832		
	T (^{0}C)	*a*	*k*	*b*			

Diffusion approximation	80	0.569273	0.97106	1.00000
	100	0.414057	2.25745	1.03247
	120	9.285317	7.67864	1.03917

Table 4. Coefficient of determination (R^2), mean relative error (P), estimated values of average error (SE) drying of soybean grains due to different temperatures for 18% (d.b.) of initial moisture content

Mathematical models	80 ^{0}C	100 ^{0}C	120 ^{0}C
		R^2 (%)	
Newton	97.57	97.25	99.64
Page	97.58	97.63	57.08
Page Modified	97.58	67.04	83.51
Henderson & Pabis	97.76	97.31	99.64
Logarithmic	98.88	98.64	99.79
Two Terms	97.76	97.31	99.64
Two Exponential Terms	97.61	98.26	99.67
Wang & Singh	97.47	88.59	99.30
Henderson & Pabis Modified	97.76	97.31	99.64
Midilli	99.75	93.40	99.99
Diffusion approximation	97.57	99.75	99.67
		SE	
Newton	0.0618	0.0792	0.0366
Page	0.0640	0.4547	0.4378
Page Modified	0.0640	0.2769	0.7287
Henderson & Pabis	0.0615	0.0859	0.8021
Logarithmic	0.0437	0.0612	0.8138
Two Terms	0.0669	0.1109	0.5355
Two Exponential Terms	0.0636	0.0693	0.8064
Wang & Singh	0.0267	0.0170	0.0260
Henderson & Pabis Modified	0.0740	0.1920	1.1344
Midilli	0.0224	0.1721	1.1528
Diffusion approximation	0.0668	0.0291	1.1411
		P (%)	
Newton	2.37	7.14	7.44
Page	2.17	9.65	6.42
Page Modified	2.17	2.18	6.55
Henderson & Pabis	8.88	4.67	6.16
Logarithmic	5.13	4.37	5.55
Two Terms	8.88	4.67	9.45
Two Exponential Terms	8.32	6.21	9.36
Wang & Singh	2.20	2.37	2.30
Henderson & Pabis Modified	8.88	4.67	9.16
Midilli	2.78	9.18	9.65
Diffusion approximation	6.00	9.67	9.99
		Distribution residue	
Newton	T	A	A
Page	T	A	A
Page Modified	T	A	A
Henderson & Pabis	T	T	A
Logarithmic	A	A	A
Two Terms	T	T	A
Two Exponential Terms	T	T	A
Wang & Singh	A	A	A
Henderson & Pabis Modified	T	T	A
Midilli	A	A	A
Diffusion approximation	T	A	A

Thus, the experimental drying results fit satisfactorily with the estimated data (Figures 3A-B). It was observed that soybean with an initial moisture content of 23% (d.b.) had a better fit (Figure 3A) for the estimated and experimental moisture ratio values in drying. This may have occurred due to the longer drying time and homogeneity, especially at temperatures of 80 and 100 °C.

These findings are consistent with that published recently[34,35,36]. The moisture remotion occurs fast in the first half of the process, afterwards, it is slower since the diffusion of the water in the grain's inner geometry is more difficult to happen. Even though the process parameters require an air temperature of 100 °C to obtain a faster drying, the literature recommends that the temperature should be lower, so as not to damage the structure of soybeans and accelerate degradation. It was found that the effects of initial moisture content and temperature on drying time were proportional, which means that both factors influenced the soybean quality.

The effective diffusion coefficient increased significantly and with a uniform variation, with the increase of the drying air temperature (Figures 3C-D) for a linear adjustment[30,31,32,33], being the higher values of diffusion obtained in the drying with initial moisture contents of 23% (d.b.). Thus, the diffusivity results reflected on soybean volumetric shrinkage, being that it was 23.20% for moisture content of 0.18 to 0.11 (d.b.) and 21.1% for moisture content of 0.23 to 0.11 (d.b.) (Figure 2B-C).

In this study, the Rahman model was the best set of data obtained volumetric shrinkage of soybeans, with a less pronounced trend of distribution of residuals (random distribution) (Table 5 and 6). These models had a higher coefficient of determination and lower estimates and average errors relative. Thus, the Rahman model was recommended to predict the phenomenon of shrinkage of the soybean.

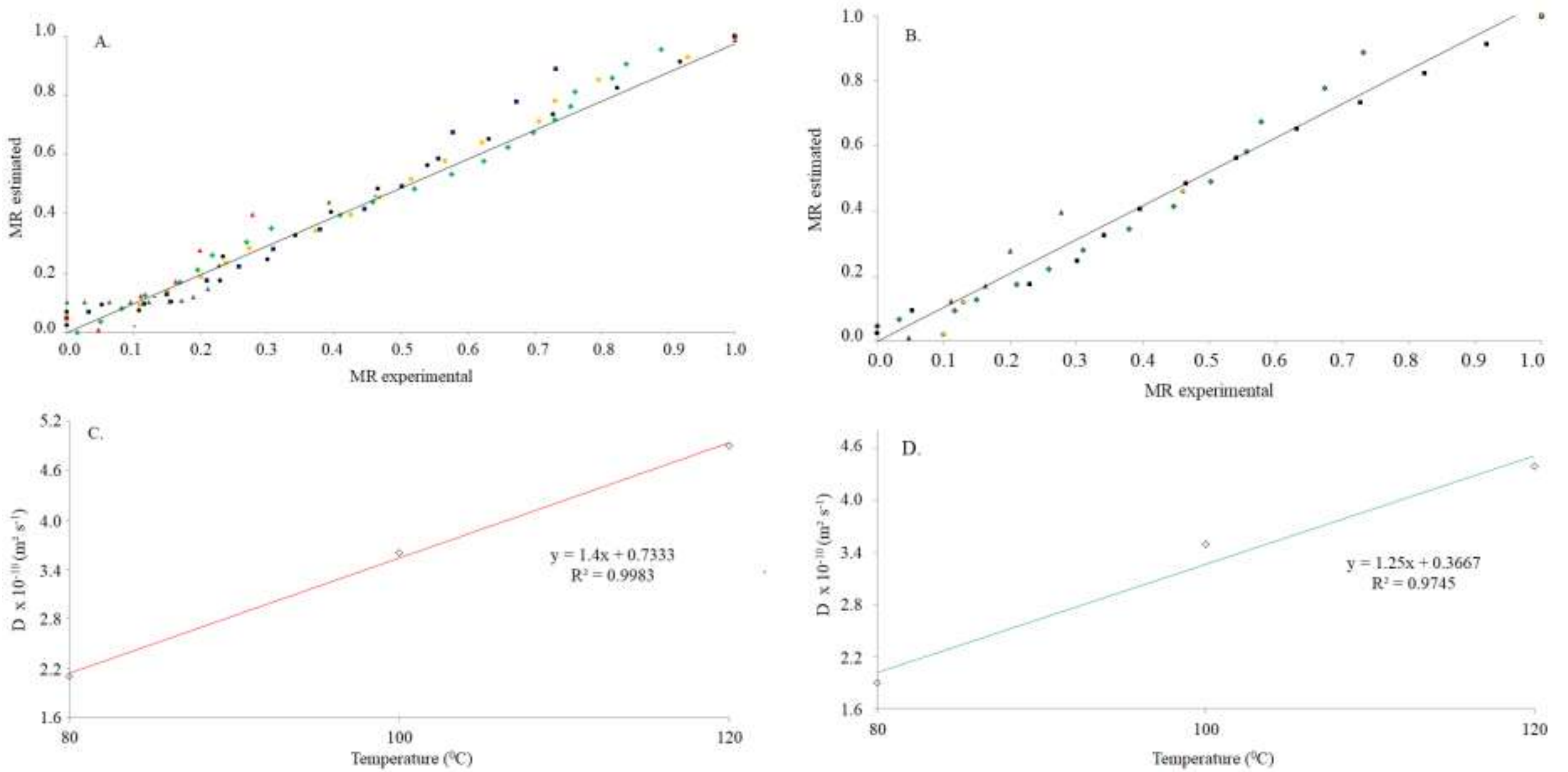

Figure 3. Ratio of experimental values and estimated by the Wang & Singh model at initial moisture content of 23% (d.b.) (A); initial moisture content of 18% (d.b.) (B); effective diffusion coefficient (m^2 s^{-1}) for 23% (d.b.) of the initial moisture content in the grains (C); effective diffusion coefficient (m^2 s^{-1}) for 18% (d.b.) of the initial moisture content in the grains (D).

Table 5. Parameters estimated, coefficient of determination (R^2), estimated average (SE) and relative error (P) and distribution of residues of the mathematical models used to describe the shrinkage of soybeans grains to different drying air temperatures and an initial moisture content of the grains of 23% (d.b.)

Mathematical models	Estimation of parameters	R^2	SE (decimal)	P (%)	Distribution of residuals
		80 ºC			
Bala and Woods	a = 0.94693 b = -17.9467	72.21	0.039817	2.275428	A
Lang and Sokhansanj	a = 2.31625	82.12	0.035181	2.136110	A
Rahman	b = 1.17238 a = 0.27142	93.22	0.018143	0.985810	A
Corrêa	a = 0.70713 b = 1.05963	90.60	0.024360	1.000093	A
Line	a = 2.51031 b = -1.16293	92.99	0.021167	1.044430	A
Exponential	a = 0.72095 b = 1.21226	91.49	0.023226	2.025056	A
		100 ºC			
Bala and Woods	a = 0.99175 b = -16.9372	98.07	0.011486	1.238779	A
Lang and Sokhansanj	a = 2.37193 b = 1.21561	81.48	0.012131	2.617105	A
Rahman	a = 0.27138	99.61	0.009125	0.987234	A
Corrêa	a = 0.72227 b = 1.14054	98.50	0.010429	1.013273	A
Line	a = 2.41417 b = -1.11077	97.37	0.013501	1.036152	A
Exponential	a = 0.74136 b = 1.23357	98.15	0.011486	1.238779	A
		120 ºC			
Bala and Woods	a = 1.10554 b =-16.0361	98.22	0.0148753	2.1352353	A
Lang and Sokhansanj	a = 3.35812 b = 1.24877	88.50	0.0426990	1.5287221	A
Rahman	a = 0.341239	99.67	0.0141121	0.9146112	A
Corrêa	a = 0.52231 b = 1.36381	99.23	0.0141216	3.4515100	A
Line	a = 2.14782 b = -1.12214	96.88	0.0194607	1.7472132	A
Exponential	a = 0.81248 b = 1.24151	94.19	0.0160931	3.2332221	A

Table 6. Parameters estimated, coefficient of determination (R²), estimated average (SE) and relative error (P) and distribution of residues of the mathematical models used to describe the shrinkage of soybeans grains to different drying air temperatures and an initial moisture content of the grains of 18% (d.b.)

Mathematical models	Estimation of parameters	R²	SE (decimal)	P (%)	Distribution of residuals
		80 ºC			
Bala and Woods	*a* = 0.96144 *b* = -18.32210	5.71	0.035730	1.195070	A
Lang & Sokhansanj	*a* = 2.14567	8.21	0.046570	2.345619	A
Rahman	*b* = 1.34560 *a* = 0.23450	9.23	0.018233	1.023451	A
Corrêa	*a* = 0.68100 *b* = 1.40000	5.85	0.021048	1.100000	A
Line	a = 2.97552 *b* = -1.59233	7.67	0.026304	1.042430	A
Exponential	*a* = 0.69567 *b* = 1.60571	6.55	0.027392	2.021655	A
		100 °C			
Bala and Woods	*a* = 1.055487 *b* = -13.4491	4.46	0.0249491	1.3962264	A
Lang & Sokhansanj	*a* = 2.21572 *b* = 1.41018	0.23	0.0317891	1.4527809	A
Rahman	*a* = 0.31017	8.45	0.0061234	1.0345167	A
Corrêa	*a* = 0.586533 *b* = 2.12000	7.56	0.0128582	1.1006289	A
Line	*a* = 3.769244 *b* = -2.28705	9.13	0.0051166	1.1773585	A
Exponential	*a* = 0.631492 *b* = 2.380158	7.87	0.0113594	2.0207547	A
		120 °C			
Bala and Woods	*a* = 1.023189 *b* = -13.1101	5.31	0.0123410	2.2981331	A
Lang & Sokhansanj	*a* = 2.12312 *b* = 1.32191	2.34	0.0123145	3.1901231	A
Rahman	*a* = 0.22141	9.48	0.0341678	2.0245178	A
Corrêa	*a* = 0.42145 *b* = 2.21344	8.21	0.0412891	4.2314561	A
Line	*a* = 3.51234 *b* = -2.12341	6.45	0.0532156	3.5414579	A
Exponential	*a* = 0.342141 *b* = 2.10231	9.41	0.0651294	3.1234526	A

The results obtained in this study confirm that drying has immediate effects on soybean quality (Table and 8). Drying at air temperatures above 100 °C negatively affects the physicochemical quality, mainly in soybeans harvested with 18% moisture (Table and 8-time zero). Similar results were observed by Mourad et al[37] and Wang et al[22] when evaluating the effect of temperature on the grain drying. It is observed that the grain cell has been compromised grain structure along with the different drying air temperatures, the higher the amount of ions leached at the drying temperature of 120 °C. The damage to the cell walls of grains causing high values of electrical conductivity affects the oil content and acidity. The increase in electrical conductivity may be implicated in the major damage caused by the drying air temperature on the soybean cellular structure during drying, causing them to lose physiological and nutritional quality[38,39].

Table 7. Quality of soybeans harvest at 23% (d.b.) moisture content subjected to drying at 80, 100 and 120 °C, stored in different environments and packaging for eight months

Analysis	Times (months)	Drying air temperature at 80 °C					
		Storage conditions					
		15 °C		23 °C		30 °C	
		P	PL	P	PL	P	PL
Moisture content (% d.b.)	0	10.31 Ba	10.31 Ba	10.31 Aa	10.31 Aa	10.31 Aa	10.31 Ba
	4	10.24 Ba	10.22 Ba	10.27 Aa	10.20 Aa	10.20 Aa	10.28 Ba
	8	11.20 Ab	12.00 Aa	9.90 Bd	10.50 Ac	9.20 Bd	11.00 Ab
Conductivity electrical (μS cm^{-1} g^{-1})	0	191 Ca	191 Ca	191 Ca	191 Ca	191 Ca	191 Ca
	4	205 Bc	196 Bd	220 Bb	197 Bd	241 Ba	209 Bc
	8	235 Ad	210 Ae	320 Ab	210 Ae	391 Aa	254 Ac
Oil contente (%)	0	25.89 Aa	25.89 Aa	25.89 Aa	25.89 Aa	25.89 Aa	25.89 Aa
	4	23.10 Ba	23.70 Ba	22.00 Bb	23.50 Ba	22.12 Bb	22.45 Bb
	8	21.29 Cb	22.27 Ca	20.29 Cc	22.27 Ca	19.89 Cd	20.50 Cc
Index of acidity (mL)	0	5.54 Aa	5.54 Aa	5.54 Ba	5.54 Aa	5.54 Ba	5.54 Ba
	4	5.75 Aa	5.58 Aa	5.78 Ba	5.60 Aa	5.62 Ba	5.61 Ba
	8	5.80 Ac	5.60 Ac	6.02 Ab	5.67 Ac	7.71 Aa	6.69 Ab
Crude protein (%)	0	35.69 Aa	35.69 Aa	35.69 Aa	35.69 Aa	35.69 Aa	35.69 Aa
	4	31.15 Bd	34.36 Ba	32.15 Bc	33.54 Bb	28.24 Be	30.45 Bf
	8	30.34 Cc	33.45 Ca	28.35 Cd	31.23 Cb	25.34 Cf	27.74 Ce
Drying air temperature at 100 °C							
Moisture content (% d.b.)	0	10.23 Ba	10.23 Ba	10.23 Aa	10.23 Aa	10.23 Aa	10.23 Ba
	4	10.12 Ba	10.13 Ba	10.41 Aa	10.26 Aa	10.39 Aa	10.20 Ba
	8	11.11 Ab	12.09 Aa	10.10 Bd	10.59 Ac	9.32 Bd	11.09 Ab
Conductivity electrical (μS cm^{-1} g^{-1})	0	200 Ca	200 Ca	200 Ca	200 Ca	200 Ca	200 Ca
	4	215 Bc	199 Bd	225 Bb	199 Bd	262 Ba	218 Bc
	8	243 Ad	217 Ae	329 Ab	214 Ae	399 Aa	264 Ac
Oil content (%)	0	24.19 Aa	24.19 Aa	24.19 Aa	24.19 Aa	24.19 Aa	24.19 Aa
	4	22.10 Ba	22.51 Ba	21.14 Bb	22.42 Ba	21.19 Bb	21.85 Bb
	8	20.13 Cb	21.16 Ca	19.67 Cc	21.36 Ca	18.65 Cd	19.66 Cc
Index of acidity (mL)	0	5.75 Aa	5.75 Aa	5.75 Ba	5.75 Aa	5.75 Ba	5.75 Ba
	4	5.85 Aa	5.69 Aa	5.89 Ba	5.79 Aa	5.76 Ba	5.86 Ba
	8	6.10 Ac	5.84 Ac	6.12 Ab	5.92 Ac	7.98 Aa	6.71 Ab
Crude protein (%)	0	34.39 Aa	34.39 Aa	34.39 Aa	34.39 Aa	34.39 Aa	34.39 Aa
	4	30.43 Bd	33.54 Ba	31.31 Bc	32.44 Bb	27.42 Be	29.47 Bf
	8	29.36 Cc	32.55 Ca	27.47 Cd	30.13 Cb	24.14 Cf	26.36 Ce
Drying air temperature at 120 °C							
Moisture content (% d.b.)	0	10.40 Ba	10.40 Ba	10.40 Aa	10.40 Aa	10.40 Aa	10.40 Ba
	4	10.56 Ba	10.62 Ba	10.60 Aa	10.55 Aa	10.51 Aa	10.62 Ba
	8	11.28 Ab	12.25 Aa	10.06 Bd	10.40 Ac	9.21 Bd	11.10 Ab
Conductivity electrical (μS cm^{-1} g^{-1})	0	208 Ca	208 Ca	208 Ca	208 Ca	208 Ca	208 Ca
	4	224 Bc	210 Bd	244 Bb	206 Bd	279 Ba	245 Bc
	8	265 Ad	229 Ae	337 Ab	222 Ae	414 Aa	296 Ac
Oil content (%)	0	23.34 Aa	23.34 Aa	23.34 Aa	23.34 Aa	23.34 Aa	23.34 Aa
	4	21.11 Ba	21.76 Ba	20.54 Bb	21.29 Ba	20.57 Bb	20.72 Bb
	8	18.54 Cb	20.18 Ca	18.75 Cc	20.61 Ca	17.45 Cd	18.58 Cc

Index of acidity (mL)	0	6.15 Aa	6.15Aa	6.15 Ba	6.15Aa	6.15 Ba	6.15 Ba
	4	6.45 Aa	6.79 Aa	6.80 Ba	6.83 Aa	6.66 Ba	6.76 Ba
	8	6.60 Ac	6.93 Ac	6.99 Ab	6.92 Ac	8.18 Aa	7.51 Ab
Crude protein (%)	0	33.56 Aa	33.56 Aa	33.56 Aa	33.56 Aa	33.56 Aa	33.56 Aa
	4	31.13 Bd	33.54 Ba	31.31 Bc	32.44 Bb	26.57 Be	28.33 Bf
	8	28.55 Cc	31.76 Ca	26.41 Cd	29.10 Cb	23.11 Cf	25.61 Ce
Mixed grains (80 / 100 / 120 °C)							
Moisture content (% d.b.)	0	10.11 Ba	10.11 Ba	10.11 Aa	10.11 Aa	10.11 Aa	10.11 Ba
	4	10.19 Ba	10.15 Ba	10.17 Aa	10.22 Aa	10.10 Aa	10.29 Ba
	8	11.09 Ab	11.80 Aa	9.85 Bd	10.42 Ac	9.10 Bd	10.87 Ab
Conductivity electrical (µS cm^{-1} g^{-1})	0	205 Ca	205 Ca	205 Ca	205 Ca	205 Ca	205 Ca
	4	213 Bc	202 Bd	222 Bb	201 Bd	258 Ba	221 Bc
	8	239 Ad	219 Ae	322 Ab	217 Ae	402 Aa	260 Ac
Oil content (%)	0	24.10 Aa	24.10Aa	24.10Aa	24.10Aa	24.10Aa	24.10Aa
	4	22.14 Ba	22.43 Ba	21.08 Bb	22.41 Ba	21.21 Bb	21.15 Bb
	8	20.35 Cb	21.40 Ca	19.19 Cc	21.45 Ca	18.76 Cd	19.30 Cc
Index of acidity (mL)	0	5.62 Aa	5.62 Aa	5.62 Ba	5.62 Aa	5.62 Ba	5.62 Ba
	4	5.78 Aa	5.52 Aa	5.75 Ba	5.68 Aa	5.68 Ba	5.71 Ba
	8	6.11 Ac	5.70 Ac	6.19 Ab	5.87 Ac	7.76 Aa	6.60 Ab
Crude protein (%)	0	34.68 Aa	34.68 Aa	34.68 Aa	34.68 Aa	34.68 Aa	34.68 Aa
	4	30.39 Bd	33.78 Ba	31.85 Bc	32.68 Bb	27.88 Be	29.47 Bf
	8	29.16 Cc	32.77 Ca	27.60 Cd	30.48 Cb	24.56 Cf	26.65 Ce

Means followed by the capital letter in the column for each time of storage and lower lines for each temperature of storage. do not differ at 1 and 5% probability. PL—polyethylene plastic bag. P—paper bag.

Table 8. Quality of soybeans harvest at 18% (d.b.) moisture content subjected to drying at 80, 100 and 120 °C, stored in different environments and packaging for eight months

Analysis	Times (months)	Drying air temperature at 80 °C					
		Storage conditions					
		15 °C		23 °C		30 °C	
		P	PL	P	PL	P	PL
Moisture content (% d.b.)	0	10.20 Ba	10.20 Ba	10.20 Ba	10.20 Ba	10.20 Aa	10.20 Ba
	4	10.56 Ba	10.13 Bb	10.41 Aa	10.10 Bb	10.12 Ab	10.19 Bb
	8	11.36 Aa	11.45 Aa	10.10 Bc	10.90 Ab	9.57 Bc	11.15 Aa
Conductivity electrical (µS cm^{-1} g^{-1})	0	199 Ca	199 Ca	199 Ca	199 Ca	199 Ca	199 Ca
	4	211 Bc	206 Bc	232 Ba	212 B	258 Ba	222 Bb
	8	244 Ac	215 A	333 Ab	221 Ad	410 Aa	276 Ac
Oil contente (%)	0	24.11 Aa	24.11 Aa	24.11 Aa	24.11 Aa	24.11 Aa	24.11 Aa
	4	22.80 Ba	23.10 Ba	22.05 Bc	22.86 Ba	21.14 Bb	20.45 Bc
	8	20.75 Ca	21.04 Ca	20.00 Cb	20.90 Ca	19.00 Cc	18.79 Cd
Index of acidity (mL)	0	5.75 Ba	5.75 Aa	5.75 Ba	5.75 Ba	5.75 Ca	5.75 Ca
	4	5.90 Bc	5.85 Ac	5.85 Bc	5.80 Bc	6.15 Bb	6.68 Ba
	8	6.10 Ac	5.90 Ac	6.12 Ac	5.96 Ac	8.64 Aa	8.10 Ab
Crude protein (%)	0	35.00 Aa	35.00 Aa	35.00 Aa	35.00 Aa	35.00 Aa	35.00 Aa
	4	31.15 Bb	34.06 Ba	30.55 Bc	32.48 Bb	27.49 Bd	29.15 Bc
	8	30.34 Cb	33.15 Ca	28.10 Cc	30.13 Cb	24.89 Cd	26.80 Cc
Drying air temperature at 100 °C							
Moisture content (% d.b.)	0	10.05 Ca	10.05 Ba	10.05 Ba	10.05 Ba	10.05 Aa	10.05 Ba
	4	10.41 Ba	9.98 Bb	10.26 Aa	9.95 Bb	9.97 Ab	10.04 Bb
	8	11.21 Aa	11.30 Aa	9.95 Bb	10.75 Aa	9.42 Bb	11.00 Aa
Conductivity electrical (µS cm^{-1} g^{-1})	0	219 Ca	219 Ca	219 Ca	219 Ca	219 Ca	219 Ca
	4	231 BC	226 BC	252 Bb	232 BC	278 Ba	242 BB
	8	264 Ad	235 Ad	353 Ab	241 Ad	430 Aa	296 Ac
Oil content (%)	0	23.86 Aa	23.86 Aa	23.86 Aa	23.86 Aa	23.86 Aa	23.86 Aa
	4	22.55 Ba	22.85 Ba	21.80 Bb	22.61 Ba	20.89 Bc	20.20 Bc

	8	20.50 Ca	20.79 Ca	19.75 Cb	20.65 Ca	18.75 Cc	18.54 Cc
Index of acidity (mL)	0	5.90 Ca	5.90 Ba	5.90 Ca	5.90 Ba	5.90 Ca	5.90 Ca
	4	6.05 Bb	6.00 Ab	6.00 Bb	5.95 Bb	6.30 Ba	6.83 Ba
	8	6.25 Ab	6.05 Ac	6.27 Ab	6.11 Ab	8.79 Aa	8.25 Aa
Crude protein (%)	0	35.18 Aa	35.18 Aa	35.18 Aa	35.18 Aa	35.18 Aa	35.18 Aa
	4	31.33 Bc	34.24 Ba	30.73 Bc	32.66 Bb	27.67 Be	29.33 Bd
	8	30.52 Cb	33.33 Ca	28.28 Cc	30.31 Cb	25.07 Cd	26.98 Cd
Drying air temperature at 120 °C							
Moisture content (% d.b.)	0	9.92 Ca	9.92 Ba	9.92 Ba	9.92 Ba	9.92 Aa	9.92 Ba
	4	10.28 Ba	9.85 Bb	10.13 Aa	9.82 Bb	9.84 Bb	9.91 Bb
	8	11.08 Aa	11.17 Aa	9.82 Bc	10.62 Ab	9.29 Cc	10.87 Ab
Conductivity electrical (μS cm^{-1} g^{-1})	0	244 Ca	244 Ca	244 Ca	244 Ca	244 Ca	244 Ca
	4	256 Bc	251 Bc	277 Bb	257 Bc	303 Ba	267 Bb
	8	289 Ab	260 Ad	378 Ab	266 Ad	455 Aa	321 Ac
Oil content (%)	0	23.60 Aa	23.60 Aa	23.60 Aa	23.60 Aa	23.60 Aa	23.60 Aa
	4	22.29 Ba	22.59 Ba	21.54 Bb	22.35 Ba	20.63 Bc	19.94 Bd
	8	20.24 Ca	20.53 Ca	19.49 Cb	20.39 Ca	18.49 Cc	18.28 Bc
Index of acidity (mL)	0	6.03 Ba	6.03 Aa	6.03 Ba	6.03 Ba	6.03 Ca	6.03 Ca
	4	6.18 Bb	6.13 Ab	6.13 Bb	6.08 Bb	6.43 Ba	6.96 Ba
	8	6.38 Ab	6.18 Ab	6.40 Ab	6.24 Ab	8.92 Aa	8.38 Aa
Crude protein (%)	0	35.01 Aa	35.01 Aa	35.01 Aa	35.01 Aa	35.01 Aa	35.01 Aa
	4	31.16 Bc	34.07 Ba	30.56 B	32.49 Bb	27.50 Be	29.16 Bd
	8	30.35 Bb	33.16 Ca	28.11 Cc	30.14 Cb	24.90 Ce	26.81 Cd
Mixed grains (80 / 100 / 120 °C)							
Moisture content (% d.b.)	0	10.17 Ca	10.17 Ba	10.17 Ba	10.17 Ba	10.17 Aa	9.92 Ba
	4	10.53 Ba	10.10 Bb	10.38 Aa	10.07 Bb	10.09 Bb	9.91 Bb
	8	11.33 Aa	11.42 Aa	10.07 Bc	10.87 Ab	9.54 Bc	10.87 Ab
Conductivity electrical (μS cm^{-1} g^{-1})	0	214 Ca	214 Ca	214 Ca	214 Ca	214 Ca	244 Ca
	4	226 Bc	221 Bc	247 Bb	227 Bc	273 Ba	267 Ba
	8	259 Ac	230 Ac	348 Ab	236 Ac	425 Aa	321 Ab
Oil content (%)	0	23.95 Aa	23.95 Aa	23.95 Aa	23.95 Aa	23.95 Aa	23.60 Aa
	4	22.64 Ba	22.94 Ba	21.89 Bc	22.70 Ba	20.98 Bd	19.94 Be
	8	20.59 Ca	20.88 Ca	19.84 Cb	20.74 Ca	18.84 Cc	18.28 Cc
Index of acidity (mL)	0	5.85 Ca	5.85 Aa	5.85 Ba	5.85 Ba	5.85 Ca	6.03 Ca
	4	6.00 Bb	5.95 Ab	5.95 Bb	5.90 Bb	6.25 Ba	6.96 Ba
	8	6.20 Ab	6.00 Ab	6.22 Ab	6.06 Ab	8.74 Aa	8.38 Aa
Crude protein (%)	0	35.26 Aa	35.26 Aa	35.26 Aa	35.26 Aa	35.26 Aa	35.01 Aa
	4	31.41 Bb	34.32 Ba	30.81 Bc	32.74 Bb	27.75 Be	29.16 Bd
	8	30.60 Cb	33.41 Ca	28.36 Cc	30.39 Cb	25.15 Cd	26.81 Cd

Means followed by the capital letter in the column for each time of storage and lower lines for each temperature of storage do not differ at 1 and 5% probability. PL—polyethylene plastic bag. P—paper bag.

Comparing the evaluations of volumetric shrinkage (Figure 2A-B) and oil yield (Table and 8), it was found that a 5% reduction in the volume of the grains provided a 4.88% decrease in the oil yield extracted. The comparative results of shrinkage of grains (Figure B-C), soybean oil content extracted and electrical conductivity (Table and 8), due to the effects of drying temperature and initial moisture content. According to the increase in drying temperature, a reduction in soybean oil extraction yield was observed. According to Timm et al[40], the drying temperature from 30 to 90 ºC can reduce the corn starch extraction yield by 10%. When drying was performed at 23 to 11% moisture content (d.b.) (Figure 2A) there was a reduction of 20, 21, and 23% in the grain volume for temperatures of 80, 100, and 120 °C (Figure 2B), respectively, while the oil content was 25.89%, 24.19%, 23.34%, respectively.

Although the diffusion process was more intense in soybeans with an initial moisture content of 23% (d.b.) compared to 18% (d.b.), mainly for the drying at 120 °C, the effects on quality in oil yield, acid index, and crude protein were better. This fact is suggested by the anticipation of soybean harvest, minimizing the effects of natural drying on the plant. Thus, harvesting with 23% (d.b.) moisture content allows the drying of the beans more slowly at a temperature around 80 °C to obtain better quality (Table and 8). Harvesting soybeans with 18% moisture content, in addition to the adverse effects of the climate that the grains were subjected to, still needs to be subjected to faster drying at a higher temperature for more efficiency in the process.

3.2 Quality of soybeans on the storage

The early harvest of soybeans with 23% (d.b.) and drying with an air temperature below 100 °C had positive effects in maintaining the quality over the storage time, regardless of the storage condition. Among the changes that occurred, it was found that the storage time reduced the moisture content by an average of 1% (d.b.) at 15 and 23 °C (Table7 and 8). These changes occurred by variations of the relative humidity of the air (40 to 30%). In storage at 30 °C, the moisture content increased from 10 to 11% (d.b.) due to the relative humidity of the ambient air at 80%. According to Bischoff et al[41], the grain storage at 30 ºC causes excessive respiration, altering the physicochemical properties and losses in oil quality of approximately 59.6% (90 days), 67% (135 days), and 76% (180 days).

The most significant effects of soybean quality reduction were observed in paper packaging and a temperature of 30 °C. According to Maciel et al[42] for a constant temperature, the equilibrium moisture hygroscopic content increases with the relative humidity. Although the temperature influences the hygroscopic equilibrium humidity, this influence is weak. This is because water is transferred from the air to the soybean when the relative humidity of the storage ambient air is higher than the equilibrium humidity[43], being more intense when the soybeans are stored in high permeability packages (Table7 and 8).

The storage conditions at 15 and 23 °C in plastic bags were favorable for quality. The soybean storage in the temperature at 15 °C was favorable to the yield and the acidity index of the extracted oil, while the storage time was the main factor that altered the change in the acidity indexes. Mbofung et al[44] reported increases in the soybean acid value for all storage conditions; however, increases in temperature and air humidity led to further grain deterioration[45]. Investigations according to evaluate the quality of the soybean grains stored in different conditions at 25 °C, the physicochemical properties, such as ash (4.7%), protein (3.9%), lipids (21.9%), and carbohydrates (34.4%) were not altered. Oppositely, at 35 °C, a reduction in the tegument color (88% to 85%) was observed, in addition to an increase in free fatty acids (3.7% to 4.7%) and, consequently, the grains acidity content due to the hydrolytic degradation of fat components by the action of lipase, in which these fatty acids are liberated from the triacylglycerol structures[18]. Assessing the effects of drying and storage on soybean quality, some studies found that the increase in grain drying temperature from 75 °C to 105 °C associated with storage conditions of 25 °C and 50%, 20 °C and 60%, 30°C and 40% relative humidity over six months reduced the oil extraction yield and increased the acid index[46,47].

Table7 and 8 were observed regardless of storage and packaging conditions, a significant reduction in the percentage of crude protein in the grains on the 8 months of storage. In the evaluation of the quality of soybeans stored for 6 months in permeable paper bags and polyethylene plastic bags at 3, 10, and 23 °C. Coradi et al[46] found that the increased storage time reduced the quality of soybeans, regardless of storage conditions and packaging. In addition, the storage temperature of 23 °C was the most negatively altering the quality of soybeans. However, the storage in air temperature of 3 °C was most favorable for the quality of soybeans, although some quality results were similar, with storage at 10 °C.

As with other quality evaluations, it was observed that the crude protein content was higher in soybeans stored at lower temperatures. Lee & Cho[48] evaluated soybean storage for 2 years, at room temperature, and observed a reduction in protein levels from 43% to 38.30%, for 1 and 2 years, respectively. Kibar[49] and Rani et al[50] studied soybean storage at different moisture contents (12 and 16% d.b.) and temperatures (8, 13, 18, 23, and 28 ºC) and reported a reduction in crude protein content with increased moisture content and the temperature. Neethirajan et al[51] found similar results, with a significant reduction in the soybean protein content at a storage temperature of 30 °C and relative humidity of 88%. Although the storage conditions affected the crude protein content in the soybean, storage at lower temperatures allowed greater conservation[44].

Ziegler et al[52] evaluated the effects of moisture content (12 and 15%) and storage temperature (11, 18, 25, and 32 °C) of soybeans on the functional properties of the protein isolate. Protein solubility reduced 18% with increasing temperature from 11 to 32 ºC in soybean stored with 12% moisture. When the soybeans were stored with 15% moisture, the protein solubility reduced by 16% with increasing temperature from 11 to 32 ºC. Furthermore, when soybeans were stored at the same temperature, for example, 25 ºC, increasing moisture from 12 to 15% reduced protein solubility by 4%.

3.4 Multivariate analysis

Cluster analysis showed the existence of four homogeneous groups for the variables evaluated (Figure4). G1 group gathered the largest number of treatments and stood out for the higher average of electrical conductivity and lower averages of acid oil and crude protein. The treatments allocated in this group belong to the higher storage times (4 and 8 months). G2 group allocated most treatments with zero storage time, which had the higher averages of oil yield and crude protein and intermediate values of electrical conductivity and acid oil. G3 and G4 groups allocated treatments from all storage times, and it is not possible to associate the grouping pattern to a specific storage period.

The treatments in the G3 group showed lower averages of electrical conductivity, in addition to intermediate values for the other variables. G4 group in turn brought together treatments with the higher averages of acid oil, in addition to intermediate values and with high variability for the other variables. The results indicated that there were effects of the association of the conditions of harvest, drying, and storage on the quality of the grains. It is important to highlight that storage time was the main study factor that impacted the groups formed[53].

Similar results were observed by Ferreira et al[54] evaluated the effects of drying temperature (30, 50, 70, 90, and 110 ºC) and storage time (0 and 12 months) on physicochemical parameters in soybean. The authors reported that the increase in drying temperature resulted in a reduction in the quality of physical. In 12 months of storage, soybeans dried at 70, 90, and 110 ºC showed higher (20, 65, and 14%, respectively) amounts of contamination than soybeans dried at 30 ºC, accelerating the metabolism of grains, reducing antioxidant compounds such as isoflavones[54], and reduces protein solubility and increases lipase activity and lipid acidity in soybeans[55].

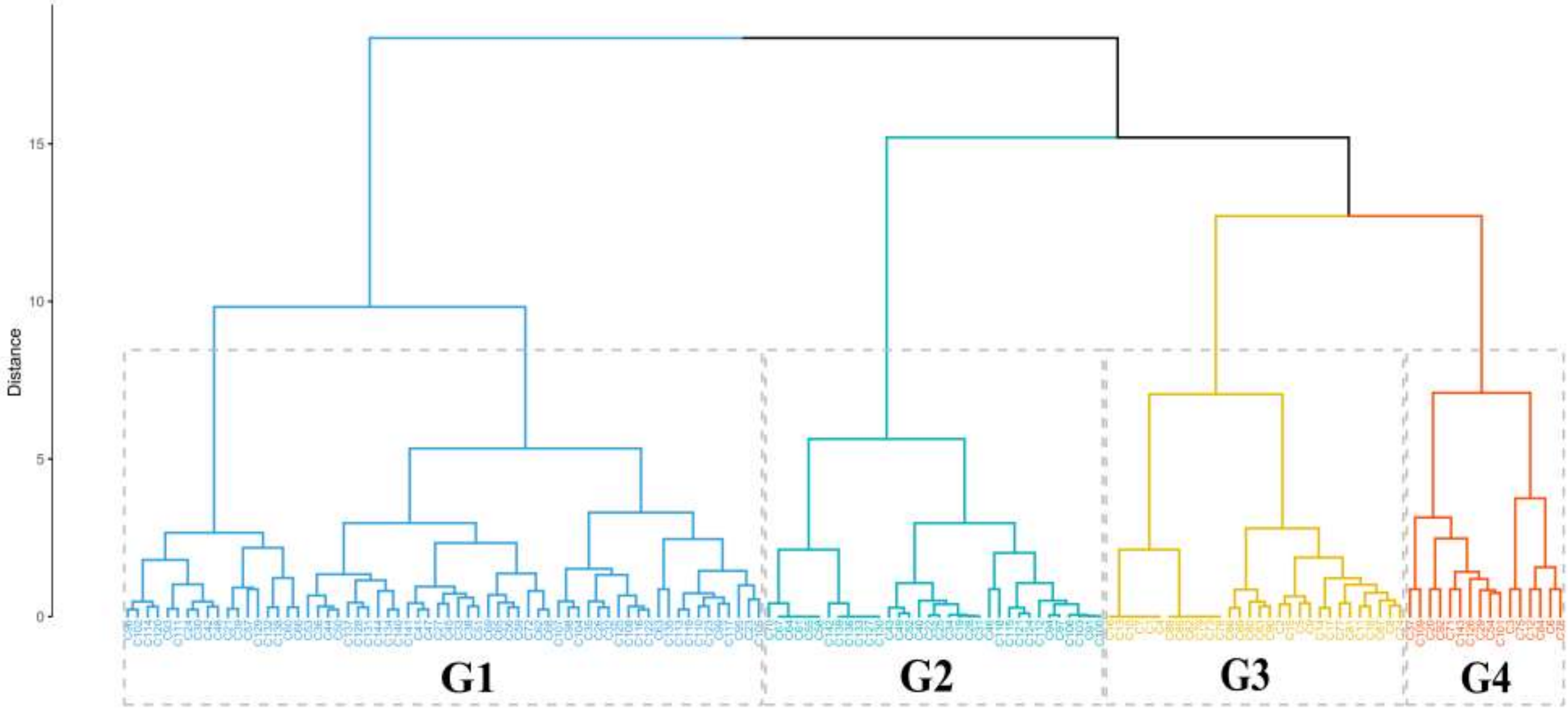

Figure 4. Cluster analysis of treatments using Euclidean distance and Ward's hierarchical method.

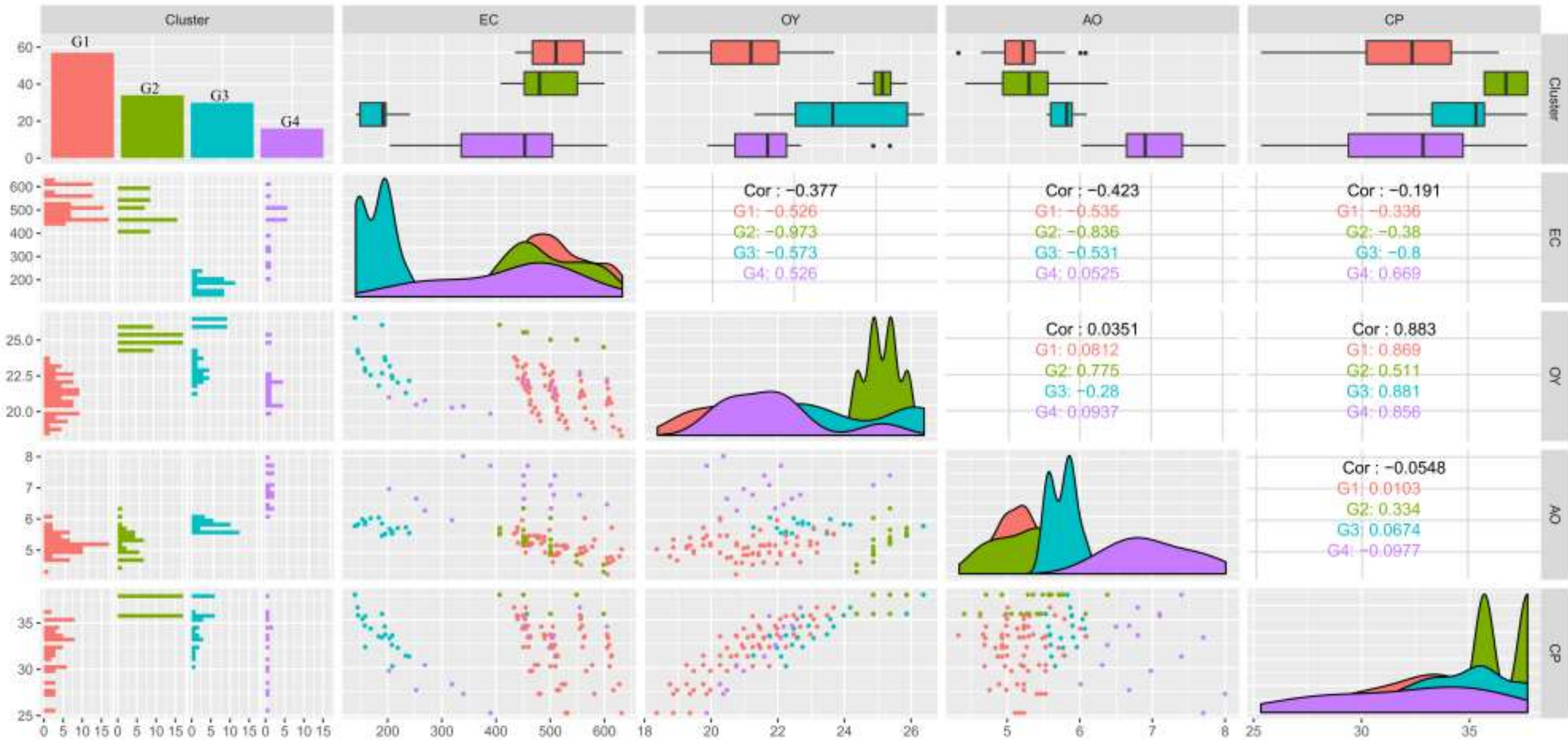

Figure 5. Dispersion and Pearson's correlation between the variables evaluated according to the groups defined by the cluster analysis.

Regarding Pearson's correlations between the variables for each group, it is noted that the direction of the correlations was similar (5). The electrical conductivity is negatively correlated and in low magnitude with all the physicochemical variables evaluated. However, it is to note that these correlations' magnitude was substantially more remarkable for the treatments allocated to the G2 group. These treatments also showed a positive and high magnitude correlation for acid oil and oil yield. Another correlation worth mentioning was that observed between crude protein and oil yield, which was positive and of high magnitude, regardless of the group formed.

Coradi et al[56] verified changes in the yield of protein and oil extracted in the grains in function from the presence of fermented, rotten, and burned soybeans caused by the high drying temperature and storage conditions. Ramos et al[55] found that the solubility of the protein isolates extracted from fermented, rotten, and burned soybeans are 17, 40, 59% lower compared to the protein isolate from not defective soybeans. The acidity of oil extracted from fermented, rotten, and burned soybeans is 969, 1350, 2248% higher than the acidity of oil extracted from not defective soybeans. Thus, the importance of optimizing the conditions for drying and storing soybeans is evident.

4. Conclusions

The low drying air temperatures decreased the effective diffusivity and the time of volumetric shrinkage. Although storage time was the main factor influencing grain quality, the early harvest at 23% moisture content, adopting drying systems with air temperatures of 80 °C, and storage in controlled environments with temperatures below 23 °C are favorable to conserve the physicochemical quality of the soybean.

The parameters obtained from soybean harvesting, drying, and storage make it possible to improve the management of the grain mass, to achieve better quality results. When applied at the farm level, it can enhance the production chain, improve transport and distribution logistics, reduce soybean losses, and add value to the marketing of soybeans. The results and conclusions obtained in this research are indicated for future investigations in soybean pre-processing and storage units, mainly at the farm level, to optimize harvest and post-harvest operations. For future research, it is suggested to carry out diagnoses on the different existing technologies of drying and storage, to propose a project that can more effectively implement the conclusive parameters of this study.

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CHAPTER 4

(Paper submitted to Food Analytical Methods)

Predicting soybean grain quality on the different drying and storage technologies in real scale using Machine Learning models

Abstract: The application of monitoring techniques associated with artificial intelligence in grain drying and storage operations can assist in decision-making processes, preventing losses deterioration. Therefore, the objective of this study was to evaluate the effects of different drying technologies (continuous drying and dryer-silos) and storage methods (vertical and horizontal silos) on the quality of soybeans associated with Machine Learning algorithms to predict changes in grain quality. The environmental and intergranular variables monitored during the processes were correlated with physical and chemical quality parameters of the grains, such as water content, apparent specific mass, dry matter loss, electrical conductivity, germination, crude protein, yield, and oil acidity for prediction through Machine Learning models. It was observed that grain subjected to drying and storage conditions in dryer-silos maintained the highest grain quality at the end of the process. Although there were differences related on the applied drying and storage technology regarding changes in grain quality, it was noticed that the Artificial Neural Networks model demonstrated superior performance in predicting grain quality. It exhibited unanimity across all evaluated processes and technologies. Thus, it is recommended to conduct post-harvest drying of soybeans and subsequent grain storage in dryer-silos, while monitoring environmental and intergranular variables. This approach is advised to be coupled with the utilization of Artificial Neural Networks models to anticipate losses and enhance grain conversation with greater efficiency.

Keywords: Artificial intelligence, Grain monitoring, Grain postharvest, Grain security.

1. Introduction

The drying and storage stages constitute important operations in grain post-harvest handling. Consequently, anticipating soybean harvesting followed by artificial drying may result in improved grain quality indices over the storage period (Bissaro et al., 2022).

In the drying process, the removal of water from the grains occurs in two phases simultaneously. First, the transfer of water vapor from the grain surface to the intergranular air, due to the partial vapor pressure gradient of water and then, the movement of water from the interior to the surface of the grains (Timm et al., 2022). Therefore, the drying temperature applied in the process is important because, along with the airflow, it is the main determinant of the drying rate (Müller et al., 2022). The consequences on grain quality limit the use of high temperatures (Wei et al., 2020). Excessively high temperatures can lead to high rate of water evaporation on the surface (Anand et al., 2021). Consequently, the rate of water transport from the interior to the surface becomes lower than the rate of water evaporation from the surface, increasing the moisture gradient between the interior and the surface of the grains, potentially causing internal tensions that result in physical damage (Privatti et al., 2022). On the other hand, drying at low temperatures may extend the drying operation time, but when combined with refrigeration storage conditions, it can provide a better environment for maintaining grain quality.

Storage systems with refrigerated environments may maintain the quality of soybean grains for longer periods, reducing the metabolic activity and respiration rates of the grain mass (Lutz and Coradi, 2022). Therefore, drying technology and the monitoring of variables such as temperature and intergranular relative humidity, as well as grain mass management, are crucial for preserving the final quality of the stored product (Bilhalva et al., 2023).

Accordingly, to predict the grain quality in different drying and storage processes, predictive algorithms can be utilized. Machine learning analyses enable the assessment of the most relevant variables and their correlation to determine which drying and storage conditions are most favorable for maintaining the quality of soybean grains and their influence on variables of interest, such as oil yield, crude protein content, and oil acidity (Dubal et al., 2023).

Machine learning models have been widely employed to predict the quality of soybean grains (Jaques et al., 2022) and corn (Lutz et al., 2022), determine wheat yield (Leal et al., 2023), as well as assess seed germination rate (André et al., 2022). Some recent studies have demonstrated the effectiveness of machine learning models in predicting the viability, vigor, and germination speed of seeds from different crops. Lin et al. (2019) achieved satisfactory results using machine learning algorithms; however, the models that best predicted soybean quality varied depending on the processing and storage conditions.

Machine learning enables the prediction of drying and storage conditions with greater speed and low operational cost, making it feasible as an auxiliary tool for decision-making in grain drying and storage units, thereby contributing to the reduction of qualitative and quantitative losses. To minimize the gaps caused by conventional grain analysis, which are dependent on personal interpretations, machine learning techniques can serve as alternatives for analyzing soybean grain quality during drying and storage. They also act as decision support tools for determining drying and storage conditions, methods, and times to maintain quality and reduce soybean quality losses. Thus, the objective of this study was to evaluate the effects of different drying and storage technologies on the quality of soybean grains associated with Machine Learning algorithms to predict changes in grain quality.

2. Material and methods

2.1 Grain mass monitoring in the drying in continuous dryer

The soybean grains were harvested with 23% of moisture content and subsequently underwent cleaning to remove impurities and foreign matter using an air machine and sieve. In the initial assessment, the soybean mass underwent drying in a continuous dryer KW model (Kepler Weber, Panambi, Brazil) with a nominal capacity of 80 ton h^{-1} and air drying temperature of 80 °C (Fig. 1).

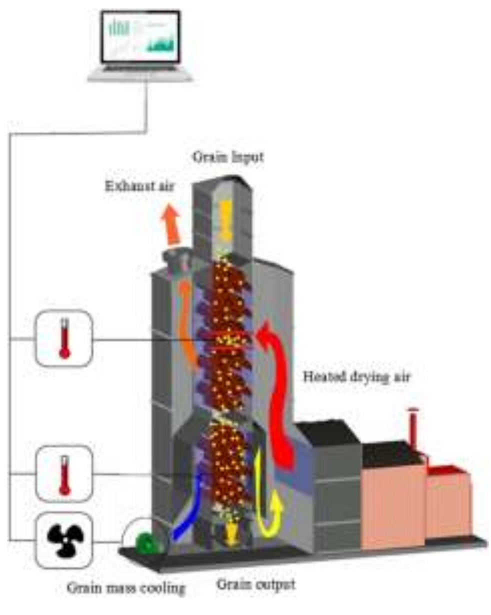

Fig. 1. Continuous dryer applied in the soybean drying.

Three drying tests were performed during the drying. The moisture content and grain mass temperature were monitored by using thermocouple sensors installed in the drying chamber. Additionally, the temperature and relative humidity of the air were monitored during the process. The drying was continued until the grains reached a moisture content of 11%. At the end of the tests, samples were collected to determine of electrical conductivity (EC), acid oil (AO), crude protein (CP), and oil yield (OY).

2.2 Grain mass monitoring during drying and storage in silo-dryer

In the second evaluation, a batch of soybeans of 20,000 bags (each weighing 60 kg) was subjected to drying in a metallic silo-dryer under ambient air temperature conditions (Fig. 2), equipped with a controlled aeration system (Widitec, Panambi, Rio Grande do Sul, Brazil).

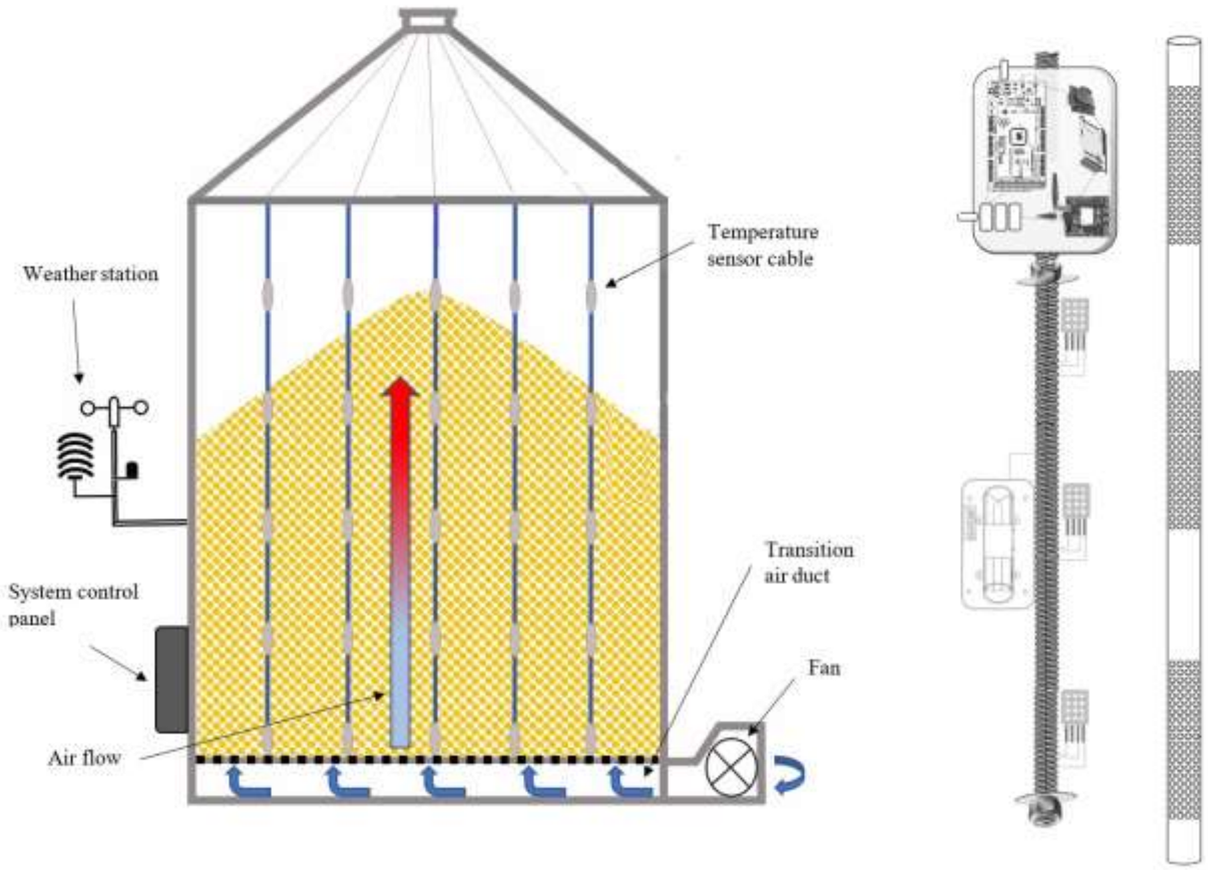

Fig. 2. Silo-dryer applied to drying soybeans.

The air velocities within the silo-dryer were monitored using a thermo-anemometer, model PCE-423 (PCE Instruments UK Ltd., Southampton, Hampshire, England). Digital sensors, positioned equidistantly, were used to monitor the temperature of the grain mass. Sampling was conducted upon completion of the drying process to assess moisture content

(MC), apparent specific mass (ASM), electrical conductivity (EC), germination (G), and oil content (OC).

2.3 Grain mass monitoring in vertical and horizontal silo storage

A portion of the soybean batches subjected to drying were stored in vertical and horizontal storage (Fig. 3).

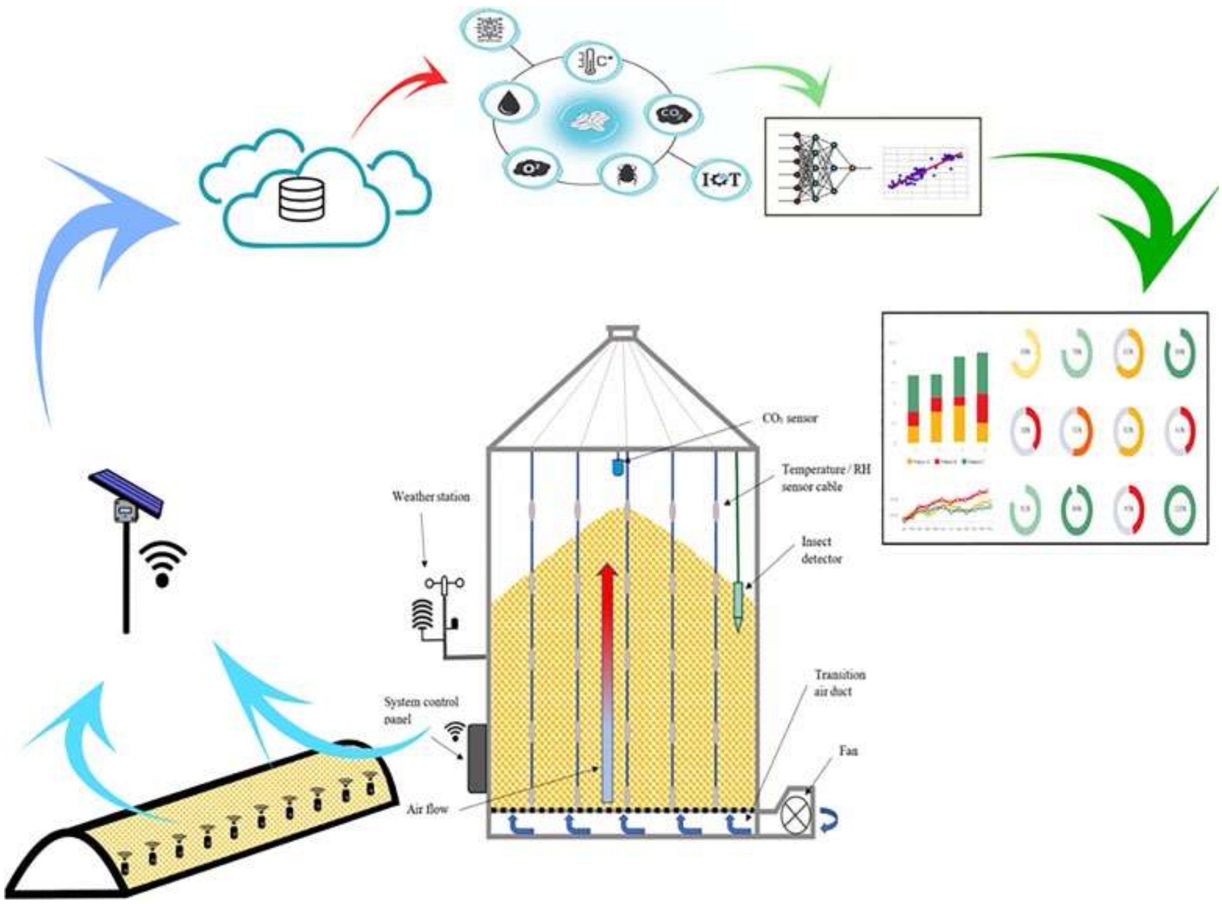

Fig. 3. Storage of soybeans in vertical storage silo and horizontal silo.

Cables sensors, specifically the Mega 2560 microcontroller model (Arduino LLC, Italy), were used to monitor the mass of soybean grains in storage (Nunes et al., 2023). The system hardware includes digital sensors for detecting air temperature and relative humidity (DHT22 model, Aosong Electronics, Guangzhou, China), a non-destructive infrared sensor for detecting CO_2 concentration (MHZ-14 model, Winsen, China), real-time clock modules (DS3231 model, flip-flop, China), and a micro-SD card (Greatzt micro SD card model, China). The equipment is powered by three batteries arranged in series, providing a total power of 27 V. The SmartStorage software and the CO_2 Reader software were used. The temperature and relative humidity was monitored using TLX thermohygrometer, model DTH-

16 (Shenzhen Tonglixing Technology, Guangdong, China), and concentration of carbon dioxide was monitored using a 77525 model (AKSON, São Leopoldo, Brazil) in the intergranular air of the soybean grain mass stored in the silo, which had a moisture of 11.5% (w.b.) over a period of six months. Samples were collected to evaluate the dry matter content in soybeans.

2.4 Equilibrium moisture content of the stored grain mass

The temperature and air intergranular relative humidity were used in the Equations 1 and 2 to calculate the equilibrium moisture content of the stored grain mass:

Air relative air humid between 0 < RH <= 55%:

$$EMC = \frac{3.96(RH)^{0.492})}{\ln(T)} \quad 1)$$

Air relative humid between 55 < RH < 100%:

$$EMC = \frac{16.21\exp(0.0274RH)}{\ln(T)} \quad 2)$$

where,

EMC: Equilibrium moisture content (%)

RH: Relative humidity (%)

T: Temperature (F)

2.5 Carbon dioxide and dry matter loss

The dry matter loss was calculated by the CO_2 concentration monitored during the grain storage period through Equation 3:

$$DML = 100(C_{CO_2} - \Delta CO_2)\left(\frac{\varepsilon P W_g}{2P_g(1-MC)RT}\right) \quad 3)$$

where,

DML: dry matter loss (%)

C_{CO_2}: CO_2 concentration C_{CO_2} (v/v) measured inside the metal silos

ΔC_{O_2}: variation of CO_2 concentration during storage considering the initial concentration of 21%

ε: granular mass porosity (40%)

P: local atmospheric pressure (96 kPa)

W_g: molar mass of glucose (180 kg kmol^{-1})

P_g: apparent specific gravity of the grains (kg m^{-3}) (750 kg m^{-3})

MC: Grain moisture content (decimal, w.b.)

R: perfect gas constant (8,314 kJ Kmol^{-1} K^{-1})

T: Temperature (K)

The determination of the mass loss of stored soybean grains was performed using Equations 4 and 5:

$$DM = \left[1 - \left(\frac{MC}{100}\right)\right] P_i \quad 4)$$

where,

DM: dry matter (g)

MC: moisture content (%)

P_i: initial grain mass (g)

$$DML_{calculated} = \left(\frac{DM_{initial} - DM_{final}}{DM_{initial}}\right) * 100 \quad 5)$$

where,

$DML_{calculated}$: dry matter loss (%)

$DM_{initial}$: initial dry matter (g)

DM_{final}: final dry matter (g)

2.6 Multivariate analysis

Pearson's correlation network analysis was performed. The proximity between the nodes was determined proportionally to the absolute value of the correlation between the them. The thickness of the edges was adjusted by applying a cut-off value of 0.60, indicating that only correlations with $|r\_XY| \geq 0.60$ had their edges highlighted. These analyses were performed using the “ggfortify” package in the free R application, following the procedures recommended by Naldi et al. (2011). Positive correlations are highlighted in green, while negative correlations are represented on a red scale.

2.7 Machine Learning models

The prediction of soybean grain dry matter loss was conducted using Multiple Linear Regression (MLR), Artificial Neural Networks (ANN), Decision Tree (REPtree), Quinlan's M5 algorithm (M5P), and Random Forest (RF) models. These models were analyzed using

Weka software 3.9.5 version (Bouckaert et al., 2010) with stratified random cross-validation of folds with 10 repetitions, utilizing a dataset containing the following input variables: temperature (T), relative humidity (RH), equilibrium moisture content (EMC), and intergranular carbon dioxide (CO_2). For MLR, the data were normalized and subjected to the Shapiro-Wilk test. Furthermore, a sensitivity analysis was performed for MLR to asses the impact in order to verify the effect of the input data variation on the results. The fits of the predicted data by the models were evaluated using the coefficient of correlation (r) and mean absolute error (MAE). These results were then analyzed by using analysis of variance (ANOVA) with ten repetitions, executed in the R software. Subsequently, the means of r and MAE obtained for each technique were grouped by the Scott-Knott test at 5% probability level. To represent these results for each output variable, boxplots were created in R software using the ExpDes.pt and ggplot2 packages.

3. Results and discussion

3.1 Soybean grain drying in continuous dryer

The magnitude of cellular damage caused to the grains depended on the initial and final moisture contents of the product, temperature, relative humidity, airflow, and drying rate, and exposure period to heated air. During the drying of soybean grains at an air temperature of 80 °C, it was observed that the moisture content decreased from 23% to 11% after 2.33 hours (Fig. 4A). According to Pearson correlation analysis (Fig. 4B), the drying air temperature (DAT) showed a strong positive correlation with electrical conductivity (EC), indicating that an increase in DAT is related to a reduction in the quality of soybean grains due to greater damage to the cellular structure.

Continuous dryers operating at high air temperatures cause high heat transfer from the air to the grains and moisture transfer from the grains to the air. Thus, in continuous drying, the heated and convective air heats the grain mass, causing movement of water in the liquid state and subsequently in the vapor state from the interior to the periphery of the grain, due to the vapor pressure difference. Consequently, grain drying occurs continuously when the vapor pressure on the surface of the grains is greater than the water vapor pressure in the drying air (Anand et al., 2021). Crude protein (CP) and oil yield (OY) showed a strong positive correlation, indicating that they are variables linked to the physicochemical quality of soybean grains. According to Pearson correlation analysis (Fig. 4B), the drying air temperature (DAT) showed a strong positive correlation with electrical conductivity (EC), indicating that the increase in DAT is related to the reduction in the quality of soybean grains due to greater damage to cellular structure.

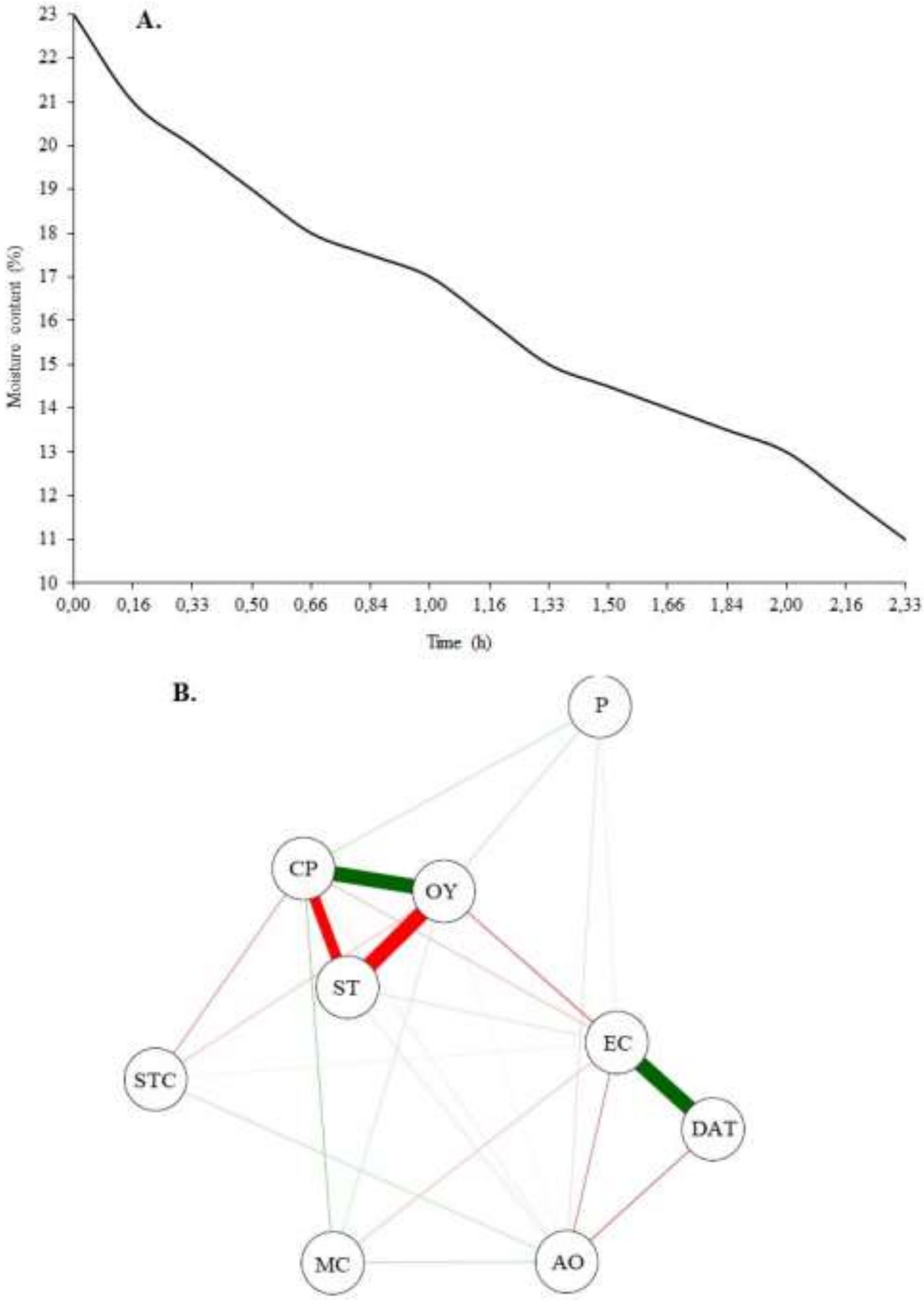

Fig. 4. (A) Soybean drying curve, (B) pearson correlation analysis of the qualitative variables (crude protein-CP, acidity oil-AO, oil yield-OY, electrical conductivity-EC, moisture content-IMC, drying air temperature-DAT, packing-P, storage temperature-ST, storage conditions-STC) of soybean grains dry in continuous dryer. Green lines link variables to positive

correlation and red lines link negatively correlated variables. The thickness of the line is proportional to the correlation magnitude.

Continuous dryers operating at high air temperatures cause high heat transfer from the air to the grains and moisture transfer from the grains to the air. Thus, in continuous drying, the heated and convective air heats the grain mass, causing movement of water in the liquid state and subsequently in the vapor state from the interior to the periphery of the grain, due to the vapor pressure difference. Consequently, grain drying occurs continuously when the vapor pressure on the surface of the grains is greater than the water vapor pressure in the drying air (Anand et al., 2021). Crude protein (CP) and oil yield (OY) showed a strong positive correlation, indicating that they are variables linked to the physicochemical quality of soybean grains.

In conditions of drying air temperatures above 40 °C, physical damage and reduction in physicochemical quality in soybean grains are observed (Darvishi et al., 2015). At high temperatures (>80°C), the protein and lipid content of the oil may decrease by up to 0.5% and 0.43%, respectively. The acidity content may increase by up to 0.23 mg KOH/g. Improper drying processes caused problems in the color of the grain tegument and other organoleptic characteristics. Additionally, a water content of 25% and high air temperatures of up to 120°C during the drying process influenced the extracted oil content, increasing the oil acidity content by up to 1.4 mg KOH/g (Coradi et al., 2017). According to Ziegler et al. (2021), high moisture levels drastically affect the physicochemical and morphological properties of grains, such as acidity content and the quality of the extracted oil.

Drying soybeans at high temperatures causes grain structure rupture, promoting fungal infection and increasing the conversion of important chemical elements into undesirable products (Ferreira et al., 2019). In a study conducted by Coradi et al. (2018) with temperatures ranging from 30 to 50°C and initial moisture contents of 20% (d.b.), it was observed that the drying time decreased from 10 hours to 2 hours. Nevertheless, the temperature increase reduced the volumetric contraction of soybean grains by up to 3.0 mm. The storage temperature (ST) showed a strong negative correlation with crude protein (CP) and oil yield (OY), indicating that higher storage temperatures effected the preservation of grain quality. It leads to a reduction in the percentage of crude protein and soybean oil yield. Pearson correlation coefficient (r) and mean absolute error (MAE) between observed and estimated values of electrical conductivity (Figs. 5A-B), oil acidity (Figs. 5C-D), crude protein (Figs. 5E-F), and oil yield (Figs. 5G-H) in soybean grains dried in a continuous dryer by different machine learning models and inputs (Table 1).

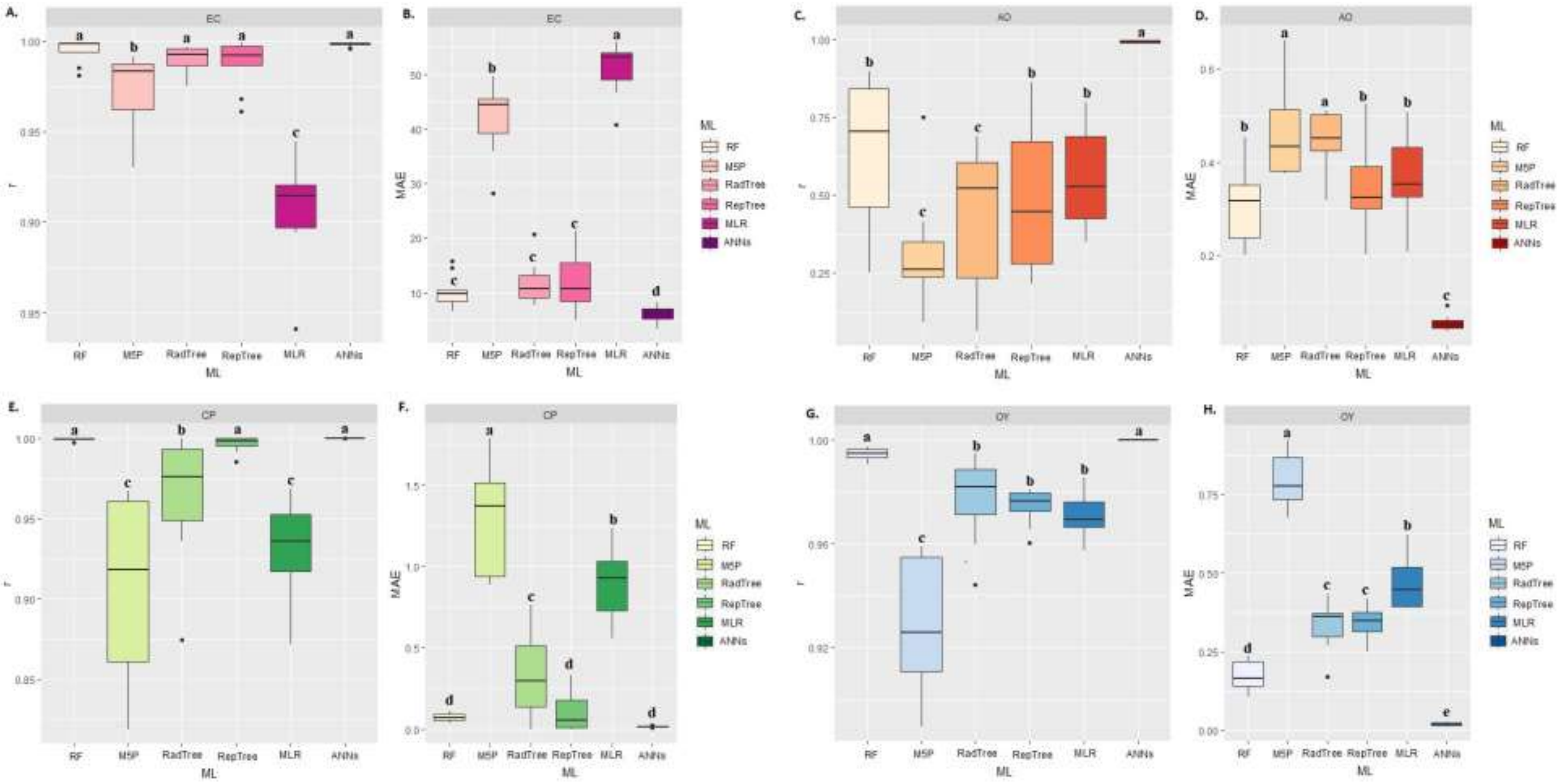

Fig. 5. Boxplot for Pearson correlation coefficient (r), and mean absolute error (MAE) between observed and estimated values of electrical conductivity (A, B), acidity oil (C, D), crude protein (E, F), oil yield (G, H) in soybean grains dry in continuous dryer by different machine learning models and inputs. Means followed by equal letters in the same column do not differ by the Scott–Knott test at 5% probability.

Among the analyzed Machine Learning models, the Artificial Neural Networks (ANNs) algorithm performed best in predicting the quality variables of soybean grains during continuous dryer drying, considering the monitoring of drying air temperature and moisture content.

Table 1 Deployment of the significant interaction between models x inputs for correlation coefficient (r), mean absolute error (MAE), coefficient of determination (R^2) between observed and estimated values of soybean grains physicochemical quality in the continuous drying, for the different models of Machine Learning

Models	**Electrical conductivity**			**Acid oil**			**Crude protein**			**Oil yield**		
	r	**MAE**	**R^2**	**r**	**MAE**	**R^2**	**r**	**MAE**	**R^2**	**r**	**MAE**	**R^2**
MLR	0.90767 c	51.07933 a	0.82388	0.55334 b	0.36662 b	0.30618	0.93200 c	0.88329 b	0.86862	0.97065 b	0.47062 b	0.94217
ANNs	0.99811 a	6.21249 d	0.99623	0.993114 a	0.05588 c	0.98627	0.99998 a	0.01516 d	0.99996	0.99993 a	0.01902 e	0.99987
M5P	0.97386 b	42.06381 b	0.94840	0.31523 c	0.45999 a	0.09937	0.90710 c	1.28811 a	0.82284	0.92964 c	0.79278 a	0.86424
RF	0.99472 a	10.31243 c	0.98947	0.64599 b	0.30971 b	0.41730	0.99941 a	0.07249 d	0.99882	0.99450 a	0.17418 d	0.98903
RadTree	0.99028 a	11.73265 c	0.98066	0.41997 c	0.44774 a	0.17637	0.96440 b	0.32663 c	0.93007	0.97781 b	0.33178 c	0.95611
RepTree	0.98785 a	12.00617 c	0.97584	0.48460 b	0.35411 b	0.23484	0.99635 a	0.09928 d	0.99272	0.97453 b	0.34140 c	0.94971

Equal letters in the column do not differ at (p<0.05) by the Scott knott test. Pearson's correlation coefficient (r), mean absolute error (MAE) and coefficient of determination (R^2) for Machine Learning models: Artificial Neural Network (ANN), Decision Tree (REPTree), Random Tree (RandTree), Quinlan's M5 algorithm (M5P), Random Forest (RF), and Multiple Linear Regression (MLR).

3.2 Drying and storage of soybean grains in a silo-dryer

During the drying of soybean grains in a silo-dryer at ambient air temperature, a reduction in moisture content from 16% to 11% achieved at the end of six months. However, under these conditions, the intergranular temperature of the grain mass ranged from 5 to 27 °C, while the relative humidity increased from 57 to 98% at the end of six months, leading to an increase in the hygroscopic equilibrium moisture content from 13.6 to 14.8% (Figs. 6A-D).

The increase in hygroscopic equilibrium moisture content intensified metabolic activity and grain mass respiration from 400 to 1100 ppm, resulting in consumption and losses of dry matter (Figs. 6E-F). According to Pearson correlation (Fig. 6G), the storage time (STM) during drying in the silo-dryer showed a strong positive correlation with electrical conductivity (EC), indicating that an increase in STM is related to a reduction in the quality of soybean grains due to greater damage to the cell structure.

The storage time (STM) in the silo-dryer exhibited a strong negative correlation with apparent specific mass (ASM) and moisture content (MC) variables. Additionally, MC and ASM showed a strong positive correlation, indicating that an increase in storage time resulted in a reduction in grain moisture content and a subsequent decrease in apparent specific mass of stored soybean grains. Electrical conductivity (EC) showed a strong negative correlation with moisture content (MC) and apparent specific mass (ASM) variables, indicating that a decrease in MC and ASM over the storage time increased EC results, indicating a reduction in physiological quality of stored grains.

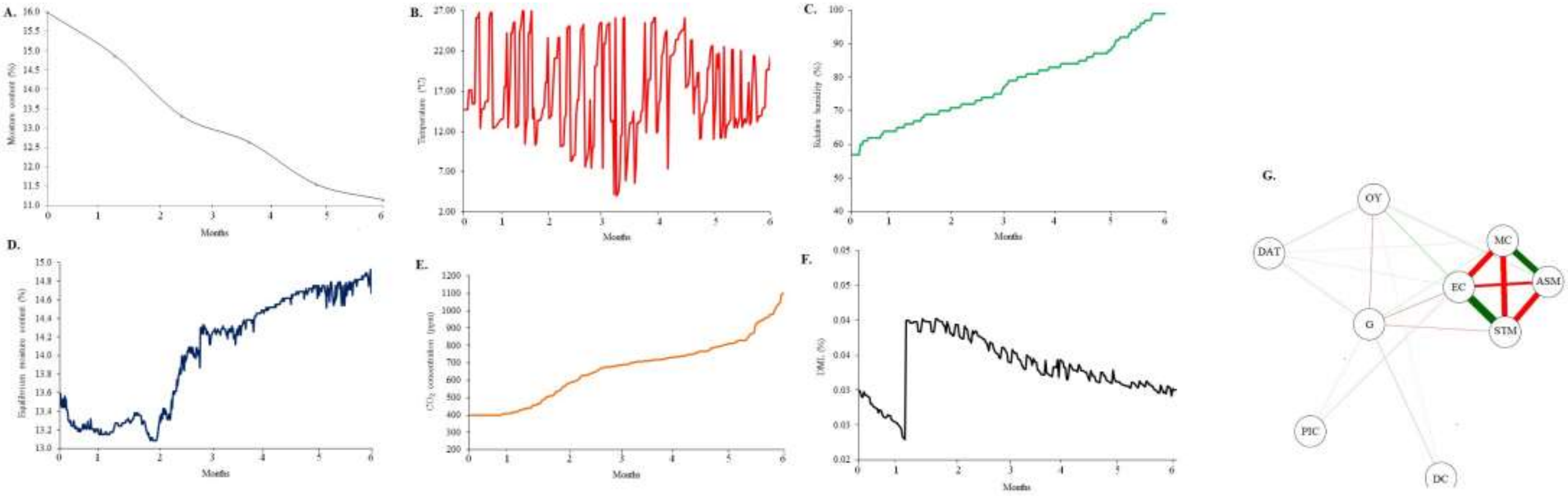

Fig. 6. (A) Soybean drying curve, (B) Monitoring of temperature air intergranular, (C) relative humidity air intergranular, (D) equilibrium moisture content, (E) CO_2 concentration, (F) dry matter loss, (G) pearson correlation analysis of the qualitative variables (drying temperature-DAT, drying cells-DC), position in cells-PIC, storage time-STM, moisture content-MC, apparent specific mass-ASM, electrical conductivity-EC, germination-G, oil yield-OY) of soybean grains dry in silo dryer. Green lines link variables to positive correlation and red lines link negatively correlated variables. The thickness of the line is proportional to the correlation magnitude.

The drying process in a silo-dryer essentially involved forcing air passing through the grain mass while it remained stationary. Precautions were taken to avoid overdrying of the grain layer closest to the air inlet while allowing water removal from the more distant layer, thereby preventing accelerated grain deterioration. Drying in perforated false bottom silo-dryers proceeded from the base to the surface of the grain mass, occurring in layers due to the formation of drying zones corresponding to the regions of water exchange between the grains and the air. The airflow was sufficient to prevent saturation before leaving the grain mass, and it could be increased as long as it was capable of absorbing all the water released by the grains. Beyond this point, the migration of water from the interior to the surface of each grain became the primary factor influencing the drying rate.

It was observed that the effect of the number of stages of simultaneous heat and mass transfer altered the quality of soybean grains, with an increase in the number of stages significantly reducing the percentage of broken grains by up to 15%. Pearson correlation coefficient (r) and mean absolute error (MAE) between observed and estimated values of moisture content, apparent mass specific, electrical conductivity, germination, and oil content in soybean grains dried in the silo-dryer by different machine learning models and inputs showed no significant differences according to the Scott-Knott test at a 5% probability level (Fig. 7 and Table 2).

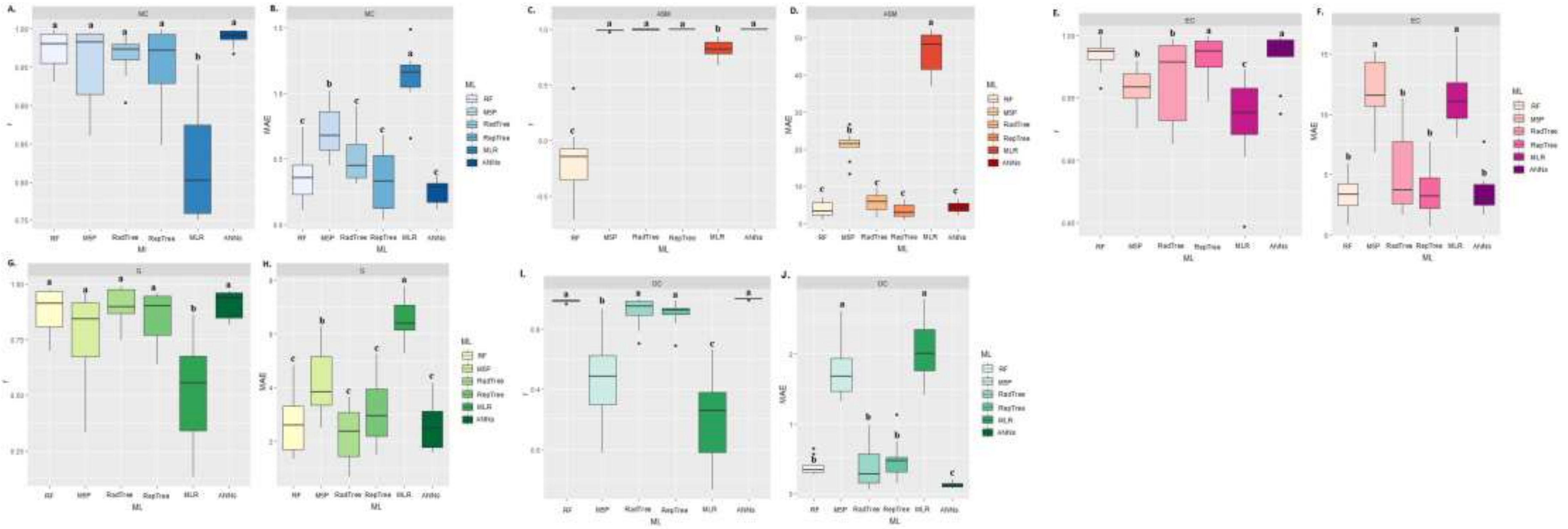

Fig. 7. Boxplot for Pearson correlation coefficient (r), and mean absolute error (MAE) between observed and estimated values of moisture content (A, B), apparent mass specific (C, D), electrical conductivity (E, F), germination (G, H), oil content (I, J) in soybean grains dry in silo dryer by different machine learning models and inputs. Means followed by equal letters in the same column do not differ by the Scott–Knott test at 5% probability.

Table 2 Deployment of the significant interaction between models x inputs for correlation coefficient (r), mean absolute error (MAE), coefficient of determination (R^2) between observed and estimated values of soybean grains physical quality in the drying and storage in silo-dryer, for the different models of Machine Learning

Models	Moisture content			Apparent specific mass			Electrical conductivity			Germination			Oil content		
	r	**MAE**	**R^2**	**r**	**MAE**	**R^2**	**r**	**MAE**	**R^2**	**r**	**MAE**	**R^2**	**r**	**MAE**	**R^2**
MLR	0.8195 b	1.1310 a	0.6716	0.8185 b	46.2739 a	0.6700	0.9311 c	11.3668 a	0.8670	0.5151 b	6.57358 a	0.26541	0.2123 c	2.0516 a	0.0451
ANNs	0.9886 a	0.2536 c	0.9775	0.9978 a	4.3958 c	0.9957	0.9820 a	3.5035 b	0.9644	0.9091 a	2.55139 c	0.82658	0.9972 a	0.12399 c	0.9944
M5P	0.9546 a	0.7154 b	0.9113	0.9896 a	20.904 b	0.9793	0.9567 b	11.8339 a	0.9154	0.7704 a	4.15092 b	0.59359	0.4659 b	1.7825 a	0.2171
RF	0.9733 a	0.3682 c	0.9473	0.1797 c	3.7789 c	0.0322	0.9837 a	3.38291 b	0.9677	0.8774 a	2.62717 c	0.76984	0.9854 a	0.3878 b	0.9711
RadTree	0.9644 a	0.5029 c	0.9302	0.9965 a	5.7079 c	0.9930	0.9638 b	5.1896 b	0.9289	0.9053 a	2.25261 c	0.81957	0.9169 a	0.3838 b	0.8408
RepTree	0.9549 a	0.3332 c	0.9118	0.9979 a	3.4183 c	0.9959	0.9827 a	3.4900 b	0.9657	0.8517 a	3.08981 c	0.72554	0.9000 a	0.4946 b	0.8101

Equal letters in the column do not differ at (p<0.05) by the Scott knott test. Pearson's correlation coefficient (r), mean absolute error (MAE) and coefficient of determination (R^2) for Machine Learning models: Artificial Neural Network (ANN), Decision Tree (REPTree), Random Tree (RandTree), Quinlan's M5 algorithm (M5P), Random Forest (RF), and Multiple Linear Regression (MLR).

3.3 Storage of soybean grains in vertical silo

Throughout the storage period of the soybean grain mass in the vertical silo, there was an increase in the intergranular temperature from 20°C to 24°C, with a 1°C difference between the lower, central, and upper layers. The intergranular temperature was lower in the lower layer at the beginning of the storage period, inverting after the second month of storage, when the upper layers had greater temperature variations.

The intergranular relative humidity had similar effects to temperature, with variations ranging from 75% to 90%, altering the hygroscopic equilibrium moisture content, mainly in the upper grain layers of the vertical silo. 16% moisture content was observed from the first month of storage until near the fifth month.

The high intergranular relative humidity condition and the rise in hygroscopic equilibrium moisture content resulted in an increase in the metabolic activity of the grains and consequently in the respiration of the grain mass, from 400 to 2000 ppm at the end of the storage period, thereby amplifying dry matter losses (Figs. 8A-E).

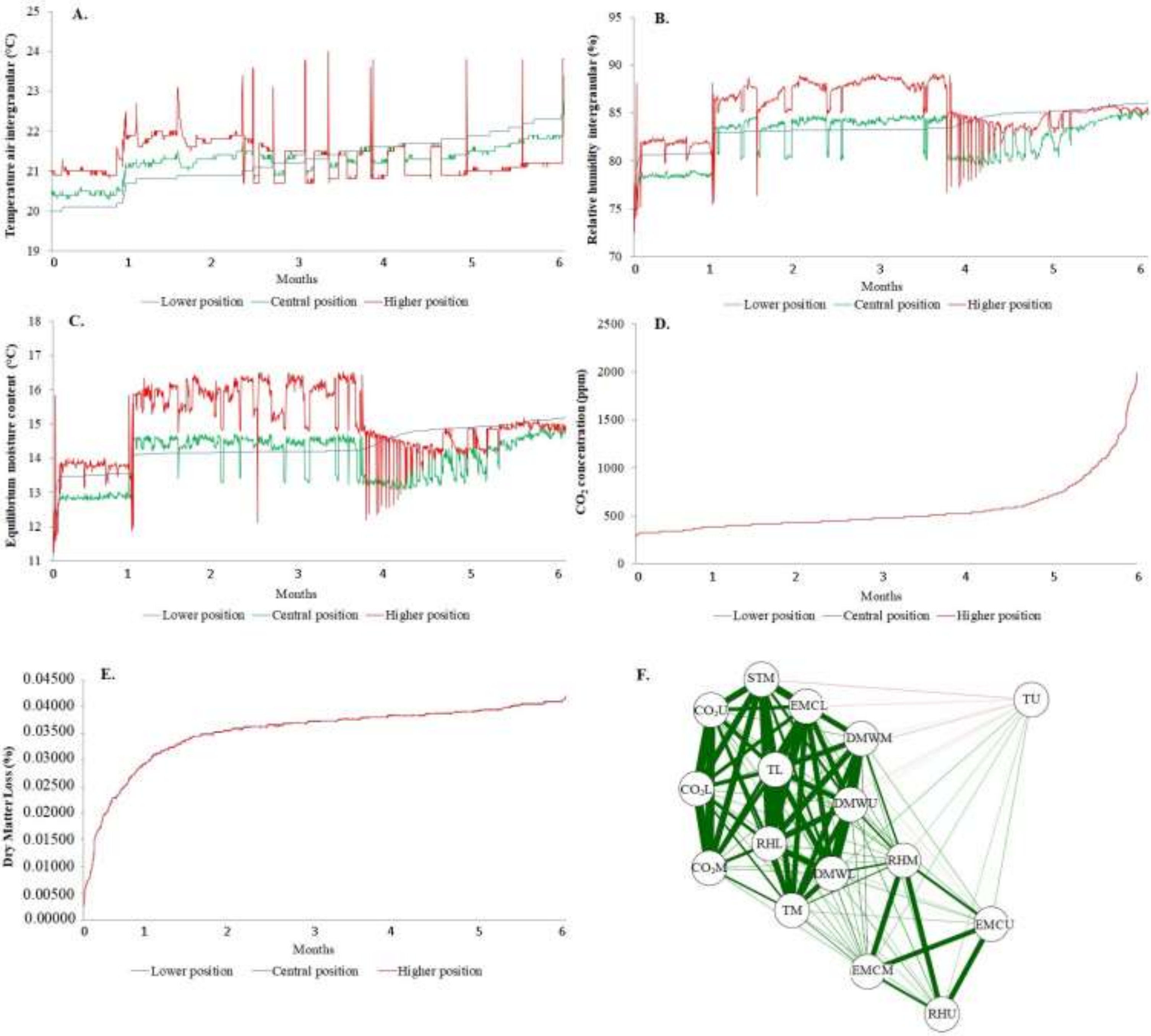

Fig. 8. (A) Monitoring of temperature air intergranular, (B) relative humidity air intergranular, (C) equilibrium moisture content, (D) CO_2 concentration, (E) dry matter loss, (F) pearson correlation analysis of the qualitative variables (storage time-STM, temperature lower-TCL, temperature medium-TCM, temperature upper-TCU, relative humidity lower-RHL, relative humidity medium-RHM, relative humidity upper-RHU, carbon dioxide lower-CO_2L, carbon dioxide medium-CO_2M, carbon dioxide upper-CO_2U, equilibrium moisture content lower-EMCL, equilibrium moisture content medium-EMCM, equilibrium moisture content upper-EMCU), dry mass weight lower-DMWL, dry mass weight medium-DMWM,

dry mass weight upper-DMWU) of soybean grains stored in silo vertical. Green lines link variables to positive correlation and red lines link negatively correlated variables. The thickness of the line is proportional to the correlation magnitude.

According to the Pearson correlation (Fig. 8F), the grain mass in the bottom layer (DMWL), middle layer (DMWM), and top layer (DMWU) exhibited similar behavior. The DMWL, DMWM, and DMWU showed a strong negative correlation with the lower layer temperature (TL) and average temperature (TM) of the stored grain mass. Each soybean-producing region has its own temperature and relative humidity characteristics, which require specific measures to be adopted. The physicochemical quality of soybean grains, stored in storage units in regions with temperatures above 30°C and relative humidity below 60% altered the color and weight of the grain mass (Zeymer et al., 2021). These authors pointed out that the value of some grain properties underwent significant variation (11.30% moisture content, 32.11% proteins, 20.62% carbohydrates, 7.76% fibers, 4.68% ashes, and 23.62% lipids) and changes in electrical conductivity.

This occurs due to the specific characteristics of the region, which high temperatures combined with low relative humidity influence the grain's equilibrium moisture content, maintaining its properties during the storage period. The interaction exhibited notably reduced strength with the upper temperature (TU), indicating that the metabolic activity of the grains was more intense in the middle and lower positions of the grain mass. The DMWL, DMWM, and DMWU showed a strong negative correlation with the lower layer hygroscopic equilibrium moisture content (EMCL) and lower layer relative humidity (RHL), indicating that the lower position of the grain mass experienced greater deterioration. The increase in grain storage time after drying potentiated the reduction in soybean quality (Cañizares et al., 2021). The effects on biochemical properties occur due to oxidation reactions associated with the temperature applied during the storage process.

In the grain storage stage at a temperature of 30 ºC, the occurrence of oil quality losses is approximately 59.6% (90 days), 67% (135 days), and 76% (180 days) (Bischoff et al., 2016). The loss of oil quality results directly from the degradation of lipids, presented in the grains (Ludwig et al., 2021). Jian et al. (2014) developed mathematical models to predict the germination rates of canola stored under controlled conditions and in storage silos. Their models explained over 96% of the variation in germination. Barreto et al. (2017) described a two-dimensional finite element model that predicted the temperature and moisture distribution due to seasonal variation of the intergranular air of stored soybeans. The authors recommended a reference value of CO_2 concentration of 3% as a limit when storing soybeans with moisture content ranging between 13 and 15%.

Meanwhile, the model described by Taher et al. (2019) aimed to predict the loss of soybean quality during storage by monitoring CO_2 concentration over the storage period, achieving a correlation of 73%. Pearson correlation coefficient (r), and mean absolute error (MAE) between observed and estimated values of dry matter loss in soybean grains stored in vertical silos by different machine learning models and inputs with means followed by equal letters in the same column do not differ by the Scott–Knott test at 5% probability (Fig. 9). It was found that the RF, M5P, and RadTree models achieved better fits for predicting dry matter loss in the lower, middle, and upper layers of the stored grain mass in vertical silos (Table 3).

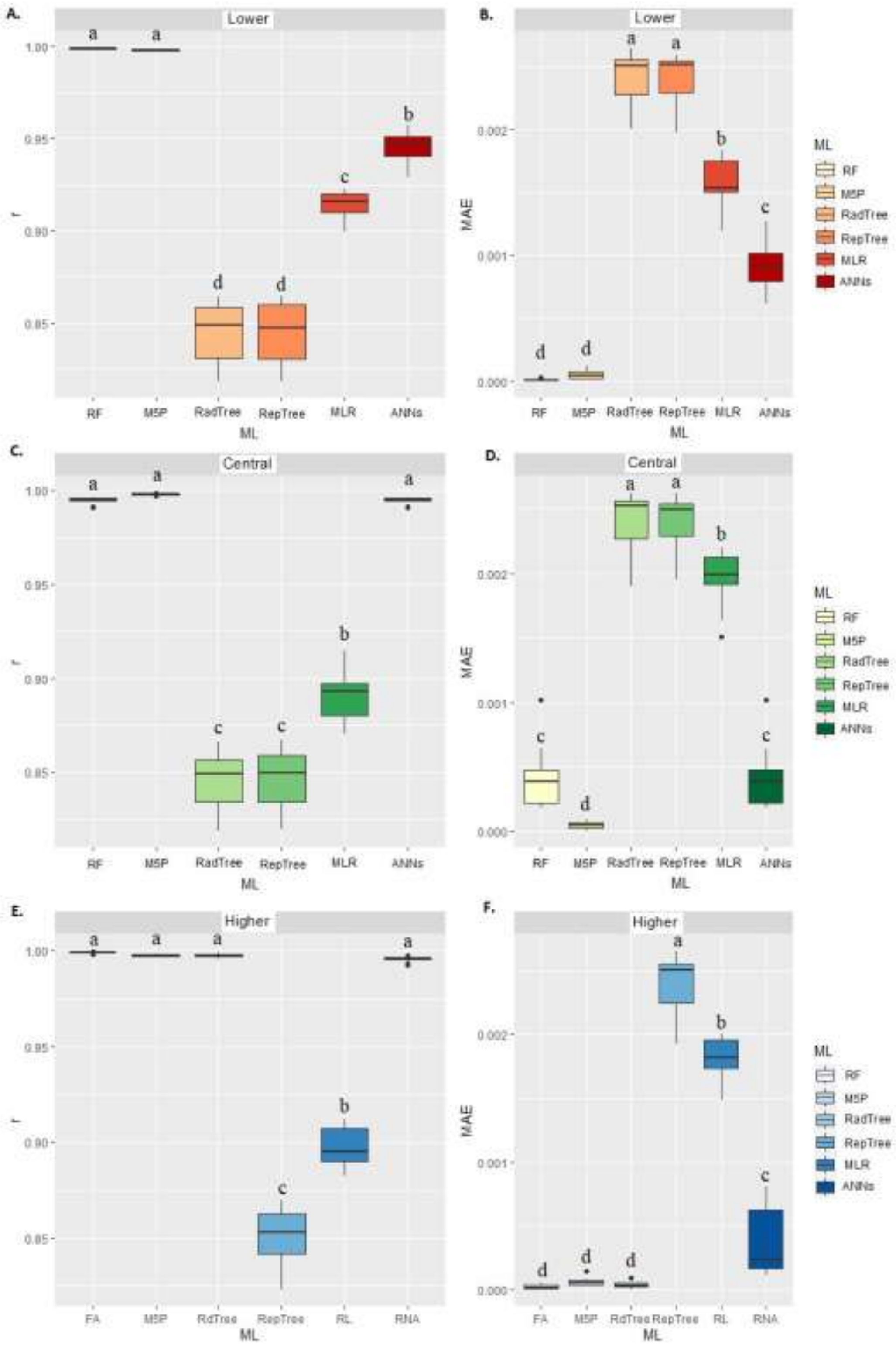

Fig. 9. Boxplot for Pearson correlation coefficient (r), and mean absolute error (MAE) between observed and estimated values of dry matter loss in soybean grains stored in vertical silo by different machine learning models and inputs. Means followed by equal letters in the same column do not differ by the Scott–Knott test at 5% probability.

Table 3 Deployment of the significant interaction between models x inputs for correlation coefficient (r), mean absolute error (MAE), coefficient of determination (R^2) between observed and estimated values of dry matter loss in soybean grains stored in vertical silo, for the different models of Machine Learning

Models	**Dry matter loss**								
	Lower position			**Central position**			**Higher position**		
	r	**MAE**	**R^2**	**r**	**MAE**	**R^2**	**r**	**MAE**	**R^2**
MLR	0.91384 c	1.56674 b	0.83510	0.89061 b	1.95168 b	0.79319	0.89732 b	1.80461 b	0.80519
ANNs	0.94558 a	9.07862 c	0.89413	0.99462 a	4.21129 c	0.98927	0.99543 a	3.75374 c	0.99089
M5P	0.99787 a	5.32220 d	0.99576	0.99805 a	4.78364 d	0.99611	0.99753 a	5.86185 d	0.99508
RF	0.99907 a	1.13594 d	0.99815	0.99462 a	4.21129 c	0.98927	0.99894 a	1.97426 d	0.99789
RadTree	0.84483 d	2.41633 a	0.71374	0.84479 c	2.41041 a	0.71368	0.99756 a	3.40854 d	0.99514
RepTree	0.84459 d	2.41213 a	0.71334	0.84590 c	2.40376 a	0.71556	0.84986 c	2.40140 a	0.72227

Equal letters in the column do not differ at (p<0.05) by the Scott knott test. Pearson's correlation coefficient (r), mean absolute error (MAE) and coefficient of determination (R^2) for Machine Learning models: Artificial Neural Network (ANN), Decision Tree (REPTree), Random Tree (RandTree), Quinlan's M5 algorithm (M5P), Random Forest (RF), and Multiple Linear Regression (MLR).

3.4 Storage of soybean grains in horizontal silos

During the storage of soybeans in horizontal silos, an increment of approximately 1°C was observed in the intergranular temperature from the beginning to the conclusion of the storage duration, accompanied by a 5% rise in intergranular relative humidity. This increase was adequate to escalate the hygroscopic equilibrium moisture content from 13.3% to 14.8%. Consequently, the respiration rate of the grain mass intensified from 400 ppm to 1300 ppm from the fourth month of storage, leading to a heightened consumption of dry matter (Figs. 10A-E). According to the Pearson correlation analysis (Fig. 10F), dry matter loss (DML) exhibited a robust positive correlation with the carbon dioxide (CO_2) variable. This represents that the augmented respiratory activity of the stored soybeans, as evidenced by the elevated CO_2 concentration, is intertwined with the rise in DML and the amplified consumption of soybean reserves, thereby compromising the nutritional quality of the grains. Additionally, DML displayed a strong positive correlation with the relative humidity (RH) variable, implying that the augmented RH correlates with increased metabolic activity of soybeans and the hastened progression of grain deterioration throughout storage. Moreover, the variables DML, CO_2, and RH demonstrated a robust positive correlation amongst themselves and with the storage time (STM) variable. The elongation of STM amassed negative outcomes on grain quality, as indicated by the DML, CO_2, and RH variables, which were exacerbated by respiratory activity, thereby its negative effects on the physicochemical quality of the stored soybeans.

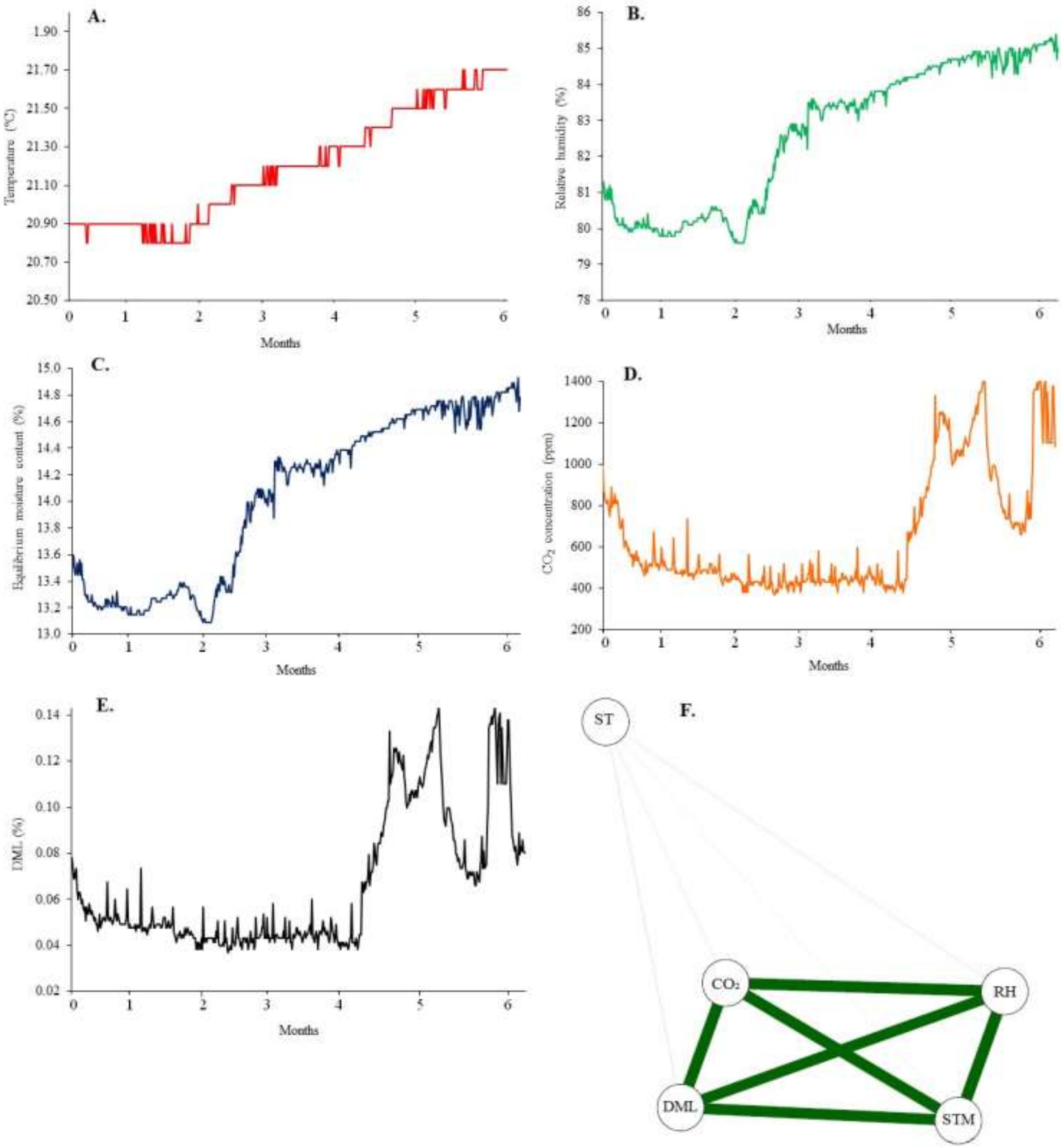

Fig. 10. (A) Monitoring of temperature air intergranular, (B) relative humidity air intergranular, (C) equilibrium moisture content, (D) CO_2 concentration, (E) dry matter loss, (F) pearson correlation analysis of the qualitative variables (storage time-STM, storage

temperature-ST, relative humidity-RH, carbon dioxide-CO_2, dry matter loss-DML) of soybean grains stored in horizontal silo. Green lines link variables to positive correlation and red lines link negatively correlated variables. The thickness of the line is proportional to the correlation magnitude.

Grain moisture content is influenced by the relative humidity of the surrounding air. Moreover, water activity associated with high temperatures intensifies the cellular respiration of the grain mass, creating a conducive environment for insect survival, external moisture variation, and dramatically affecting hygroscopic equilibrium (Coradi et al., 2022). According to Ludwig et al. (2021), changes in atmospheric composition can occur due to the metabolic activity of all living organisms, resulting in a reduction of O2 and an increase in CO2, particularly for soybeans. Excessive respiration of the grain mass not only modifies physical and chemical properties but also reduces germination vigor. Moisture losses cause ruptures in hydrocarbon structures responsible for grain structure stability and, through high cellular respiration, alter important properties such as carbohydrates, proteins, and lipids (Wenneck et al., 2022). Storage conditions can mitigate deterioration by inhibiting microorganism development through hypoxia with O_2 levels below 3% and high CO_2 concentration (Ochandio et al., 2017). Once grains are under anoxic conditions, the oxidation rate decreases, mitigating unfavorable oxidative processes and increasing the longevity of the stored product (Buijs et al., 2020).

From the monitored variables (ST, CO2, RH, and T), the prediction of dry matter loss in stored grains was performed using Machine Learning models. Pearson correlation coefficient (r), and mean absolute error (MAE) analysis between observed and estimated values of dry matter loss in soybean grains stored in horizontal silo by different machine learning models and inputs with means followed by equal letters in the same column do not differ by the Scott–Knott test at 5% probability level (Fig. 11 and Table 4).

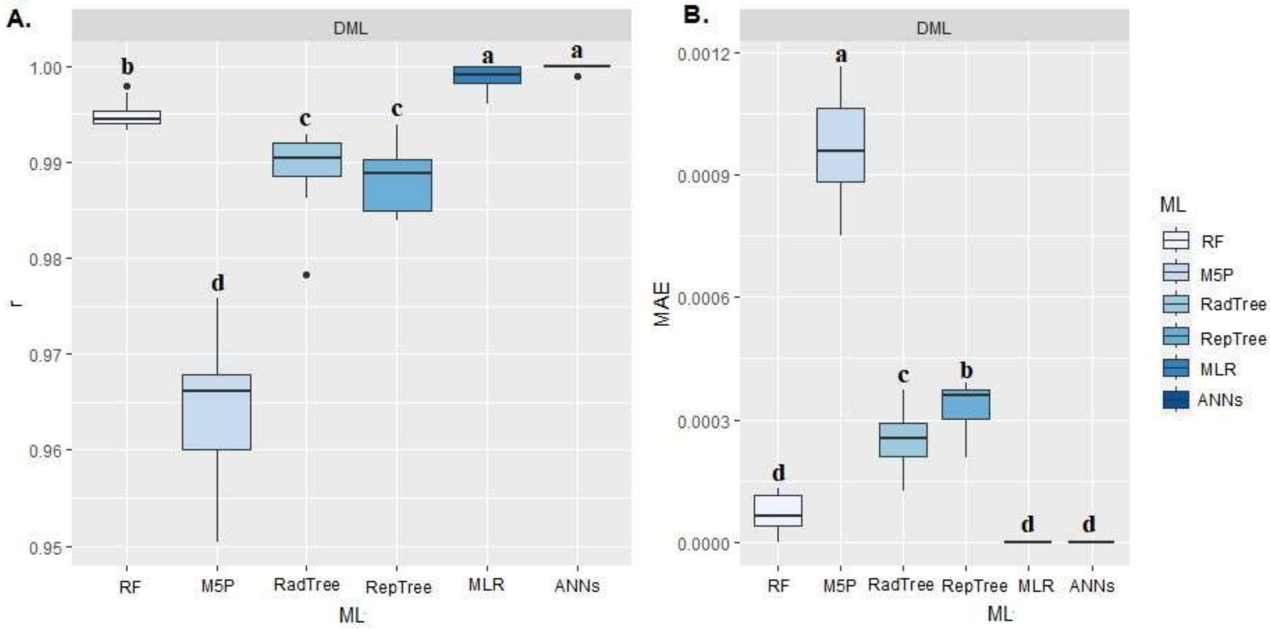

Fig. 11. Boxplot for Pearson correlation coefficient (r), and mean absolute error (MAE) between observed and estimated values of dry matter loss in soybean grains stored in horizontal silo by different machine learning models and inputs. Means followed by equal letters in the same column do not differ by the Scott–Knott test at 5% probability.

Table 4 Deployment of the significant interaction between models x inputs for correlation coefficient (r), mean absolute error (MAE), coefficient of determination (R^2) between observed and estimated values of dry matter loss in soybean grains stored in horizontal silo, for the different models of Machine Learning

Models	**Dry matter loss**		
	r	**MAE**	**R^2**
MLR	0.99874 a	0.00000 d	0.99748
ANNs	0.99989 a	0.00000 d	0.99979
M5P	0.96486 d	9.66304 a	0.93096
RF	0.99499 b	6.73913 d	0.99002
RadTree	0.98919 c	2.48369 c	0.97851
RepTree	0.98830 c	3.28985 b	0.97675

Equal letters in the column do not differ at (p<0.05) by the Scott knott test. Pearson's correlation coefficient (r), mean absolute error (MAE) and coefficient of determination (R^2) for Machine Learning models: Artificial Neural Network (ANN), Decision Tree (REPTree), Random Tree (RandTree), Quinlan's M5 algorithm (M5P), Random Forest (RF), and Multiple Linear Regression (MLR).

Among the assessed models, Multiple Linear Regression (MLR) and Artificial Neural Networks (ANNs) demonstrated comparable performance and emerged as the models yielding the most accurate prediction of dry matter loss. The application of Artificial Neural Network models in real-time monitoring is based on the use of intelligent sensing of the grain storage environment. In this setup, devices can communicate and relay environmental data to a web server for interpretation and analysis. This approach shows enormous potential for product quality control during the storage period. Wu et al. (2021) conducted an analysis of grain losses during storage, based on a predictive algorithm. The model corresponded to different grain storage conditions and thus predicted losses due to insect and other associated microorganism attacks. In a recent study, Nyabako et al. (2020) studied, through a machine learning approach, the prediction of insect population and the consequential damage to the stored grain mass. Data integration into the algorithm was performed by collecting information at storage units and correlating it with the meteorological conditions specific to each location. Subsequently, models were developed to predict insect infestation and the damage to stored grains, using parameter selection algorithms and machine learning techniques.

4. Conclusion

Among the technologies, drying and storing grain mass in silo-dryers ensured better preservation of soybean quality. In predicting grain quality during drying and storage operations, the best adjustments were achieved by Artificial Neural Network models, satisfactorily predicting the physical and physicochemical quality of soybeans. Therefore, it is recommended to undertake soybean grain drying in fixed layers and storage in silo-dryers equipped with monitoring and predictive capabilities in grain quality using Artificial Neural Network models.

5. References

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CONSIDERAÇÕES FINAIS

A produção sustentável envolve adaptação de processos e redução de perdas nas etapas pós-colheita. Os estudos realizados estabeleceram relações abrangentes dos processos de pós-colheita da soja, com ampla discussão sobre o desempenho de diferentes técnicas e tecnologias aplicadas durante a dinâmica de secagem e armazenagem da soja.

As etapas de pós-colheita visam à conservação da qualidade dos grãos e a redução de perdas, constituindo um elo entre o setor produtivo primário, a indústria e o mercado consumidor, com importante participação na logística da cadeia produtiva. Entre os resultados obtidos verificou-se que a antecipação do período de colheita da soja impactou nos processos de pós-colheita. Ainda assim observou-se, que o gerenciamento dos lotes de grãos de soja em unidades armazenadoras dependem dos processos tecnológicos de secagem e armazenagem adotados. Com isto, os sistemas associados de secagem com secador contínuo + silo-secador e secador contínuo + silo-aerador aumentaram a eficiência do processo e mantiveram com mais consistência a integridade dos grãos. A secagem em baixa temperatura e o uso de tecnologia de armazenamento com embalagem impermeáveis conservaram a qualidade dos grãos.

Assim, a colheita precoce da soja associada às condições de secagem e armazenamento reduz as perdas no campo e aumenta o fluxo de grãos nas unidades armazenadoras. Na modelagem destes resultados, verificou-se que o modelo de Redes Neurais Artificiais demonstrou maior desempenho para predição da qualidade dos grãos em todos os processos e tecnologias avaliadas. Com isto, vislumbram-se novas ideais para a continuidade da pesquisa nessa área de engenharia de pós-colheita, visando maior controle dos processos e manejo da massa de grãos para tomada de decisão nas operações de secagem e armazenagem.