Original Article
Food Science and Technology

ISSN 0101-2061 (Print)
ISSN 1678-457X (Online)

DOI: https://doi.org/10.1590/fst.101022

Performance of industrial drying and soybean grains quality

Wellytton Darci QUEQUETO[1*], Osvaldo RESENDE[1], Silvia Amelia Verdiani TFOUNI[2], Valdiney Cambuy SIQUEIRA[3], Paulo Fernando TRUGILHO[4], Jacson ZUCHI[1], José Ronaldo QUIRINO[5], Elivânio dos Santos ROSA[5]

Abstract

Thus, the objective of this work was to evaluate the performance of industrial drying and the quality of soybean grains using a direct-fire furnace automatically fed by wood chips. To represent the grains before drying, four samples were collected together with the sampling of the loads in the trucks carried out to classify the product in the storage unit. At drying, performance evaluations and specific energy consumption were carried out. The grains were evaluated for moisture content, germination, electrical conductivity, apparent specific mass, color, acidity index, and PAHs. Drying showed an average efficiency of 75.50%. The average chip consumption was 0.4403 kg of chip/kg of evaporated water. The specific energy consumption was 8,099.50 kJ/kg of evaporated water. The grains showed differences after drying in the characteristics of germination, electrical conductivity, and chroma. Six PAHs were detected in the samples before drying: (B(a)A, Chr, 5 MC, B(j)F, Dib(ai)P, and IcdP). After drying, in addition to the PAHs obtained before drying, five more were detected (B(b)F, B(k)F, B(a)P, Dib(al)P, and Dib(ah)A). Mean PAH concentrations were higher than the maximum values allowed by European Union legislation.

Keywords: *Glycine max* (L.) Merril; polycyclic aromatic hydrocarbons; post-harvest.

Practical Application: New solutions to reduce grain contamination by carcinogenic agents.

1 Introduction

Brazil is the world's largest producer and exporter of soybeans, reaching around 136 million tons in the 2020/2021 harvest and exporting 86 million tons (Brasil, 2021a). During the harvest season, the grains are susceptible to weather conditions, with rapid removal from the field and containing high moisture content, making drying necessary. The drying process aims to ensure the quality of the stored product, reducing grain metabolism and decreasing the potential for the development of microorganisms (Kumar & Kalita, 2017).

Generally, there are some discrepancies in drying practices regarding operational parameters and drying performances based on energy consumption as well as final product quality between the industry and the laboratory. The temperature and relative humidity conditions that generate high drying rates tend to negatively affect the quality and stability of the product (Ju et al., 2016). Thus, it is necessary to evaluate the performance of the drying or the drying system to verify its operational conditions (Sarker et al., 2013), as the rise in the air temperature can influence the rate and drying time and, consequently, energy consumption and operating costs.

To perform drying, it is necessary to heat the air that will be directed to pass through the grains. In this process, the synchronous transfer of heat and mass of water between the air and the grains occurs. Direct-fire furnaces are commonly used to provide heat to the drying air, therefore, as an alternative, wood is the most used energy source in Brazil (Weber, 2005). The transformation of wood into chips results in better-operating conditions such as automation of the supply of the furnace, increase in combustion due to a larger contact area, reduction in the formation of ash, more precise control, and regularity in the temperature of the drying air, reduction of manpower and risk of accidents, as well as the reduction of costs (Quequeto et al., 2022a).

During the incomplete combustion process of the biomass in the direct-fire furnace, the formation of smoke occurs, which may contain contaminants such as polycyclic aromatic hydrocarbons (PAHs) that come into direct contact with the grains. The PAHs are a class of compounds considered contaminants and some of them have genotoxic and carcinogenic potential. The Joint FAO/WHO Expert Committee on Food Additives (JECFA) evaluated 33 PAHs and concluded that 13 were carcinogenic and genotoxic (World Health Organization, 2005).

The effects of PAHs on human health depend on the duration and route of exposure, the amount that is exposed, and toxicity (Valavanidis et al., 2010). Several other factors can also impact health, including subjective factors such as health conditions and age. The ability of PAHs to cause short-term effects on human health is still unclear, however, their carcinogenic and mutagenic potential has been already shown. Thus, considering

Received 29 Sept., 2022
Accepted 22 Feb., 2023
[1] *Instituto Federal de Educação, Ciência e Tecnologia Goiano – IF Goiano, Campus Rio Verde, Rio Verde, GO, Brasil*
[2] *Centro de Ciência e Qualidade de Alimentos, Instituto de Tecnologia de Alimentos – ITAL, Campinas, SP, Brasil*
[3] *Universidade Federal da Grande Dourados – UFGD, Dourados, MS, Brasil*
[4] *Universidade Federal de Lavras – UFLA, Lavras, MG, Brasil*
[5] *Caramuru Alimentos S.A., Rio Verde, GO, Brasil*
*Corresponding author: wellytton_quequeto@hotmail.com

the importance of food safety and the fast pace of the industrial sector, more incentives are needed in studies focused on minimizing the formation of PAHs during food processing.

In this sense, the objective of this work was to evaluate the performance of industrial drying and the quality of soybean grains using a direct-fire furnace automatically fed by wood chips.

2 Materials and methods

2.1 Soybean grains samples

Conventional soybeans (2018/2019 harvest) were mechanically harvested and transported by trucks to the storage unit located in the municipality of Montividiu, state of Goiás (17°26′38″S, 51°10′30″ W). The amount of product used in the experiment was 146.5 tons of grain. To represent the grains before drying (wet grains), four samples were collected together with the sampling from truck loads carried out for classification in the storage unit. As for the collection of samples after drying (dry grains), they were removed from the dryer discharge conveyor (Redler) at 5-minute intervals, totaling 20 samples with approximately 1 kg each.

2.2 Drier and furnace

Grain was dried in a mixed flow dryer (Kepler Weber, ADS) with a nominal capacity of 100 t/h (Figure 1). The temperature and relative humidity of the room and exhaust air of the dryer were monitored using a data logger (Novus, LogBox-RHT-LCD). The drying air temperature was measured using a thermocouple sensor (intermediate position of the drying chamber) and the air temperature in the furnace was verified using an infrared thermometer.

2.3 Evaluation of the dryier

The system performance was evaluated based on the methodology proposed by Bakker-Arkema et al. (1978), with the specific energy consumption (SEC) determined according to Equation 1:

$$SEC = \frac{(FCt \times CFl) + EC}{We} \quad (1)$$

In which:

SEC – Energy-specific consumption, kJ/kg; FCt – Total fuel consumption, kg; CFl – Lower calorific fuel power, kJ/kg; EC – Electric energy consumption, kJ, and We – Evaporated water, kg.

The evaporated water was calculated with the aid of the breakage percentage of moisture content of the wet and dry grains.

Electric energy consumption was estimated by the number of electric motors used during the drying process, involving dryer exhaust fans and air supply in the furnace.

The efficiency of the dryer was measured using the temperatures of the air of drying, exhaust air, and air of the room according to Equation 2:

$$\eta = \frac{Tda - Tea}{Tda - Tra} \times 100 \quad (2)$$

where:

η - drying Efficiency, (%); Tda – drying air temperature (°C); Tea – exhaust air temperature (°C), and Tra – environment air temperature (°C).

The calorific power of the fuel (kJ/kg) was directly calculated in a calorimetric pump.

Fuel consumption (kg of chip/ton of dry product) was calculated using the number of eucalyptus chips used in drying, in relation to the total amount of dry product.

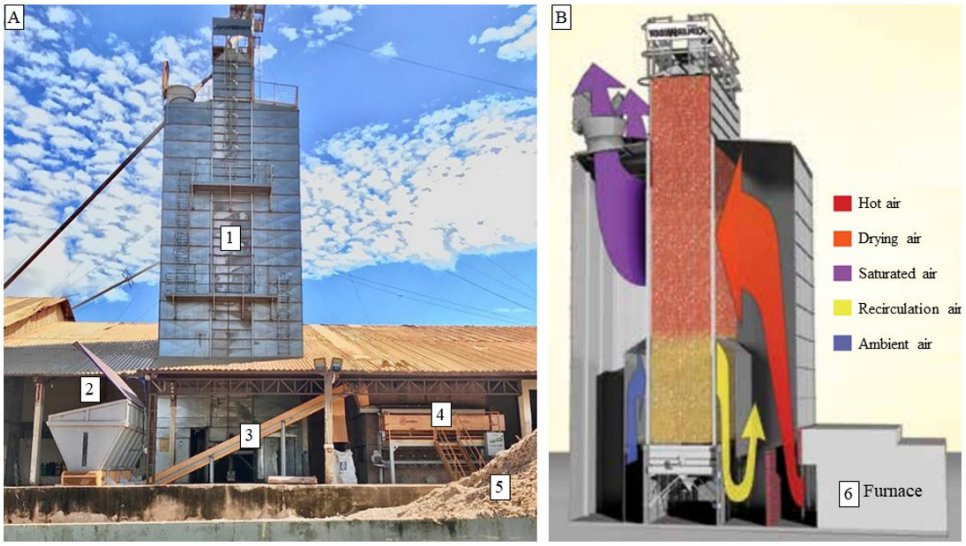

Figure 1. (A). Eucalyptus wood chips automate-fed dryer used for grains drying. 1. KW ADS model dryer with column tower; 2. Chip storage box; 3. Chip conveyor; 4. Furnace feeding platform and control panel; 5. Eucalyptus wood chips; (B) Dryer working diagram and movement of drying air coming from the furnace; 6. Furnace. Source: Figure A: authors; Figure B adapted: kepler.com.br

2.4 Soybean grains evaluations

Grain moisture content (%, w.b.) – It was determined, before and after drying, using the oven method (Marconi, MA035) with forced air circulation, at a temperature of 103 ± 1 °C, for 72 h, in three replications, as recommended by American Society of Agricultural Engineers (2000), method S352.2.

Germination (%) – it was determined according to the Rules for Seed Analysis (Brasil, 2009), using four repetitions of 50 grains, on three sheets of Germitest® paper, moistened with distilled water at a volume of two and a half times the mass of dry paper. Then, they were placed in a Biochemical Oxygen Demand (B.O.D.) type incubator chamber regulated at 25 ± 1 °C. The evaluations took place on the eighth day after the test was set up, and an r1-mm root protrusion was considered.

Apparent specific mass (kg/m^3) - a container of known volume was used, filled with grains at a fixed drop height. After filling and weighing, the apparent specific mass was determined through the ratio of mass (g) and volume (m^3) on a hectoliter weight scale, in three replicates.

Electrical conductivity (μS/cm/g) – the methodology described by Krzyzanowski et al. (2020) was adopted. Four subsamples of 50 grains were used, from each repetition over time, weighed on a 0.001 g-resolution scale. The samples were placed for soaking in plastic cups with 75 mL of deionized water and kept in a B.O.D. type incubator chamber, with a controlled temperature of 25 °C, for 24 h. The solutions containing the grains were slightly shaken and immediately read on a digital conductivity meter (Instrutherm, CD-850).

Color – Color was determined in a spectrophotometer (Color Flex EZ, Canada), in duplicate. The results were expressed in L^*, a^*, and b^*, with L^* values (luminosity or brightness) ranging from black (0) to white (100); those of chroma a^*, from green (-60) to red (+60) and those with chroma b^*, from blue (-60) to yellow (+60). Using the values of the a^* and b^* coordinates, the Chroma (Equation 3) and the hue angle (Equation 4) were calculated.

$$\text{Chroma} = \sqrt{a^{*2} + b^{*2}} \tag{3}$$

$$\text{Hue} = \tan^{-1}.\left(\frac{b^*}{a^*}\right) \tag{4}$$

Acidity index (mg/KOH) – The acidity index was obtained according to Association of Official Analytical Chemists (1995) standards. Ten samples taken at regular intervals were selected to represent this characteristic (1, 3, 5, 7, 9, 11, 13, 15, 17, and 19), based on initial tests that showed small variations in values and homogeneity in the oil quality. The grains were previously ground and the oil was extracted in a Soxhlet apparatus for 8 h using hexane (Neon, Suzano) as a solvent, soon after, the oil/solvent was separated utilizing rotoevaporation. Titratable acidity was determined using titration in potassium hydroxide solution (KOH) and 1% phenolphthalein solution.

Polycyclic Aromatic Hydrocarbons (μg/kg) - the samples were analyzed at the Food Technology Institute – ITAL, and the levels of 13 PAHs were determined: benzo(a)anthracene (B(a)A); benzo(b)fluoranthene (B(b)F); benzo(j)fluoranthene (B(j)F); benzo(k)fluoranthene (B(k)F); benzo(a)pyrene (B(a)P); chrysene (Chr); dibenzo(ah)anthracene (DahA); dibenzo(ae) pyrene (DaeP); dibenzo(ah)pyrene (DahP); dibenzo(al)pyrene (DaiP); dibenzo(al)pyrene (DalP); indene(1,2,3-cd)pyrene (IcdP) and 5-methylchrysene (5 MChr).

PAH (B(a)A, DahP, DahA, DalP, DaeP, B(j)F)) standards were acquired from Supelco brands (Bellefonte, PA) and Sigma-Aldrich DaiP, B(k)F, Chr, B (b)F, B(a)P, IcdP (Saint Louis MO), and IRMM BCR-08IR (5 MChr)) (Geel, Belgium). The HPLC grade solvents and reagents used were hexane, N-dimethylformamide (Scharlab S.L., Sentmenat), methanol, acetonitrile (JT Baker), anhydrous sodium sulfate (Synth, Labsynth) and silica gel (70-230 mesh, ASTM, Merck). Also, 0.45 μm filters (HV PVDF 0.45 μm, Millipore, Cork, Ireland) were used to filter the extracts before injection into the chromatograph. The water was obtained through a Milli-Q purification system (Millipore, Bedford).

The methodology used in this work was based on Speer et al. (1990) where 5 g of sample were weighed, 50 mL of hexane was added and the mixture was placed in an ultrasound bath (Unique Ultracleaner 1400) for 15 minutes and transferred to a separatory funnel. The extraction was carried out with three portions of dimethylformamide-water (9:1, v/v) (50, 25, and 25 mL) and then 100 mL of 1% sodium sulfate were added to the aqueous phase, then a new extraction was performed with three portions of hexane (50, 35 and 35 mL). The organic phase was then washed with water, dried over anhydrous sodium sulfate, and evaporated on a rotary evaporator at 45 °C (IKA, HB10 RV 10). To clean the extract, a glass column packed with silica gel (deactivated with 15% water) was used. The extract was eluted with hexane, collected in a round-bottomed flask, concentrated on a rotary evaporator, and suspended in 2 mL of acetonitrile for subsequent injection into the chromatograph.

The technique used in this experiment was high-performance liquid chromatography with fluorescence detection (HPLC-FDL), using a Shimadzu chromatographic system (Kyoto, Japan) composed of an LC-20AT quaternary pump, DGU-20A5 online degasser, SIL- 20A (30 μL injection volume), CTO-20A column oven and RF-10AXL fluorescence detector. For the separation of compounds, it was used a C18 polymeric Vydac 201 TP54 column (25 cm x 4.6 mm i.d., 5 μm, stabilized at 30 °C, Vydac, Hesperia, CA, USA) and a mobile phase gradient composed of acetonitrile (A) and water (B) at a flow rate of 1 mL/min as follows, 0-20 min: 70 to 75% A; 20-35 min: 75 to 100% A, 35-55 min: 100% A A, 55-60 min: 75 to 70% A, 60-75 min: 70% A. The PAHs were detected using the following excitation and emission wavelengths (nm): B(a)A, Chr and 5 MChr (274/414), B(j)F (312/507), B(b) F, B(k)F, B(a)P, DalP and DahA (290/430), IcdP (300/500), DaeP (397/403) and DaiP and DahP (304/457).

The compounds were quantified using the external standardization method. The analytical curves were constructed from the injection of standard solutions, containing the 13 PAHs, at seven concentration levels in acetonitrile (0.30 to 20 μg/L).

2.5 Statistical analysis

The experiment was carried out in a completely randomized design (CRD), where the samples were collected before and after drying. The results were submitted to analysis of variance and the means compared by contrast analysis (Scheffé, 1953) using the Sisvar software, at a 5% significance level. For the evaluation of the dryer, descriptive statistics were used.

3 Results and discussion

3.1 Dryer and furnace

During the drying of the soybean grains, moderate variations were observed in the internal temperature of the furnace, with an average value of 741.12 ± 33 °C (Figure 2). The activation of the equipment responsible for feeding the furnace was performed automatically, according to the temperature programmed (between 70 to 90 °C) by the operator during drying. So, when approaching the programmed temperature, the feeding speed decreases. Upon reaching the stipulated temperature, the feeding system maintains the chip supply, aiming at uniformity in the drying process.

The drying system showed an average efficiency of 75.50%, which is considered satisfactory for systems that use a direct-fire furnace (Kudra, 2012) (Figure 3). The same author reports that, although almost 100% of the thermal energy contained in the fuel is transferred to the drying air in dryers with direct fire furnaces, the additional heat losses to the environment through radiation, conduction, and with the gases of exhaust reduce overall performance to 60% or less. Quequeto et al. (2022b) also obtained satisfactory results with 75.61% in the average performance of drying soybeans using a direct-fire furnace.

The drying efficiency can vary from 0 (when the exhaust air temperature is equal to the drying air temperature) to 100% (when the exhaust air temperature is equal to the ambient air temperature), that is, the smaller the loss of heat in the system and better use of the drying air, the greater the efficiency.

As the grain entered the dryer, the temperature of the drying air raised and also the exhaust air, as a consequence, which reduced the efficiency. The rotation was performed, as the grains still had a high moisture content for storage, and it was necessary to return the grains through the drying chamber. As the grains exited the dryer, there was a decrease in drying efficiency due to the loss of heat by the exhaust air and a lower heat transfer capacity between the air and the grains.

Drying with heated air at a high temperature requires high energy consumption, due to the difficulty in transferring heat from the air to the product, and a significant amount of energy is lost with the exhaust air, even if its temperature approaches the wet bulb temperature, even more so for convective dryers which represent about 85% of industrial dryers (Kudra, 2012).

During the drying process, for each 1 kg of water evaporated from the grains, an average of 8,099.50 kJ of specific energy was required (Table 1). Specific energy consumption can be defined as the amount of energy required to evaporate a unit mass of water present in the product during drying (Lima et al., 2016; Mabasso et al., 2021).

The average consumption of wood chips was 0.4403 kg of wood chips/kg of evaporated water and the average moisture content was 46.58% (w.b.). The chip used during the process had a high moisture content, with less than 30% (w.b.) recommended (Garstang et al., 2002). However, the lower calorific value can be considered satisfactory for biomass in energy generation (Brand et al., 2014).

The characteristics or factors that influence energy changes include material size and different production methods, geographic location, storage time, moisture content during stacking and use, storage season, and tree species composition (Brand et al., 2011). Therefore, the use of wood for energy production requires certain care to avoid the use of materials with low calorific properties.

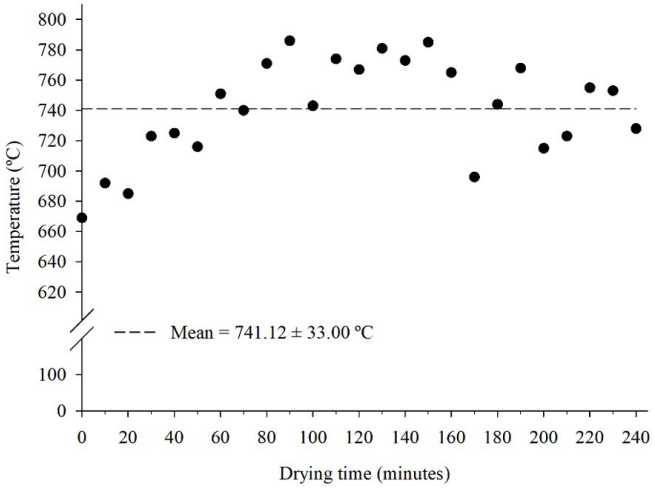

Figure 2. Values of the inner temperature of the furnace obtained during the soybean grain drying time.

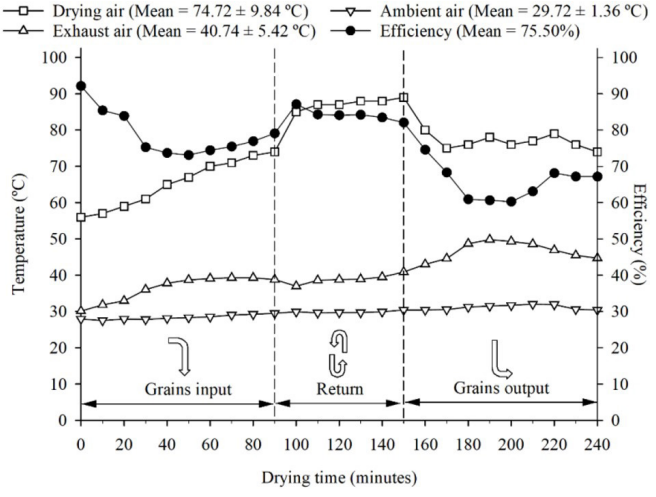

Figure 3. Efficiency and temperatures of the drying air, exhaust air, and room air over soybean grain drying time.

Table 1. Fuel and dryer characteristics over soybean grain drying.

FCt	FC	CFl	EC	We	SEC
4,212.78	0.4403	18,292.82	973,066.50	9,634.75	8,099.50

Total Fuel Consumption (FCt, kg), Fuel Consumption (FC, kg of chips/kg of dry product), Lower Calorific Value (CFl, kJ/kg), Electricity Consumption (EC, kJ), Evaporated Water (We, kg) and Specific Energy Consumption (SEC, kJ/kg).

3.2 Soybean grains

The average moisture content for the wet grains was about 16.59% (w.b.) and the dry grains 12.65% (w.b.), which was less than the most commercially used of 14% (Figure 4A). However, in regions with a tropical climate, with high temperatures and relative humidity, the recommended moisture content for the safe storage of soybeans is 12.00% (Smaniotto et al., 2014). Therefore, the drying process becomes essential, to remove the excess water from the grains, minimizing metabolic reactions and avoiding degradation by insects and microorganisms, thus helping to manage the quality of the product during storage.

The germination of the soybean grains showed a difference between before and after drying (Figure 4B). The wet grains presented average values of 88.00% and there was a high decrease after drying to 49.35%. Depending on the drying conditions, there may be a reduction in the physiological quality, due to the intensification of the deterioration phenomenon (Marcos, 2015).

High temperatures cause high drying rates, exerting tensions on the most superficial layers of the product, forcing the rapid removal of water. Thus, due to the maximum temperature of the drying air of 89 °C (Figure 2), germination was affected. However, for feeding, this evaluation does not only influence the quality of the product but can also impair the conservation of the grains during storage.

Corroborating the germination test, the electrical conductivity showed a difference after drying and higher values (Figure 4C). Also, the higher result shows the lower integrity of the cell membrane of the grains. It is noteworthy that the solution containing the grains before drying already had a high electrical conductivity value (124.77 μS/cm/g), which could have been caused by mechanical damages precursor to processing, such as impacts during harvesting, unloading, and transport of grains. Likewise, damage intensified after drying (216.18 μS/cm/g).

The mean values of acidity value of the crude oil extracted from the grains showed no difference before (1.51 mg/KOH) and after drying (1.36 mg/KOH) (Figure 4.D). According to the National Health Surveillance Agency (Anvisa), the maximum limit allowed for commercialization is 4.0 mg/KOH (Brasil, 2021b), so the values obtained in the present work are below those established by the standard.

The average results of the apparent specific mass of the grains showed no difference between before and after drying (Figure 4E). The increase in values after drying (689.41 kg/m^3) is directly associated with water loss and grain contraction, thus, with the best arrangement, the number of grains in the same volume increases. The apparent specific mass is a physical characteristic often used to evaluate the quality of the mass/lot of grains, so, normally, the greater its magnitude, the better the quality of the product (Botelho et al., 2015).

The chroma parameter showed a difference between treatments before (35.05) and after drying (33.65), showing a small decrease in grain color saturation (Figure 4F). As for the hue parameter, the average values showed no difference between before and after drying, with no interference in the grain color (Figure 4G). The drying air temperature can promote changes in heat-sensitive compounds, in this case, due to the high drying temperature, there was a greater influence on the saturation of the grains.

Six PAHs were detected in the samples before drying, (B(a) A, Chr, 5 MChr, B(j)F, Dib(ai)P, and IcdP) and in addition to these, five more were detected after drying, (B(b)F, B(k)F, B(a)P, Dib(al)P and Dib(ah)A), totaling 11 PAHs (Table 2). Out of the 13 assessed PAHs, two were not detected, which were Dib(ae) P and Dib(ah)P.

Only the mean values of B(j)F and Dib(ai)P showed differences between before and after drying. Some PAHs showed a higher average in the grains before drying (5 MChr, B(j)F, Dib(ai)P, and IcdP), however, it is worth mentioning that all the maximum sample values of the grains were higher after drying. Contamination by PAHs can also occur through environmental pollution, particles from atmospheric air, soil, and water through transfer and/or deposition (WHO, 2005).

The PAHs can be classified according to the number of carbon rings into "heavy PAHs" with 4-6 aromatic rings or "light PAHs" with 2-3 rings (Purcaro et al., 2013). In general, heavy PAHs tend to be more stable and toxic than lighter PAHs (Yebra-Pimentel et al., 2015). As the molecular mass (MM) increases, PAHs intensify and above 202 g/mol they are considered to have high molecular mass. All PAHs found in this work are considered heavy and of high molecular weight, the largest with six aromatic rings and 302 g/mol (Dib(ai)P and Dib(al)P).

Over incomplete combustion (at about 400 to 800 °C), organic compounds are partially fractionated into smaller and unstable molecules containing two to three aromatic rings (pyrolysis). These fragments, mainly highly reactive free radicals with a short half-life, through recombination reactions, can, but not necessarily, originate larger and more stable compounds, containing four to six rings (pyrosynthesis). However, both the amount and the composition vary depending on the material to be pyrolyzed, the combustion temperature, the residence time of the molecules in the gaseous state, and the oxygen concentration (McGrath et al., 2003).

In this context, corroborating the results obtained in the present work, the formation of PAHs with high MM is directly associated with the average temperature inside the furnace of 741.12 °C and due to the increase in the exposure time of the grains with the rotation in the drying chamber. Quequeto et al.

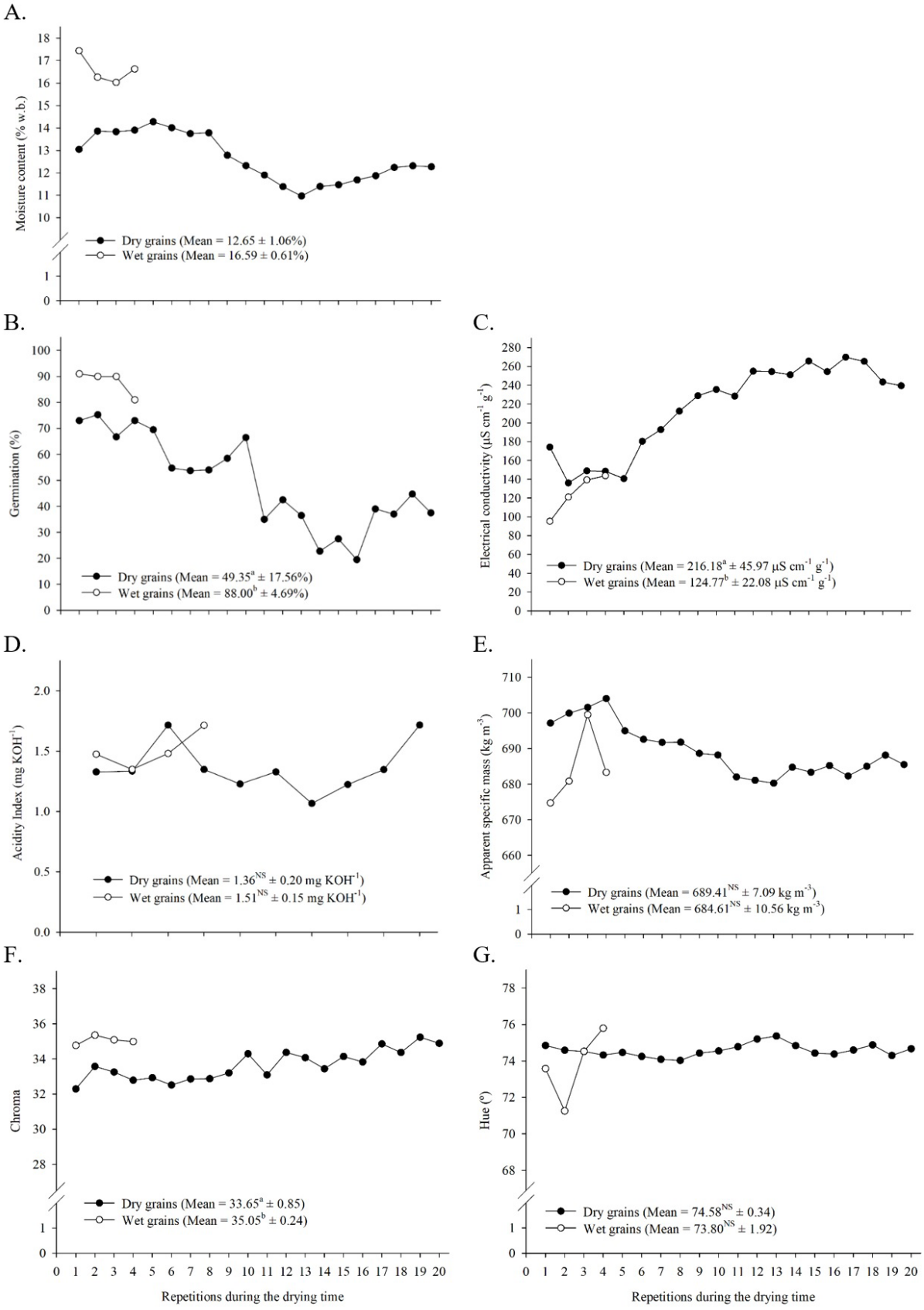

Figure 4. Evaluations for characterization of the quality of soybeans before and after drying. ($n = 3$). (A) Moisture content; (B) Germination; (C) Electrical conductivity; (D) Acidity Index; (E) Apparent specific mass; (F) Chroma; (G) Hue angle. Means followed by the same letters are not different from each other by the test of Scheffé at the 0.05 probability level. ^{NS}Not-significant.

Table 2. Mean values of PAH (μg/kg) estimated for soybean grains before and after drying using a dryer with a eucalyptus chip-fed furnace.

PAHs	PAH levels (μg/kg)		CV (%)[3]
	Wet[1]	Dry[2]	
B(a)A	0.1163 a (< LOD – 0.2294)	0.2139 a (< LOD – 0.3916)	4.68
Chr	0.2819 a (0.1335 – 0.5231)	0.4795 a (< LOD – 0.9614)	9.00
5 MChr	0.0535 a (< LOD – 0.1585)	0.0160 a (< LOD – 0.1916)	3.00
B(j)F	1.0434 a (1.0574 – 1.2606)	0.4350 b (< LOD – 1.8010)	16.08
Dib(ai)P	0.1696 a (0.1544 – 0.1819)	0.0574 b (< LOD – 0.1855)	3.05
IcdP	0.3215 a (0.2105 – 0.4756)	0.2786 a (< LOD – 2.5742)	17.69
B(b)F	< LOD	0.0139 (< LOD – 0.1394)	-
B(k)F	< LOD	0.1689 (< LOD – 1.6890)	-
B(a)P	< LOD	0.3928 (< LOD – 1.9877)	-
Dib(al)P	< LOD	0.6532 (< LOD – 4.5572)	-
Dib(ah)A	< LOD	0.7251 (< LOD – 4.7181)	-
Total	1.9861 a	3.4342 a	34.62

Means followed by the same letter in the row are not statistically different from each other by the test of Scheffé ($p < 0.05$); [1]$n = 4$ samples with two determinations each; [2]$n = 10$ samples with two determinations each; [3]CV – Coefficient of variation, transformed data $(x+1)^{0.5}$; LOD = 0.04 μg/kg PAHs; LOD = 0.4 μg/kg Indene and Benzo(j)Fluoranthene; (Minimum sample value - Maximum sample value).

Table 3. Mean values of the 4 PAHs (μg/kg) used as markers determined in soybeans after drying using a dryer with a furnace fed by eucalyptus chips.

Compounds	B(a)A	Chr	B(b)F	B(a)P	Total
Levels of the PAHs (μg/kg)	0.2139	0.4795	0.0139	0.3928	1.1001

(2022b) obtained similar results with the average temperature inside the furnace of 457 °C, identifying high MM PAHs, (B(a)A, Chr, B(a)P, B(k)F, and B(b)F) in the grains, however in smaller amounts and concentrations (<1 μg/kg) in relation to the present work, where the grain rotation is not necessary.

Since 2011, the European Food Safety Authority (EFSA) has changed the previous recommendation through European Union Regulation No. 835/2011, where only the B(a)P is not adequate as the sole PAHs marker in food, thus, the system of 4 [B(a)A, Chr, B(a)P and B(b)F] or 8 PAHs was adopted as an indicator of the presence of PAHs in foods (European Union, 2011). This change is due to the sum of these PAHs, which better reflects the occurrence of carcinogenic and genotoxic PAHs and different food categories.

The European Community Regulation (ECR) No. 835/2011, defined the maximum allowed level of 1.0 μg/kg for B(a)P, and this same limit for the sum of the 4 PAHs, detected in foods processed at the cereal base. The average concentration of the sum of the 4 PAHs detected in soybeans after drying was higher than the maximum values allowed for this category of processed products based on cereals and food for babies and children (Table 3).

Soybean-derived products subjected to drying using a direct-fire furnace can lead to PAH contamination. Thus, consumers may be more exposed to PAH contamination by ingesting these processed products, especially oilseeds, due to their highly lipophilic characteristics. In an experiment carried out by Rojo Camargo et al. (2011), relatively high and variable levels of PAHs (10.4 to 112.0 μg/kg) were identified in 42 samples of commercially available soybean oils in the Brazilian market. Several other studies were carried out with different products on the occurrence of PAH contamination, such as corn grains (Resende et al., 2022; Silva et al., 2018), soybeans (Quequeto et al., 2022b), smoked meat sausages (Mirbod et al., 2022), grilled meat (Siddique et al., 2021), canola, sunflower and corn oils (Molle et al., 2017), infant milk and cereals (Rey-Salgueiro et al., 2009), yerba mate (Vieira et al., 2010), toasted bread (Rey-Salgueiro et al., 2008).

4 Conclusion

The drying system showed an average efficiency of 75.50% for the drying of soybean grains, considered satisfactory for systems that use a direct-fire furnace. The average consumption of wood chips was 0.4403 kg of wood chips/kg of evaporated water. The specific energy consumption to remove 1.0 kg of water was 8,099.50 kJ.

The grains showed differences after drying in the characteristics of germination, electrical conductivity and chroma.

Drying with a direct-fire furnace using wood chips promoted contamination by PAHs in soybeans. Six PAHs were detected in the grains before drying and in addition to them, five more were detected after drying.

Mean concentrations of PAHs in soybeans were higher than the maximum values allowed by European Union legislation.

Acknowledgements

To IF Goiano, CAPES, FAPEG, FINEP and CNPq, for the very important financial aid for the execution of this work. To the companies Caramuru Alimentos S/A and ComBer Indústria Ltda.

References

American Society of Agricultural Engineers – ASAE. (2000). *Moisture measurement: unground grain and seeds*. St. Joseph: ASAE.

Association of Official Analytical Chemists – AOAC. (1995). *Official methods of analysis* (1141 p.). Arlington: AOAC.

Bakker-Arkema, F. W., Lerew, L. E., Brook, R. C., & Brooker, D. B. (1978). *Energy and capacity performance evaluation of grain dryers*. St. Joseph: ASAE.

Botelho, F. M., Granella, S. J., Botelho, S. C. C., & Garcia, T. R. B. (2015). Influência da temperatura de secagem sobre as propriedades físicas dos grãos de soja. *Engenharia na Agricultura*, 23(3), 212-219. http://dx.doi.org/10.13083/1414-3984/reveng.v23n3p212-219.

Brand, M. A., Muñiz, G. I. B., Quirino, W. F., & Brito, J. O. (2011). Storage as a tool to improve wood fuel quality. *Biomass and Bioenergy*, 35(7), 2581-2588. http://dx.doi.org/10.1016/j.biombioe.2011.02.005.

Brand, M. A., Stähelin, T. S. F., Ferreira, J. C., & Neves, M. D. (2014). Produção de biomassa para geração de energia em povoamentos de *Pinus taeda* L. com diferentes idades. *Revista Árvore*, 38(2), 353-360. http://dx.doi.org/10.1590/S0100-67622014000200016.

Brasil, Companhia Nacional de Abastecimento – CONAB. (2021a). *Acompanhamento da safra brasileira de grãos, v. 8, safra 2020/21, n. 12, décimo segundo levantamento, setembro*. Brasília. Retrieved from https://www.conab.gov.br/info-agro/safras/graos/boletim-da-safra-de-graos

Brasil, Ministério da Agricultura, Pecuária e Abastecimento. (2009). *Regras para análise de sementes - RAS*. Brasília: Secretaria de Defesa Agropecuária.

Brasil, Ministério da Agricultura, Pecuária e Abastecimento, Agência Nacional de Vigilância Sanitária – ANVISA. (2021b, March 17). Estabelece a lista de espécies vegetais autorizadas, as designações, a composição de ácidos graxos e os valores máximos de acidez e de índice de peróxidos para óleos e gorduras vegetais (Instrução normativa IN. nº 87, de 15 de março de 2021). *Diário Oficial [da] República Federativa do Brasil*. Retrieved from http://www.anvisa.gov.br

European Union, Commission of the European Communities – CEC. (2011, August 20). Setting maximum levels for certain contaminants in foodstuffs (Commission Regulation (EC) nº 835/2011 of 19 August 2011). *Official Journal of European Union*. Retrieved from http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L2011:215:0004:0008:PT:PDF

Garstang, J., Weekes, A., Poulter, R., & Bartlett, D. (2002). *Identification and characterization of factors affecting losses in the large-scale, nonventilated bulk storage of wood chips and development of best storage practices* (116 p.). United Kingdom: Department of Trade and Industry.

Ju, H. Y., Zhang, Q., Mujumdar, A. S., Fang, X. M., Xiao, H. W., & Gao, Z. J. (2016). Hot-air drying kinetics of yam slices under step change in relative humidity. *International Journal of Food Engineering*, 12(8), 783-792. http://dx.doi.org/10.1515/ijfe-2015-0340.

Krzyzanowski, F. C., Vieira, R. D., Marcos, J. Fo., & França-Neto, J. B. (2020). Teste de condutividade elétrica. In F. C. Krzyzanowski, R. D. Vieira, J. Marcos Fo., & J. B. França-Neto (Eds.), *Vigor de sementes: conceitos e testes* (2ª ed., 601 p). Londrina: ABRATES.

Kudra, T. (2012). Energy performance of convective dryers. *Drying Technology*, 30(11-12), 1190-1198. http://dx.doi.org/10.1080/07373937.2012.690803.

Kumar, D., & Kalita, P. (2017). Reducing postharvest losses during storage of grain crops to strengthen food security in developing countries. *Foods*, 6(1), 8. http://dx.doi.org/10.3390/foods6010008. PMid:28231087.

Lima, A. G. B., Delgado, J. M. P. Q., Farias, S. No., & Franco, C. M. R. (2016). Intermittent drying: fundamentals, modeling and applications. In J. M. P. Q. Delgado, A. G. B. Lima (Eds.), *Drying and energy technologies* (pp. 19-41). Cham: Springer. http://dx.doi.org/10.1007/978-3-319-19767-8_2.

Mabasso, G. A., Siqueira, V. C., Quequeto, W. D., Jordan, R. A., Martins, E. A., & Schoeninger, V. (2021). Energy efficiency and physical integrity of maize grains subjected to continuous and intermittent drying. *Revista Brasileira de Engenharia Agrícola e Ambiental*, 25(10), 710-716. http://dx.doi.org/10.1590/1807-1929/agriambi.v25n10p710-716.

Marcos, J. Fo. (2015). *Fisiologia de sementes de plantas cultivadas* (2ª ed., 659 p.). Londrina: ABRATES.

McGrath, T. E., Chan, W. G., & Hajaligol, M. R. (2003). Low temperature mechanism for the formation of polycyclic aromatic hydrocarbons from the pyrolysis of cellulose. *Journal of Analytical and Applied Pyrolysis*, 66(1-2), 51-70. http://dx.doi.org/10.1016/S0165-2370(02)00105-5.

Mirbod, M. A., Hadidi, M., Huseyn, E., & Mousavi Khaneghah, A. (2022). Polycyclic aromatic hydrocarbon in smoked meat sausages: effect of smoke generation source, smoking duration, and meat content. *Food Science and Technology*, 42(1), e60921. http://dx.doi.org/10.1590/fst.60921.

Molle, D. R. D., Abballe, C., Gomes, F. M. L., Furlani, R. P. Z., & Tfouni, S. A. V. (2017). Polycyclic aromatic hydrocarbons in canola, sunflower and corn oils and estimated daily intake. *Food Control*, 81, 96-100. http://dx.doi.org/10.1016/j.foodcont.2017.05.045.

Purcaro, G., Moret, S., & Conte, L. S. (2013). Overview on polycyclic aromatic hydrocarbons: occurrence, legislation and innovative determination in foods. *Talanta*, 105, 292-305. http://dx.doi.org/10.1016/j.talanta.2012.10.041. PMid:23598022.

Quequeto, W. D., Resende, O., Tfouni, S. A. V., Gomes, F. M. L., Borges, A. X., Almeida, A. B. D., Cabral, J. C. O., Costa, L. M., & Oliveira, L. P. D. (2022a). Corn grains drying using direct-fired furnace with wood chips: Performance, quality and polycyclic aromatic hydrocarbons. *Food Science and Technology*, 42(1), e27122. http://dx.doi.org/10.1590/fst.27122.

Quequeto, W. D., Resende, O., Tfouni, S. A. V., Leme Gomes, F. M., Borges, A. X., Santos, M. R. B., Costa, E. R., Ferreira, W. N. Jr., Glasenapp, M., Quirino, J. R., & Rosa, E. S. (2022b). Drying of soybean grains with direct-fired furnace using wood chips: Performance, quality, and polycyclic aromatic hydrocarbons. *Drying Technology*, 40(10), 2164-2174. http://dx.doi.org/10.1080/07373937.2021.1929293.

Resende, O., Costa, E. R., Quequeto, W. D., Costa, L. M., Oliveira, D. E. C. D., Tfouni, S. A. V., Gomes, F. M. L., Quirino, J. R., & Lima, R. R. D. (2022). Quality of corn grains subjected to drying using direct-fired furnace fed with eucalyptus chips and firewood. *Food Science and Technology*, 42(1), e55820. http://dx.doi.org/10.1590/fst.55820.

Rey-Salgueiro, L., García-Falcón, M. S., Martínez-Carballo, E., & Simal-Gándara, J. (2008). Effects of toasting procedures on the levels of polycyclic aromatic hydrocarbons in toasted bread. *Food Chemistry*, 108(2), 607-615. http://dx.doi.org/10.1016/j.foodchem.2007.11.026. PMid:26059139.

Rey-Salgueiro, L., Martínez-Carballo, E., García-Falcón, M. S., González-Barreiro, C., & Simal-Gándara, J. (2009). Occurrence of polycyclic aromatic hydrocarbons and their hydroxylated metabolites in infant foods. *Food Chemistry*, 115(3), 814-819. http://dx.doi.org/10.1016/j.foodchem.2008.12.095.

Rojo Camargo, M. C. R., Antoniolli, P. R., Vicente, E., & Tfouni, S. A. V. (2011). Polycyclic aromatic hydrocarbons in Brazilian commercial soybean oils and dietary exposure. *Food Additives & Contaminants.*

Part B, Surveillance, 4(2), 152-159. http://dx.doi.org/10.1080/19393210.2011.585244. PMid:24785726.

Sarker, M. S. H., Ibrahim, M. N., Aziz, N. A., & Punan, M. S. (2013). Drying kinetics, energy consumption, and quality of paddy (MAR-219) during drying by the industrial inclined bed dryer with or without the fluidized bed dryer. *Drying Technology*, 31(3), 286-294. http://dx.doi.org/10.1080/07373937.2012.728270.

Scheffé, H. A. (1953). Method for judging ali contrast in analysis of variance. *Biometrika*, 40(1), 87-104.

Siddique, R., Zahoor, A. F., Ahmad, S., Ahmad, H., Mansha, A., Zahid, F. M., Faisal, S., & Aadil, R. M. (2021). GC-MS analysis of PAHs in charcoal grilled rabbit meat with and without additives. *Food Science and Technology*, 41(1, Suppl. 2), 702-707. http://dx.doi.org/10.1590/fst.34720.

Silva, L. D. S., Resende, O., Bessa, J. F. V., Bezerra, I. M. C., & Tfouni, S. A. V. (2018). Ozone in polycyclic aromatic hydrocarbon degradation. *Food Science and Technology*, 38(1, Suppl. 1), 184-189. http://dx.doi.org/10.1590/fst.06817.

Smaniotto, T. A. D. S., Resende, O., Marçal, K. A., Oliveira, D. E., & Simon, G. A. (2014). Qualidade fisiológica das sementes de soja armazenadas em diferentes condições. *Revista Brasileira de Engenharia Agrícola e Ambiental*, 18(4), 446-453. http://dx.doi.org/10.1590/S1415-43662014000400013.

Speer, K., Steeg, E., Horstmann, P., Kühn, T., & Montag, A. (1990). Determination and distribution of polycyclic aromatic hydrocarbons in native vegetable oils, smoked fish products, mussels and oysters, and bream from the river Elbe. *Journal of High Resolution Chromatography*, 13(2), 104-111. http://dx.doi.org/10.1002/jhrc.1240130206.

Valavanidis, A., Fiotakis, K., & Vlachogianni, T. (2010). The role of stable free radicals, metals and PAHs of airborne particulate matter in mechanisms of oxidative stress and carcinogenicity. In F. Zereini & C. Wiseman (Eds.), *Urban airborne particulate matter* (pp. 411-426). Berlin: Springer. http://dx.doi.org/10.1007/978-3-642-12278-1_21.

Vieira, M. A., Maraschin, M., Rovaris, Â. A., Amboni, R. D., Pagliosa, C. M., Xavier, J. J., & Amante, E. R. (2010). Occurrence of polycyclic aromatic hydrocarbons throughout the processing stages of ervamate (*Ilex paraguariensis*). *Food Additives & Contaminants. Part A, Chemistry, Analysis, Control, Exposure & Risk Assessment*, 27(6), 776-782. http://dx.doi.org/10.1080/19440041003587310. PMid:20349373.

Weber, É. A. (2005). *Excelência em beneficiamento e armazenagem de grãos* (586 p.). Canoas: Salles.

World Health Organization – WHO. (2005). *Summary report of the sixty-fourth meeting of the Joint FAO/WHO Expert Committee on Food Additive (JECFA).* Geneva: WHO.

Yebra-Pimentel, I., Fernández-González, R., Martínez-Carballo, E., & Simal-Gándara, J. (2015). A critical review about the health risk assessment of PAHs and their metabolites in foods. *Critical Reviews in Food Science and Nutrition*, 55(10), 1383-1405. http://dx.doi.org/10.1080/10408398.2012.697497. PMid:24915328.