




Drying of soybean grains with direct-fired furnace using wood chips: Performance, quality and polycyclic aromatic hydrocarbons

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ABSTRACT

The search for new technologies and options of activities to improve agricultural production systems are goals continuously desired by companies. Thus, the objective of this study was to evaluate the performance of soybean grain drying, using a furnace dryer automatically fed with eucalyptus chips, the quality of the grains before and after drying, as well as contamination by polycyclic aromatic hydrocarbons (PAHs). Twenty-seven samples were collected before drying and 27 samples were collected after drying, totaling 54 samples of around 1.0 kg each, at 5-minute intervals. The following experimental evaluations were carried out: dryer – performance, calorific value and fuel consumption; grains – moisture content, germination, electrical conductivity, apparent specific mass, thousand-grain weight, color, oil acidity index and polycyclic aromatic hydrocarbons. The dryer showed an average efficiency of 75.61% for drying the grains. The average fuel consumption was 21.78 kg of chip per ton of dry grains. The specific energy consumption to remove 1.0 kg of water was 11,871.80 kJ. In general, drying did not compromise the final quality of soybeans. Soybeans showed the presence of two PAHs before drying and three more PAHs appeared after drying. Average concentrations were lower than the maximum values allowed by European Union Law No 835/2011. The drying conditions used for soybean grains influenced the low formation of PAHs.

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1. Introduction

In the industry in general, drying represents a significant fraction of the use of industrial energy, which can vary from 27 to 70% depending on the type of product processed, so its rational use becomes essential.^[1,2] The high energy demand is associated with the heat required to remove water from the grains, the capacity of heat transfer between the drying air and the product, as well as the associated losses in most industrial dryers.^[3]

To carry out artificial drying, it is necessary to increase the drying potential of the air. In this case, it is necessary to provide energy in the form of heat, which will promote the increase of temperature and reduction of the relative humidity of the drying air, and the furnaces are basically used for this purpose. As an alternative source of energy, wood is the most used fuel for drying grains in Brazil, mainly due to its

low cost and high availability.^[4] Wood processing into smaller sizes generates chips, which promote as advantages the automation of furnace supply, increase of combustion due to a larger contact area, reduction in ash formation, more precise control and regularity in drying air temperature, reduction of labor and risks of accidents, as well as reduction of costs.

In the direct-fired furnace, thermal energy is used directly in drying and the gases resulting from combustion are forced to pass through the grains. When biomass burning is incomplete, it can cause the formation of chemical compounds, called polycyclic aromatic hydrocarbons (PAHs), thus, it can cause contamination of the grains. PAHs can be considered as one of the main carcinogens, as they are widely distributed in the environment.^[5] Among PAHs, benzo(a)pyrene is the best known and most studied and stands out for being highly carcinogenic, classified in

group 1 by the International Agency for Research on Cancer (IARC), that is, as carcinogenic in humans.^[6]

The presence of residues and contaminants in food has stood out in recent years. Among them, PAHs have been detected in various foods, such as rice grains,^[7] corn grains,^[8,9] cocoa beans and derived products,^[10] canola, sunflower and corn oils.^[11] However, the quantification of PAHs in grains is still incipient and limited to foods already processed.^[8]

Motivated by economic and food safety issues, researchers seek to improve combustion processes and develop more efficient equipment, as well as energy alternatives to replace fossil fuels. In this context, the objective of this study was to evaluate the drying performance, the quality of soybean grains and the contamination by PAHs using a direct-fired furnace automatically fed with wood chips.

2. Material and methods

2.1. Soybean samples

Soybean grains (2018/19 season) were mechanically harvested and soon after transported by trucks to a storage unit in the municipality of Montividiu – GO, Brazil, to be dried in a dryer coupled to an automatic furnace fed with eucalyptus wood chips. Twenty-seven samples were collected at intervals of 5 minutes before drying (wet grains), from the duct that feeds the dryer bucket lift; after drying (dry grains), more 27 samples were collected from the dryer discharge conveyor (redler), totaling 54 samples with approximately 1.0 kg each. The total drying time was 190 minutes and the total sample collection time was 272 minutes, considering the loading and unloading of the dryer.

2.2. Dryer and furnace

Grain drying was conducted in a mixed-flow dryer (Kepler Weber, ADS, Brazil) with a nominal capacity of 100 tons per hour. The temperature and relative humidity of the ambient air and exhaust air of the dryer were monitored using a data logger. Drying air temperature was measured by thermocouple sensor and air temperature inside the furnace was verified using an infrared thermometer.

2.3. Dryer evaluations

The system's performance evaluation was based on the methodology proposed by Bakker-Arkema et al.,^[12] with specific energy consumption (SEC) determined by Equation (1):

$$SEC = \frac{(FCt \times LCV) + Ec}{WL} \quad (1)$$

where SEC – Specific energy consumption, kJ/kg; FCt – Total fuel consumption, kg; LCV – Lower calorific value of fuel, kJ/kg; Ec – Electricity consumption, kJ and WL – Water Loss, kg.

The efficiency of the dryer was determined based on the temperatures of drying air, exhaust air and ambient air, according to Equation (2):

$$\eta = \frac{T_{da} - T_{ea}}{T_{da} - T_{aa}} \times 100 \quad (2)$$

where η – drying efficiency, (%); T_{da} – drying air temperature (°C); T_{ea} – exhaust air temperature (°C) and T_{aa} – ambient air temperature (°C).

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

Fuel consumption (kg of chip per ton of dry product) was determined by the amount of eucalyptus chips used in the drying, measured by weighing on mechanical scale, in relation to the total amount of dry product.

2.4. Evaluations of soybean grains

Grain moisture content (% , wb) – determined before and after drying at temperature of 103 ± 1 °C using the method of forced air circulation oven (Marconi, MA035, Brazil), for 72 h, in three replicates, according to the recommendations of ASAE,^[13] method S352.2.

Germination (%) – determined according to the Rules for Seed Analysis,^[14] using four replicates of 50 grains, on three sheets of Germitest® paper, moistened with distilled water using a volume of 2.5 times the mass of dry paper. These sheets were then placed into a B.O.D.-type chamber set at 25 ± 1 °C. Evaluations were performed on the 8th day after the test was set up, and root protrusion of 1 mm was considered.

Apparent specific mass (kg/m^3) – determined using a container with known volume filled with the grains from a fixed fall height. After filling and weighing, the apparent specific mass was determined based on the ratio between mass (g) and volume (m^3) in a hectoliter weight scale, in three replicates.

Thousand-grain weight (g) – determined based on the weight of 100 grains, in eight replicates, and subsequently extrapolated to 1000 grains.^[14]

Electrical conductivity ($\mu\text{S/cm/g}$) – determined by the methodology described by Vieira and Krzyzanowski,^[15] using four subsamples of 50 grains, from each repetition over time, weighed on a scale

with resolution of 0.001 g. Samples were placed to soak 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 stirred and reading was immediately carried out in a digital conductivity meter (Instrutherm, CD-850, Brazil).

Color – determined in spectrophotometer (Color Flex EZ, Canada), in duplicate. The results were expressed in L^* , a^* and b^* , where the values of L^* (lightness or brightness) can vary from black (0) to white (100), those of chroma a^* from green (-60) to red (+60) and those of chroma b^* from blue (-60) to yellow (+60). The values of the coordinates a^* and b^* were used to calculate Chroma (Equation (3)) and Hue angle (Equation (4)).

$$\text{Chroma} = \sqrt{a^{*2} + b^{*2}} \quad (3)$$

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

Acidity index (mg/KOH) – obtained according to standards of AOAC.^[16] Ten samples taken at regular intervals were selected to represent this characteristic (1, 4, 7, 10, 13, 16, 19, 20, 22 and 25), based on initial tests that demonstrated low variation of values and homogeneity in oil quality. The grains were previously ground, and the oil was extracted in a Soxhlet apparatus for 8 h using hexane as solvent (Neon, Suzano, Brazil); soon after, the separation of the oil/solvent was performed by rotoevaporation. Titratable acidity was determined by titration in potassium hydroxide (KOH) solution and 1% phenolphthalein solution as indicator.

Polycyclic Aromatic Hydrocarbon ($\mu\text{g}/\text{kg}$) – samples were analyzed at the Institute of Food Technology – ITAL to determine the levels of 13 PAHs: 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 (D(ah)A), dibenzo(ae)pyrene (D(ae)P), dibenzo(ah)pyrene (D(ah)P), dibenzo(ai)pyrene (D(ai)P), dibenzo(al)pyrene (D(al)P), indene(1,2,3-cd)pyrene (I(cd)P) and 5-methylchrysene (5MChr).

PAH standards were acquired from the brands Supelco (B(a)A, D(ah)P, D(ah)A, D(al)P, D(ae)P, B(j)F) (Bellefonte, PA, USA) and Sigma-Aldrich (D(ai)P, B(k)F, Chr, B(b)F, B(a)P, I(cd)P) (Saint Louis MO, USA) and IRMM BCR-08IR (5-MChr) (Geel, Belgium). The HPLC grade solvents and reagents used were: hexane, N-dimethylformamide (Scharlab S.L., Sentmenat, Spain), methanol, acetonitrile (JT Baker,

Mexico City, Mexico), anhydrous sodium sulfate (Synth, Labsynth, Diadema, SP, Brazil) and silica gel (70–230 mesh, ASTM, Merck, Darmstadt, Germany). Filters of 0.45 μm (HV PVDF 0.45 μm , Millipore, Cork, Ireland) were also used to filter the extracts before injection into the chromatograph. The water used was obtained by means of a Milli-Q purification system (Millipore, Bedford, MA, USA).

The methodology used was based on Speer et al.,^[17] in which 5 g of sample were weighed, 50 mL of hexane were added, and the mixture was placed in an ultrasound bath (Unique Ultracleaner 1400, Indaiatuba, SP, Brazil) for 15 minutes and transferred to a separation funnel. Extraction was done with 3 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, followed by another extraction with 3 portions of hexane (50, 35 and 35 mL). The organic phase was then washed with water (40 and 40 mL), dried with anhydrous sodium sulfate and evaporated in a rotary evaporator at 45 °C (IKA, HB10 RV 10, Guangzhou, China). For cleaning 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 in a rotary evaporator and suspended in 2 mL of acetonitrile for later injection into the chromatograph.

The technique used was high-performance liquid chromatography with fluorescence detection (HPLC-FLD), using a Shimadzu chromatographic system (Kyoto, Japan) composed of an LC-20AT quaternary pump, DGU-20A5 online degasser system, SIL-20A automatic injector (30 μL injection volume), CTO-20A column oven and RF-10AXL fluorescence detector. The compounds were separated using a C18 column (Vydac 201 TP54, 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% of A, 20–35 min – 75 to 100% of A, 35–55 min – 100% of A, 55–60 min – 75 to 70% of A, 60–75 min – 70% of A. PAHs were detected using the following excitation and emission wavelengths (nm): BaA, Chr and 5MChr (274/414), B(j)F (312/507), B(b)F, B(k)F, BaP, DalP and DahA (290/430), I(cd)P (300/500), DaeP (397/403) and DaiP and DahP (304/457).

The compounds were quantified by the external standardization method. The analytical curves were constructed from the injection of standard solutions,

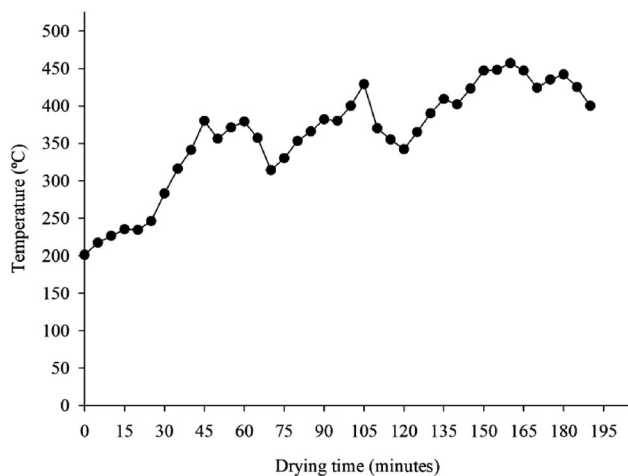


Figure 1. Values of the internal temperature of the furnace obtained during the soybean drying operation.

containing the 13 PAHs, at seven levels of concentration in acetonitrile (0.30 to 20 $\mu\text{g/L}$).

2.5. Statistical analysis

The experiment was carried out in a completely randomized design (CRD), and the samples were collected before and after drying. The means were compared by the t-test at the 0.05 probability level, using the Sisvar software. Descriptive statistics were used to evaluate the dryer.

3. Results and discussion

3.2. Dryer and furnace

The continuous and uniform temperature control inside the furnace becomes complex, due to the oscillations that are caused by the wood chip filling intervals, controlled by the automatic system, according to the adjustment made by the professional operator of the dryer (Figure 1). These temperature variations occur until the drying air reaches the desired temperature inside the dryer, which will depend on the initial conditions of the product, equipment and fuel used.

According to Table 1, 11,871.80 kJ of specific energy were spent to remove 1.0 kg of water. The average consumption of wood chips was 21.78 kg per ton of dry product and the moisture content was 28.90% (wb). According to Garstang et al.,^[18] biomass for the generation of energy must have moisture content equal to or lower than 30% (wb). The minimum lower calorific value desired for biomass used in energy cogeneration plants is 7,949.60 kJ/kg.^[19] Therefore, the chip used for drying showed satisfactory conditions of energy performance.

Table 1. Fuel and dryer characteristics during drying of soybean grains.

FCt	FC	LCV	Ec	WL	SEC	AFR
3,192.20	21.78	18,665.87	774,481.50	5,084.29	11,871.80	17.86

Total Fuel Consumption (FCt, kg), Fuel Consumption (FC, kg of chip/ton of dry product), Lower Calorific Value (LCV, kJ/kg), Electricity Consumption (Ec, kJ), Water Loss (WL, kg), Specific Energy Consumption (SEC, kJ/kg) and Air Flow Rate (AFR, $\text{m}^3/\text{min}/\text{ton}$).

According to Queiroz and Valente,^[20] in addition to the effect that drying under severe conditions has on the quality of the product, increasing susceptibility to breakage, it can represent financial losses when poorly designed or operated. Isquierdo et al.^[21] report that high drying air temperatures and flow rates, despite promoting reduction in energy consumption, can cause deterioration of the cell membranes of the grains.

Figure 2 shows the average values of drying air temperature, ambient temperature and exhaust temperature during drying of soybean grains. The dryer had an average efficiency of 75.61%, a result considered satisfactory for furnace dryers that use direct-fired heating system.^[22] In energy terms, this value is attributed to the air flow and the heat transfer that occurs inside the dryer between the drying air and the grains, so that the closer the exhaust temperature is to the ambient air temperature, the greater the efficiency. Melo et al.^[23] built and evaluated a direct-heating furnace supplied with firewood and obtained efficiency between 77.4 and 86.5%, which was considered satisfactory by the authors.

The high initial values of efficiency are directly related to the removal of free water from the grains and the utilization of drying air, consequently, to the low variation of the exhaust air temperature. After this period, the efficiency decreases, so it is necessary to increase the drying potential of the air by increasing the temperature, making it possible to remove the water that is associated internally in the grains.

The drying air temperature reached values close to 70°C, with an average of 57.23°C (Figure 2), considered adequate for soybean grains for industrial purposes.^[4] For most of the time, the exhaust air temperature was equal to 34.16°C. The average ambient air temperature was 26.72°C, and this air was responsible for mixing in the cyclone with the air coming from the furnace. Increasing the drying temperature can influence the drying rate and time and, consequently, energy consumption and operating cost. However, the continuous supply of heated air with high temperature can cause structural and physical-chemical changes in the product.

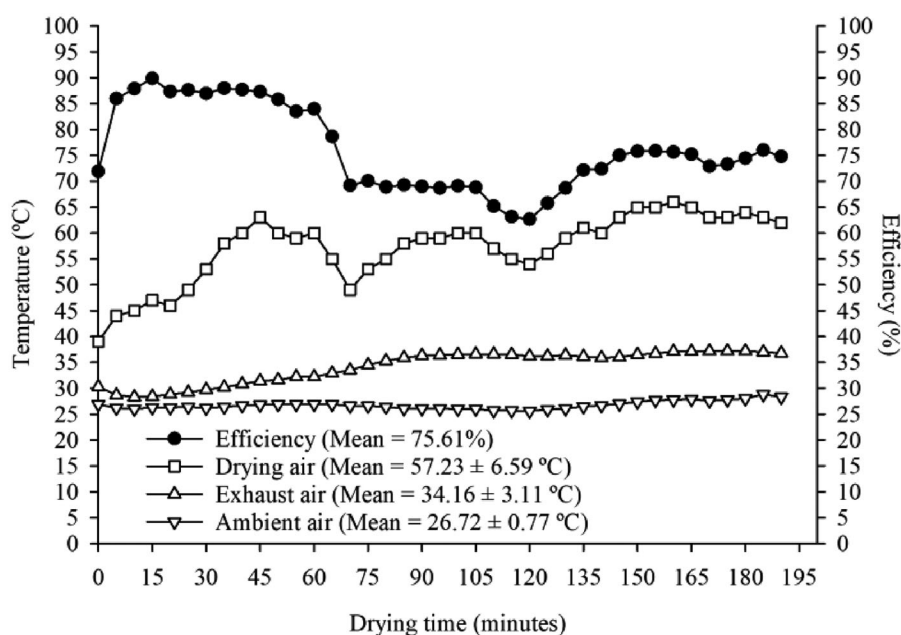


Figure 2. Efficiency and temperatures of drying air, exhaust air and ambient air during the drying period of soybean grains.

3.2. Soybean grains

The average value of the moisture content of the grains was 14.47% (wb) before drying (wet) and 12.11% (wb) after drying (dry grains), below the commercially recommended value (14%, wb) (Figure 3A). However, for tropical climate countries, where high temperatures and rainfall prevail, this final moisture content is close to the condition established as safe for grain storage, which is 12.0% (wb).^[24] Moisture content is the most significant factor for preventing grain deterioration during storage. Keeping the moisture content and grain temperature low minimizes the effects of the attack of microorganisms and respiration; therefore, drying becomes fundamental to maintain the quality of the grains.

The average values of acidity index of the crude oil extracted from the grains showed a difference between before drying and after drying, this fact may be due to the dry grains presenting lower moisture content and lower hydrolytic reactions, presenting lower values and greater stability of the quality. However, the values are below the maximum limit allowed for commercialization by the National Health Surveillance Agency (ANVISA),^[25] which is 4.0 mg KOH/g (Figure 3B).

The mean values of germination showed difference between before drying and after drying (Figure 3C). It was also possible to observe that there was a high variation, which is due to the large volume and heterogeneity of product (145.5 tons), originating from different cultivars and production sites. Tozzo and

Peske^[26] evaluated germination of grains and found values above 80%, but based on vigor tests they did not indicate their use as seeds for the formation of commercial plantations. However, it is important to point out that physiological analyses, traditionally used for seeds, also help in grain evaluations, since better physiological quality is indicative of adequate physicochemical characteristics and, consequently, better quality for industrial use.

The mean values of electrical conductivity also differed between before drying and after drying, with high variation and oscillation between replicates over time for wet and dry grains (Figure 3D). It is emphasized that the average value found for wet grains was 121.43 $\mu\text{S}/\text{cm}/\text{g}$, which may be due to mechanical damage from previous processes, such as harvesting and transporting of the grains. Moreover, it is evident that the mechanical damage was intensified with the drying process, leading to microcracks at cellular levels, which increased the average values of electrical conductivity in the soaking solution of the dry grains (137.83 $\mu\text{S}/\text{cm}/\text{g}$).

The mean values of apparent specific mass showed difference between before drying and after drying (Figure 3E), and the increase was due to the reduction of grain volume (shrinkage) through loss of water during drying. This fact results from the better arrangement of the grains in occupying intergranular spaces. High values of apparent specific mass ensure a better quality of the agricultural product for marketing purposes. Thus, considering this characteristic, soybean grains were within a range of good quality.^[4]

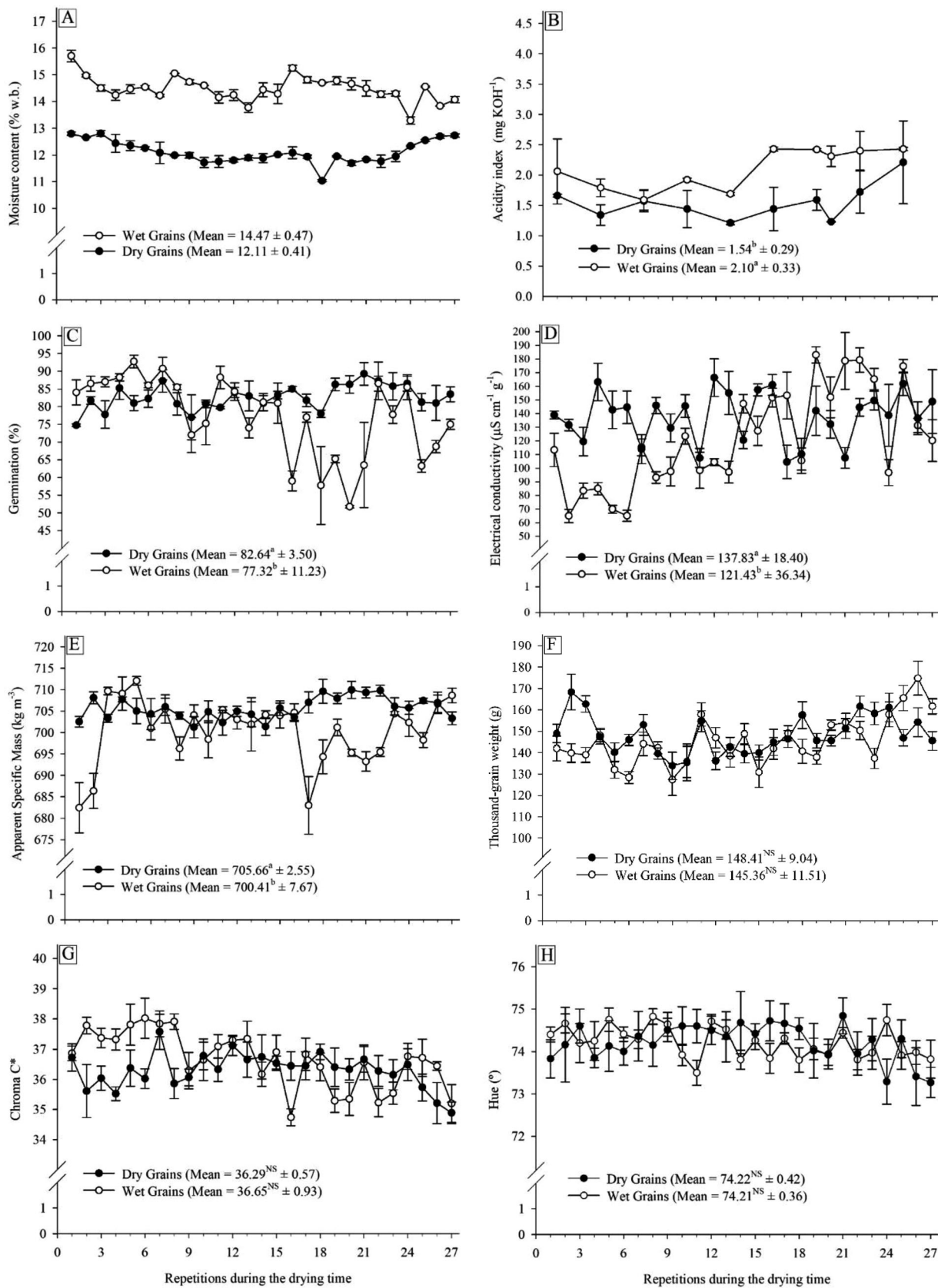


Figure 3. Evaluations to characterize the quality of soybean grains before and after drying ($n = 3$). (A) Moisture content; (B) Acidity index; (C) Germination; (D) Electrical conductivity; (E) Apparent specific mass; (F) Thousand-grain weight; (G) Chroma; (H) Hue angle. Means followed by equal letters do not differ by the t-test at 0.05 probability level. ^{NS}Not significant.

Table 2. Average values of PAHs determined in soybeans before drying (wet) and after drying (dry) using dryer with wood chip-fed furnace.

PAHs	PAH levels ($\mu\text{g}/\text{kg}$)*		CV (%)**
	Wet	Dry	
Benzo(a)Anthracene	0.1485 ^a	0.1085 ^a	7.21
Chrysene	0.4794 ^a	0.3365 ^a	18.88
Benzo(b)Fluoranthene	ND	0.0247	–
Benzo(k)Fluoranthene	ND	0.0099	–
Benzo(a)Pyrene	ND	0.0224	–
Total	0.6280 ^a	0.5021 ^a	22.05

Means followed by equal letters in the row do not differ by t-test at 0.05 probability level; ND = Not detected; LOD = 0.04 $\mu\text{g}/\text{kg}$ PAHs.

*Original mean values ($n = 10$, with 2 determinations).

**CV: Coefficient of variation, data transformed to $(x + 1)^{0.5}$.

Botelho et al.^[27] evaluated the influence of temperature (40 to 80 °C) on the apparent specific mass of soybean grains and observed that this property decreased as temperature increased, indicating damage to product quality. The apparent specific mass provides information on the occupied volume and mass of the product, which facilitates the planning and designing of the structural volume of the storage units and the operation of equipment, such as grain conveyors.

The thousand-grain weight showed no difference between before drying and after drying (Figure 3F). Due to the large volume of grains processed during drying, the samples collected from the wet and dry grains showed heterogeneity before drying and after drying, a behavior similar to that of germination, thus hampering the results expressed by these tests. However, the apparent specific mass may be related to the quality of the grains, because it considers the relationship between the mass and the volume occupied by them, while the thousand-grain weight test is related only to the mass of the product.

Regarding the color characteristics of the grains, the mean value for the parameters chroma and hue angle did not differ between before drying and after drying, with a small decrease after drying, evidencing a low reduction in color saturation intensity (Figure 3G,H). The drying process can cause color degradation due to changes in heat-sensitive compounds.^[28] Thus, it is evidenced that the temperature used during drying (mean = 57.23 °C) did not promote significant alteration in these grain characteristics.

The reduction in moisture content during drying can significantly alter the quality and physical, physiological and chemical properties of the grains and seeds, depending on the method and drying conditions to which they were subjected, compromising the commercial value of the product.

Parameters such as temperature and relative humidity of the ambient air, temperature and flow rate of the drying air, initial and final moisture contents of the grains, flow rate of the product in the dryer, type of fuel and furnace, among others, are directly related to the drying time and, consequently, to the final quality of the grains.

Among the 13 PAHs analyzed for soybean grain samples, two were detected before (wet) and five were detected after (dry) the drying process, with no statistical difference (Table 2). The following PAHs were not detected in the grain samples: benzo(j)fluoranthene (BjF), dibenzo(ah)anthracene (DahA), dibenzo(ae)pyrene (DaeP), dibenzo(ah)pyrene (DahP), dibenzo(ai)pyrene (DaiP), dibenzo(al)pyrene (DalP), indene (1,2,3-cd)pyrene (IcdP) and 5-methylchrysene (5MChr). The lower concentrations for B(a)A and Chrysene after drying are possibly due to the high grain flow of the dryer (69.93 ton/h), and it was not possible to analyze the same grains before drying and after drying. However, each sample was retained at equal intervals (5 minutes) throughout the drying time, that is, at the beginning of drying (dryer inlet) and after the grains passed through the drying chamber (dryer outlet). However, it was demonstrated and evident that drying causes contamination by PAHs in the grains, with the addition of three compounds. Silva et al.^[9] also identified contamination by PAHs in grains subjected to convective drying with direct-fired furnace.

Several complex factors can interfere in the formation of PAHs during drying and also in the contamination of the product, such as time of exposure, nutritional composition of the product, combustion temperature, moisture content of the material, among others. Thus, the results obtained are according to the conditions and materials evaluated during the experiment. However, other studies cited in the literature showed higher levels of PAHs using other materials and drying conditions.

The Joint FAO/WHO Expert Committee on Food Additives (JECFA), during the 64th meeting in 2005, concluded that among the 33 PAHs evaluated, 13 are proven carcinogenic and genotoxic.^[29] The five PAHs found in soybean grains are classified as carcinogenic and genotoxic. JECFA evaluated the toxicological effect of B(a)P and identified carcinogenicity as the most significant characteristic. The degree of carcinogenicity of this compound, for humans, has been confirmed by its classification as carcinogenic since 1985 by the International Agency for Research on Cancer.^[6]

B(a)P was considered for several years as a marker of the presence of PAHs in food; however, a new evaluation by the European Food Safety Authority (EFSA) concluded that this compound alone is not an adequate marker, hence adopting a system of 4 [B(a)A, Chrysene, B(a)P and B(k)F] or 8 PAHs as an indicator of the presence of PAHs in food.^[30] This change is due to the fact that the sum of these PAHs reflects better the occurrence of carcinogenic and genotoxic PAHs in different categories of food.

The PAHs detected in the grains of the present study are compounds with high molar mass (MM), above 202 g/mol, and have more than 4 benzene rings. However, it must be pointed out that the average concentration was lower than the maximum values allowed for the category of processed products based on cereals and foods for infants and children, according to the European Union Law No. 835/2011, both in relation to B(a)P (maximum level = 1 µg/kg) and the 4 PAHs [B(a)A, Chrysene, B(a)P and B(k)F] (maximum level = 1 µg/kg). Therefore, it is possible to observe that the formation of PAHs also occurs during the drying process and this is associated with several complex factors. However, according to the drying conditions used in the present study, the formation of these compounds was relatively low.

The formation of PAHs is particularly favored by carbonized biomass at temperatures between 400 and 800 °C, but both the quantity and composition vary depending on the material to be pyrolyzed, combustion temperature, time of permanence of the molecules in the gaseous state and concentration of oxygen.^[31] Therefore, the low concentration of PAHs formed is associated with the internal combustion temperature of the furnace, which reached the maximum value of 457 °C (Figure 1), and also the fuel used in drying, eucalyptus wood chips; which due to the size has a larger contact area during burning inside the furnace.^[32,33] Another factor is the aid of forced air blown by fans under the grid, which also contributes to a more complete combustion of the chips and, consequently, to less gas formation, thus generating less contamination in the grains.

Lima et al.^[8] analyzed the contamination by PAHs in corn grains subjected to drying with eucalyptus wood and detected seven compounds with high values, above the levels permitted by European Legislation (no. 835/2011), four of which were considered of low molecular mass (<128 to 202) and three of high molecular mass (between 228 and 278); these values were justified by the longtime exposure of the grains to the drying process. Moreover, even with all

the distinct factors that interfere in the contamination of the grains during drying, as well as the type of grain, it is worth mentioning that in the study conducted by Lima et al.,^[8] in which high values were identified, whole eucalyptus firewood was used as fuel, unlike the present study, in which eucalyptus wood chips were used.

Escarrone et al.^[7] observed values on the order of 1.0 to 7.0 µg/kg for fluoranthene and naphthalene, respectively, in white rice and parboiled rice. These authors did not justify the fact that grains dried with LPG (liquefied petroleum gas) had higher concentrations than grains dried with wood and also did not report the values of PAHs before drying.

In Brazil, there is no specific legislation regarding PAH levels for grains. The ANVISA establishes a maximum level only for benzo(a)pyrene in olive pomace oil (2.0 µg/kg) and flavorings for artificial smoking (0.03 µg/kg), and an Ordinance of the Ministry of Health establishes the maximum level for drinking water (0.7 µg/L).^[34–36]

Before drying (wet), the grains showed the presence of PAHs. However, food can be contaminated by PAHs through contact with particles of atmospheric air, soil, water, or during processing phases, in particular those that use high temperatures such as drying, roasting, smoking or different forms of cooking.^[37] This contamination can occur from environmental pollution, such as fruits, meats, vegetables and grains.^[38]

Lipid-rich foods are promising sources of contamination by PAHs, since these contaminants have a highly lipophilic characteristic, thus facilitating their solubility in these food products.^[39] In addition, lipids act as vehicle for PAHs, increasing the speed of intestinal absorption of these agents and thus maximizing the potential for contamination.^[40]

The presence of PAHs detected in soybean grains dried using direct-fired furnace can lead to contamination of the derived products produced from this raw material, such as soybean oil. In a study conducted by Camargo et al.,^[41] relatively high and variable levels of PAHs (10.4 to 112.0 µg/kg) were identified in 42 samples of soybean oils commercially available in the Brazilian market, and the authors also emphasize that these compounds remain concentrated on the surface of the grains and are transferred to crude oil during the extraction processing. Garcia et al.^[42] analyzed the contamination of PAHs in soybean grains sold in vegetarian stores and detected levels from 0.80 to 38.78 µg/kg, and one sample contained 204.46 µg/kg (sum of 6 PAHs).

Thus, PAHs are compounds that deserve attention in the field of food safety, because the growing concern with the presence of contaminants makes it a topic of great interest not only for researchers in the area, but also for the population in general, since the search for quality of life has been shaping consumers who are increasingly aware of the right to purchase health-safe products. With the results obtained, new equipment is being designed with different dimensions and will be tested in other dryers.

4. Conclusions

The dryer had an average efficiency of 75.61% for the drying of soybean grains, which is considered satisfactory for systems that use direct-fired furnace. The average consumption of wood chips was 21.78 kg of chips per ton of dry soybean grains. The specific energy consumption to remove 1.0 kg of water was 11,871.80 kJ.

In general, drying did not compromise the final quality of the grains for the properties of moisture content, germination, electrical conductivity, apparent specific mass, color, acidity index and thousand-grain weight.

Soybeans showed contamination by two PAHs before drying and three other PAHs appeared after drying. Average concentrations were lower than the maximum values allowed by European Union Law No 835/2011.

The drying conditions used for soybean grains influenced the low formation of PAHs.

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Disclosure of interest statement

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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