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Energy-Qualitative and Sustainable Impacts on Differents Soy Grain Drying Technologies

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Abstract

The objective of this current paper is to evaluate, in real production scale, the management of soybean batches in the storage unit of harvested grains that are submitted to drying processes with different technologies, such an evaluation can contribute to minimizing energy and qualitative losses, and to ensuring the grain quality and sustainability of the postharvest system. The experiment was realized in full-scale production and the treatments utilized were lots moist soybean crop (SUL), RR dry soybean (SSLRR), RR2 dry soybean (SSLRR2), dried soybean in continuous dryer (SSS1) (11.0%), dried soybean silo-dryer (SSS2) (12.5%), dried soybean in silo aerator (SSS3) (14.0%). Energy losses and grain quality as a function of drying management ranged from 2.5 to 16.4% in energy, from 0.23 to 3.26% in crude protein and 0.15 to 3.05% in oil—the maximum yield of wet soybeans harvested from the crop (SUL) at 17% (w.b.). Considering the annual Brazilian soybean production, energy losses reach up to 162,282.50 m³ of firewood, approximately 2,116,963,470 kg of crude protein and 810,616,800 liters of crude oil. This would ensure lower losses and higher grain quality, including better yield of protein and crude oil, specifically reducing energy impacts by increasing the efficiency of the drying system. The current study concluded that the SSS1 drying system reduces energy-environmental impacts by 80.23%, reduces crude protein losses by 94.73%, and crude oil by 95.08%.

Keywords: energy, post-harvest, pre-processing, quality

1. Introduction

Soybeans (*Glycine max* (L.) Merrill) are the most widely cultivated oilseed in the world, and the grain produced is destined for the oil and meal extraction industries (CONAB, 2019; USDA, 2019). The soybean postharvest stages aim to conserve the quality of harvested grains until commercialization through proper grain management during receiving, pre-cleaning, drying and storage operations (Anderson & Westerlund, 2014; Babu et al., 2018).

Drying the crop reduces grain water content for storage conditions (Helvacı & Akkurt, 2018; Reyes et al., 2016). Although drying is a fundamental operation, the thermal process must be gentle in terms of time and temperature, because in addition to removing water, drying can interfere with the physicochemical structure of the grains, causing cell tissue disruption and accelerating the process of grain deterioration. Consequently, this may increase the acidity index and reduce the oil and protein content (Alencar et al., 2009; Coradi et al., 2017; Hartmann et al., 2016; Samadi et al., 2013).

On the other hand, the heterogeneity of grain lots harvested from the beginning to the end of the harvesting period hinders the capacities of the dryers. This means it is necessary to closely monitor and manage water content in the grain mass, the drying air temperature to ensure process optimization regarding energy consumption and grain quality. Seed genetic diversity has emerged as a new parameter of variation for drying speed, energy consumption and postharvest grain quality (Amjad et al., 2015; Bowser et al., 2011; De Bonis & Ruocco, 2008; Li et al., 2007).

Optimization of grain dryers has two main objectives: minimizing energy costs and maximizing drying capacity. The energy used in drying comes from fuel burning, but especially biomass in the form of eucalyptus forests. This is owed to the lower cost when compared to other options, such as diesel oil and LPG. In this sense, there has been a recurring concern with the origin, maintenance, and reduction of consumption of this natural resource for energy. An alternative would be to explore the operating conditions of drying by improving temperature and air flow control (Boroze et al., 2014; Bowser et al., 2011; Coskun et al., 2009; Rabha et al., 2017).

The most commonly used models for drying agricultural products are based on displacement of the heated airflow through the mass of the product (Prakash et al., 2014; Singh & Sethi, 2018). Some studies have evaluated variations in airflow and drying air temperature, such as Srzedinicki and Driscoll (2008) who stated that high-temperature grain drying is one of a number of techniques that reduce drying time. Ibrahim et al. (2013), Ibrahim et al. (2014) and Tajaddodi (2012), all studied the performance of dryers and verified the variation of airflow direction (which interferes with the energy consumption in the dryer) as an important means to increase drying capacity and grain quality. Brooker and Bakker-Arkena (1992), Devahastin and Pitaksuriyarat (2006), Mayor and Sereno (2004), and Mulet et al. (1999) each evaluated the energy consumption in the drying process and found average results of 60% furnace/dryer system efficiency, specific energy consumption of 1101 kcal kg^{-1}, specific hourly energy consumption of 2,252.174 kcal h^{-1} and biomass consumption of 643 kg h^{-1}.

Given the surrounding environmental concerns and finite nature of fossil fuels, it is necessary to further reduce energy consumption in the food sector, which will also help to decouple food prices from unstable fossil fuel prices (Chen et al., 2010). Leveraging renewable energy is a desirable means of drying agricultural products; concurrently associating them with current drying technologies will also improve efficiency vastly. Accordingly, the objective of this work is to evaluate, in real production scale, the management of soybean batches in the storage unit of harvested grains, and particularly those submitted to drying processes with different technologies.

2. Material and Methods

2.1 Characterization of Experimental Units

The experimental work was conducted in one hundred twenty one grains storages units located in the south and Midwest of the Brazil. The batch management was realized according to the water content ranges in the grain mass. The storage units evaluated presented different characteristics of preprocessing: a wet product line with receiving, pre-cleaning, drying, and storage system, and unit storage of dry product without a drying system. The unit storage of wet product with receiving, pre-cleaning, drying, and storage was characterized by receiving grain in a set of hoppers with capacity until 360 tons. Grains were moved from the hoppers to the vertical transport elevator via a conveyor belt at the bottom of the hopper with capacity until 120 ton h^{-1}. For pre-cleaning were used machines until 250 ton h^{-1}. For drying was used equipped with a continuous system that had a static capacity until 200 ton h^{-1}. The storage system was composed of metal silos with a capacity of 20,000 bags. This was also equipped with aeration systems complete. The unit storage, received the dry product consisting of a single hopper until 100 tons, pre-cleaning machine with capacity until 250 ton h^{-1}. There were also metal conical-bottom silos with a capacity of 100 tons with aeration system. The grain elevator had an automated grain storage management system that drives or disables grain handling systems (conveyor belts and mug lifts), pre-cleaning machines, dryer loading and unloading systems, and the temperature control drying air and dryer loading level. Moreover, the system indicates the volumes of grain stored in the silos, the loading levels of the silos, and controls and drives the aeration fan motors. It does all this according to weather conditions measured by a weather station, which it then uses to perform real-time measurements of ambient temperature and relative humidity. Finally, the automated system monitors leverages a thermometry system to monitor stored grain conditions using cables and thermocouple sensors.

2.2 Experimental Scheme

The current study evaluated the energy balance and quality of soybean drying for the different postharvest management of grain lots. The lots of soybeans under evaluation were divided into groups: dry soybeans and wet soybeans from the crop (cultivar RR and RR2), and dry soybeans in the drying unit. The following experimental treatments occurred: treatment 1—wet soybean crops (SUL), treatment 2—dry soybeans (SSLRR), treatment 3—dry soybeans (SSLRR2), treatment 4—dry soybeans in continuous dryer (11%) (SSS1), treatment 5—dry soybeans in continuous dryer (12.5%)±silo-dryer (SSS2), treatment 6—dry soybeans in continuous dryer (14%)±aerator-silo (SSS3).

2.3 Sampling and Physical Analysis

The grain receiving and storage unit consists of bulk storage structures. Trucks transport the soybean batches to the storage unit, when they are weighed in the entrance of the unit and subjected to composting samplers. The collected samples were sent to a quality control room where technicians analyze the contents of water, impurities, and foreign matter, and subject the soybeans to physical classification to determine healthy and damaged grains. To determine the percentage of impurities, the current study used a working sample of 375 grams. During the drying of the grains was monitored the air temperature using thermocouple sensor installed in the dryer itself and positioned in the transition space of the drying chamber (air-grain mixture) and cooling chamber. Measurement of the grain mass temperature occurred during drying, with sample collection at the dryer outlet and with the aid of a container. The sample was placed next to an iodine thermometer to obtain the temperature. A paddle anemometer measured the air velocity at the furnace inlet and cyclone.

2.4 Physicochemical Analysis

The water contents of grain samples during drying were measured indirectly, which correlates the electrical capacitance with product moisture content. The current study classified soybean batches according to Normative Instruction No. 11 of May 15, 2007, of the Ministry of Agriculture, Livestock, and Supply (Brazil, 2007).

In a homogenized working soybean sample, the study determined group (I or II), class (yellow or mixed) and batch type based on the percentage of burnt and burnt, moldy, greenish, broken, broken and dented, foreign matter and impurities. The electrical conductivity test was performed on soybeans according to the methodology described by Vieira and Krzyzanowski (1999). Four repetitions of fifty grains were used for each repetition of each treatment. Researchers weighed the beans on a digital scale to two decimal places and placed them in plastic cups (200 mL), then added 75 mL of deionized water to each container (Brazil, 2007).

The cups were placed in germination previously set at 25 °C for 24 hours. After this time, researchers removed the containers and gently shook them. For conducting the tests, the study incorporated an AK51 electric conductivity meter with automatic calibration and automatic temperature compensation. Results were expressed in $\mu S\ cm^{-1}\ g^{-1}$ (Brazil, 2007).

In order to determine the percentage of dry matter (DM) of the soybean samples, they were previously ground to millimeter size after placing the samples in a drying oven at 105 °C for eight hours (AOAC, 1984).

The study calculated the percentage of dry matter of the sample using the initial and final weight difference. The protein content was determined by the Kjeldahl method (Method 984.13; AOAC, 1997), determining the nitrogen (N) content of the sample to be 0.20 g, placed in a digester block together with the 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. 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. It was nitrogen to protein transforming using ta factor considering 16% nitrogen (100/16 = 6.25).

The determination of lipid contents (ether extract-EE) was determined by AOCS Method Am5-04 (2005), using ANKOM XT15 equipment and ANKOM XT4 filter bags. Petroleum ether was used as a solvent, adopting a temperature of 90 °C for 60 minutes of extraction. After the extraction period, researchers placed the beaker in an oven until all the solvent had evaporated, and then it went in the desiccator until it reached the constant temperature for weighing.

2.5 Statistical Analysis

To evaluate the results, the study performed analysis of variance and means tests through a Tukey test at 5% probability using Sisvar 5.6 software.

2.6 Mass and Energy Balance of Drying Systems

The initial water mass in the soybeans in the drying system was determined by Equation 1:

$$P_{ti} = P_t U_i \tag{1}$$

where,

P_{ti}: initial water body in the product (kg); P_t: total product mass (kg); U_i: final product moisture (w.b.) (%).

The final water mass in the soy beans in the drying system was determined by Equation 2:

$$P_{tf} = P_t U_f \tag{2}$$

where,

P_{tf}: final mass of water in the product (kg); P_t: total product mass (kg); U_f : final product moisture (w.b.) (%).

The mass of water evaporated in the soybeans in the drying system was determined by Equation 3:

$$W_{evap} = W_1 - W_2 \tag{3}$$

where,

W_{evap}: evaporated water mass (kg); W_1: initial mass of water in the product (kg); W_2: final water body in the product (kg).

The final mass of soybeans after drying was determined by the Equation 4:

$$P_f = P_t - W_{evap} \tag{4}$$

where,

P_f: final product mass (kg).

The yield of the soybean drying system was determined by Equation 5:

$$R_t = \frac{W_{evap}}{P_{ti}} \tag{5}$$

where,

R_t: drying yield (%).

To determine the relative humidity of the air, Equation 6 was used:

$$UR = \frac{P_v}{P_{vs}} \times 100 \tag{6}$$

where,

UR: relative humidity (%); P_v: steam pressure (kPa); P_v: saturation vapor pressure (kPa).

The actual vapor pressure was determined by Equation 7:

$$P_v = P_{vs} - A \cdot P_{atm}(T - T_u) \tag{7}$$

where,

A: psychrometric constant (aspirated psychrometers = 6.7 × 10^{-4} °C^{-1}); P_{atm}: local atmospheric pressure (kPa); T: dry bulb temperature (ºC); T_u: wet bulb temperature (°C).

Atmospheric pressure was determined by the Equation 8:

$$P_{atm} = 101.3 \times \left[\frac{(293 - 0.0065\,h)}{293}\right] \tag{8}$$

where,

h: altitude (m).

The saturation vapor pressure was determined by the Equation 9:

$$P_{sat} = 6.1078 \times 10^{\left[\frac{7.5\text{T}}{237.3\text{T}}\right]} \tag{9}$$

where,

P_{sat}: saturation vapor pressure (kPa).

The global heat balance used in the drying system was determined by the Equation 10:

$$Q = \left\{W\left[\left(\frac{100 - U_i}{100}\right)c_m \pm \left(\frac{U_i}{100}\right)c_{H_2O}\right]\left(t_s - t_m\right) \pm \left[\frac{W(U_i - U_f)}{100 - U_f}\right] r \pm P\right\} \tag{10}$$

where,

Q: amount of heat from the drying system (kcal kg^{-1}); W: input weight of the product to be dried (kg); U_i: initial water content (w.b.) (%); U_f: final water content (w.b.) (%); C_m: specific heat of the product to be dried (grain ~ 0.47 kcalkg^{-1} °C^{-1}); C_{H_2O}: specific heat of water (kcal kg^{-1} °C^{-1}); r: latent heat of water vaporization (~ 568 kcal kg^{-1}°C^{-1}); t_s: drying air temperature (°C); t_m: grain mass temperature (°C); P: losses (~ 30%).

To calculate the mass flow rate of fuel consumed during drying operations, the equation was used 11:

$$V_{mc} = \frac{M_c}{t_o} \tag{11}$$

where,

V_{mc}: mass fuel flow (kg h^{-1}); M_c: fuel mass, considering eucalyptus firewood 450 kg m^{-3}; t_o: operating time (h).

The energy entering the dryer was calculated using the Equation 12:

$$E_e = \frac{V_{mc}}{Q_{ta}} PCI \tag{12}$$

where,

E_e: dryer input power (kcal kg^{-1}); Q_{ta}: amount of product (kg); PCI: can lower calorific (kcal kg^{-1}).

The output energy of the dryer from the dryer was calculated by the Equation 13:

$$E_s = E_e - Q \tag{13}$$

where,

E_s: dryer output power (kcal kg^{-1}).

The thermal performance of the dryer was calculated using the Equation 14:

$$R_s = \frac{Q}{E_e} \times 100 \tag{14}$$

where,

R_s: thermal efficiency of the dryer (%).

3. Results and Discussion

The main objective of drying agricultural products is to reduce vegetable water activity to a level that slows microbial growth and reaction rate (less than 0.6). For this, there are two guiding principles: heat transfer to provide the necessary latent heat of vaporization and the movement of water or water vapor through a material. Soybean lots were harvested and submitted to drying management under the conditions presented in Table 1.

Table 1. Conditions of ambient air and soybeans for drying

Treatments	Ambient air conditions		Grain conditions	
	RH (%)	$T_{ambiente\ air}$ (°C)	U_i (%)	U_f (%)
SSS1	82.0±3.0	26.1±1.0	17±0.2	11.0±0.1
SSS2	73.0±3.0	21.5±1.0	17±0.2	12.5±0.1
SSS3	63.0±3.0	24.2±1.0	17±0.2	14.0±0.1

Note. RH: relative humidity (%); *T*: ambient air temperature (°C); *Ui*: initial product moisture (w.b.) (%); *Uf*: final product moisture (w.b.) (%).

At the beginning of drying, there was a significant reduction of grain moisture, distributed in the inner layers near the grain surface, influenced by the drying air temperature conditions. The researchers dried SSS1 soybean batches for 90 minutes to reduce water content from 17% to 11.0%, with grain mass temperature varying from 36 to 41 °C. SSS2 soybean batches had a 60-minute drying period, which reduced water contents from 17% to 12.5%, wherein grain mass temperature ranged from 39 to 42 °C. The SSS3 soybean lots dried for 60 minutes to reduce water content from 17% to 14.0%, with grain mass temperature ranging from 37 to 42 °C. According to Yassen and Al-Kayiem (2016), removing water from the product through drying results from the difference in the vapor pressure of the grain relative to the air, creating a gradient of vapor tension. This gradually transfers water from the interior of the grain to the periphery, due to capillary movements, moisture diffusion, and vapor pressure gradients. As for the physical quality of SUL, SSS1, SSS2, SSS3 SSLRR, and SSLRR2 soybean lots, the current study classified satisfactory results in Group I c, meeting the standard for soybeans destined for fresh consumption (Table 2) according to Normative Instruction No. 11 of May 15, 2007 and Normative Instruction No. 37 of July 27, 2007, which establishes the Soy Technical Regulation. The Regulation defines official classification standards with the Intrinsic and Extrinsic Identity and Quality Requirements, Sampling and Marking or Labeling for soybeans from the species (*Glycine max* (L.) Merrill).

Table 2. Physical classification of soybeans from different lots after drying

Treatments	*I* (%)	*F* (%)	*A* (%)	*Q* (%)	*IM* (%)
SUL	0.29	0.76	0.28	2.03	0.69
SSS1	1.21	0.37	0.37	2.33	0.34
SSS2	0.25	0.29	0.27	1.22	0.00
SSS3	0.91	0.20	0.11	3.35	0.11
SSLRR	0.41	0.29	0.06	3.31	0.23
SSLRR2	0.20	0.26	0.06	3.39	0.17

Note. I: Impurities; *F*: Fermented; *A*: Burned; *Q*: Broken; *IM*: Immature.

Of the lots that went through the drying process, the dry lots and the wet lots did not differ in relation to the dry mass content, unit-specific mass, apparent specific mass and porosity (Table 3). This contradicted Botelho et al. (2015), who observed reduction of apparent specific mass and unit-specific mass of soybean linearly, the drying temperature having increased. Alencar et al. (2009) verified the maintenance of water contents of stored grains in environmental conditions of low temperatures and high relative humidity, reducing the losses of dry matter and the apparent specific mass of grains. These are generally intensified under warmer conditions.

Table 3. Physical and physical-chemical quality of soybean grain lots handled in a receiving, drying and storage unit

Analysis	Treatments					
	SUL	SSLRR	SSLRR2	SSS1	SSS2	SSS3
U (%)	17.00 C	11.69 A	11.03 A	13.31 AB	15.85 B	16.20 B
MS (%)	83.00 A	88.31 C	88.97 C	86.69 B	84.15 B	83.80 A
PB (%)	42.87 D	38.50 A	38.91 A	42.64 D	42.02 D	39.61 B
EE (%)	23.37 C	22.75 B	20.47 A	23.41 C	23.52 C	23.34 C
ρ_{un} (kg m^{-3})	933.52 A	933.24 A	931.73 A	955.20 A	965.20 A	971.64 A
ρ_{ap} (kg m^{-3})	616.85 A	595.88 A	627.34 A	643.06 A	633.45 A	650.05 A
ξ (%)	33.90 A	36.17 A	32.68 A	32.67 A	34.42 A	33.11 A
EC (µS cm^{-1} g^{-1})	137.78 B	51.78 A	49.14 A	133.45 B	120.67 B	51.78 B

Note. U: water content; *MS*: dry matter; *PB*: crude protein; *EE*: ethereal extract; ρ_{un}: specific unit mass; ρ_{ap}: apparent specific mass; ξ: porosity; *EC*: electrical conductivity.

However, improper handling of the grain or drying system can cause serious damage to the grains. Coradi et al. (2017) described how drying soybeans with water content above 19% and drying air temperature at 120 °C significantly increases the acidity and yield of crude oil and protein compared to drying at lower temperatures such as 75, 90 and 105 °C. Hartmann Filho et al. (2016) evaluated soybeans with water content of 23% (w.b.), having subjected them to drying at temperatures of 40, 50, 60, 70 and 80 ºC until the water content was 12.5±0.7% (w.b.). Their study concluded that the quality of soybean and crude oil decreases as the drying air temperature increases. Tables 4, 5 and 6 show the results of the mass and energy balance of the drying system. The current study found that when the evaporated water mass in the drying process was increasingly smaller, the mass of dried product and the drying yield were increasingly lower (Table 4). Moreover, the lower the final water content of the grains, the higher the energy that the drying process consumed for a higher fuel mass flow and higher energy efficiency of the dryer. The results the current study obtained are favorable for a sustainable system, considering the growth in the use of heat sources based on sustainable biomass. This study presents a viable option for grain-producing regions experiencing high energy costs, allowing collaboration in the reduction of greenhouse gas emissions and carbon emissions associated with the use of fossil fuels—a global concern in reducing climate change trends. According to results that Tables 4, 5 and 6 present, there are significant differences between drying technologies in terms of developing more sustainable systems.

Table 4. Mass balance of soybeans in the drying

Treatments	T_s (°C)	P_t (kg)	P_{ti} (kg)	P_{tf} (kg)	W_{evap} (kg)	P_f (kg)	*Rt* (%)
SSS1	90±15	1	0.1700	0.1140	0.0560	0.9440	29.41
SSS2	90±15	1	0.1700	0.1380	0.0320	0.9680	18.82
SSS3	90±15	1	0.1700	0.1410	0.0290	0.9710	17.05

Note. T_s: temperature air drying (°C); P_{ti}: initial water mass in product (kg); P_{tf}: final water mass of the product; W_{evap}: evaporated water body (kg); P_f: final mass of product (kg); *Rt*: drying yield (%); *Pt*: total mass of product (kg).

Table 5. Energy balance of the drying system

Treatments	*W* (kg)	U_i (%)	C_m (kcal kg^{-1} °C$^{-1)}$	C_{H2O} (kcal kg^{-1} °C$^{-1)}$	T_s (°C)	T_m (°C)	U_f (%)	*r* (kcal kg^{-1} °C^{-1})	*P* (%)	*Q* (kcal kg^{-1})
SSS1	1	17.0	0.47	1	90	41	11.0	568	30	82.34
SSS2	1	17.0	0.47	1	90	40	12.5	568	30	63.82
SSS3	1	17.0	0.47	1	90	37	14.0	568	30	63.51

Note. Q: amount of heat from the drying system (kcal kg^{-1} of product); *W*: input weight of the product to be dried (kg); U_i: initial water content (w.b.) (%); U_f: final water content (w.b.) (%); C_m: specific heat of the product to be dried (grain ~ 0,47 kcal kg^{-1} °C^{-1}); C_{H2O}: specific heat of water (kcal kg^{-1} °C^{-1}); *r*: latent heat of water vaporization (~ 568 kcal kg^{-1} of water °C^{-1}); T_s: drying air temperature (°C); T_m: grain mass temperature (°C); *P*: losses (~ 30%).

Table 6. Energy balance of the drying system—continued

Treatments	*W* (kg)	[1]Wood (m^3)	M_c (kg)	t_o (h)	V_m (kg h^{-1})	V_{mc}/Q (kg)	*PCI* (kcal kg^{-1})	E_e (kcal)	E_s (kcal kg^{-1})	R_s (%)
SSS1	1	2.5	1125	1.5	750	0.01875	4500	84.38	2.04	97.5
SSS2	1	1.5	675	1.0	675	0.01687	4500	75.92	12.10	84.0
SSS3	1	1.5	675	1.0	675	0.01687	4500	75.92	12.41	83.6

Note. [1]Total biomass used to dry 40 tonnes of grain; V_{mc}: mass fuel flow (kg h^{-1}); M_c: fuel mass, considering specific mass of eucalyptus firewood from 450 kg m^{-3} (kg); t_o: operating time (h); E_s: dryer output power (kcal kg^{-1} of product); *PCI*: lower calorific value (kcal kg^{-1}); R_s: thermal efficiency of the dryer (%); *Q*: amount of heat from the drying system (kcal kg^{-1}); E_e: energy entering the dryer (kcal kg^{-1} of product).

According to Lisboa et al. (2018), when attempting to overcome the bottlenecks of traditional drying systems, although the use of sustainable energy is an alternative for drying agricultural products, choosing the drying method according to the conditions of soybean batches enhances the system itself. Making post-harvest systems more sustainable plays a significant role in reducing losses, as well as creating a qualitative and sustainable environment with concern to the operational aspects of production. The proper use of different technologies allows drying of agricultural products in a sustainable environment, especially considering the yield and thermal utilization of dryers, at the same time ensuring the quality of agricultural products, reducing physical losses and physical and chemical characteristics observed in Tables 2 and 3. During the drying process, the water withdrawal from the product occurs by the difference of the vapor pressure of the grain about the air. Drying of the grain occurs when there is a gradient of vapor tension from the grain to the air, gradually transferring water from the interior of the grain to the periphery due to capillary movements, moisture diffusion, and vapor pressure gradients. This means that the warmer the air, the more water it retains, the better the grain surface dries out (Taşeri et al., 2018). According to these concepts, the drying process may be faster or slower depending on the drying technology system and energy use. This study has observed that the continuous grain flow and faster drying predominated regarding energy utilization and grain quality. Table 7 presents the results of energy balance and grain quality as a function of drying management.

Table 7. Impacts in the energy balance and quality of soybeans in the differents drying systems at a production scale Brazilian

T	Q_{taEn} (kcal)	Biomass (kg)	R_s (%)	P_E (%)	R_{PB} (%)	P_{PB} (%)	R_{OB} (%)	P_{OB} (%)
SUL	-	-	-	-	42.87	0.00	23.52	0.00
SSLRR	-	-	-	-	38.50	4.37	22.75	0.77
SSLRR2	-	-	-	-	38.91	3.96	20.47	3.05
SSS1	3,530,120,000.000	784,471,111.11	97.5	2.5	42.64	0.23	23.41	0.15
SSS2	2.053.888.000.000	456,419,555.55	84.0	16.0	42.02	0.85	23.37	0.15
SSS3	1,861,336,000.000	413,630,222.22	83.6	16.4	39.61	3.26	23.34	0.18

Note. Q_{taEn}: amount of energy consumed in the soybean drying Brazilian; $R_{s:}$ thermal yield; P_E: loss of energy; R_{PB}*:* crude protein yield; P_{PB}: loss of crude protein; R_{OB}: crude oil yield; P_{OB}: loss of crude oil.

Significant losses in grain quality were observed in Table 7 due to the drying management of 0.23 to 3.26% crude protein and 0.15 to 3.05% crude oil, corresponding to approximately 2,116,963,470 kg of crude protein and 810,616,800 liters of crude oil. Similarly, losses for energy used in drying were from 2.5 to 16.4%, which translates to approximately 1.743.269.13 m³ of firewood when considering the annual Brazilian soybean production. On the other hand, the energy losses due to the drying system are only a fraction, corresponding to about 162,282.50 m³ of firewood.

4. Conclusions

Managing SSS1 soybean drying to the initial water content of 17% (w.b.) and final storage water content of 11.0% (w.b.) is the best alternative that ensures lower losses and higher grain quality, as well as improving yield of protein and crude oil, thereby reducing energy impacts with increased efficiency of the drying system. This study concludes that the SSS1 drying system reduces energy-environmental impacts by 80.23%, losses with crude protein by 94.73%, and crude oil by 95.08% for a much more sustainable postharvest system.

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