ISSN 1807-1929
Revista Brasileira de Engenharia Agrícola e Ambiental
Brazilian Journal of Agricultural and Environmental Engineering
v.28, n.8, e280005, 2024
Campina Grande, PB – http://www.agriambi.com.br – http://www.scielo.br/rbeaa

DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v28n8e280005

Original Article

Equilibrium moisture content: Use of intergranular relative air humidity sensors in silos[1]

Teor de água de equilíbrio: Uso de sensores de umidade relativa do ar intergranular em silos

Weder N. Ferreira Junior[2], Osvaldo Resende[2]*, Kelly A. de Sousa[2],
Lilian M. Costa[2] & José R. Quirino[3]

[1] Research developed at Instituto Federal de Educação, Ciência e Tecnologia Goiano, Campus Rio Verde, Rio Verde, GO, Brazil
[2] Instituto Federal de Educação, Ciência e Tecnologia Goiano/Campus Rio Verde, Rio Verde, GO, Brazil
[3] Caramuru Alimentos S.A., Rio Verde, GO, Brazil

HIGHLIGHTS:

Monitoring intergranular temperature and relative air humidity provides real-time moisture content of stored grains.
The content of impurities in stored grains may vary in the hygroscopic equilibrium of the grains.
The chemical composition of the grains affects the estimated equilibrium moisture content.

ABSTRACT: Grains are hygroscopic materials and, during storage, they are subject to exchanging moisture with the environment according to temperature and relative air humidity, making it important to monitor these factors. Digital temperature and relative air humidity sensors appear as an alternative for monitoring the moisture of grain mass inside silos; they are simple to install and use. Digital sensors present outstanding precision in temperature measurements. The objective in this study was to assess the efficiency and applicability of intergranular relative air humidity sensors linked to digital temperature sensors in the thermometry system of silos storing soybeans. Two samples of soybeans were analyzed in the upper, middle and lower thirds of the silo, for grain mass temperature, intergranular relative air humidity, estimated equilibrium moisture content according to collected data, and moisture content of the sampled grains. Moisture contents obtained from sensor measurements using the hygroscopic equilibrium equation and determined using the oven method were compared. The equilibrium moisture content estimated by the data provided by the sensors did not differ by the Tukey test ($p \leq 0.05$) from the moisture content determined by the oven method. Digital temperature and relative air humidity sensors have proven to be efficient, as they contribute to estimating the equilibrium moisture content with satisfactory precision.

Key words: water activity, hygroscopicity, mathematical modeling

RESUMO: Grãos são materiais higroscópicos, e em seu armazenamento estão sujeitos às trocas de vapor de água de acordo com a temperatura e umidade relativa do ar, sendo importante o monitoramento desses fatores. Os sensores digitais de temperatura e umidade relativa do ar surgem como alternativa para monitoramento da temperatura da massa de grãos no interior de silos, apresentando simplicidade de instalação e utilização. Sensores digitais apresentam destacada precisão nas medições de temperatura. O objetivo deste estudo foi verificar a eficiência e aplicabilidade de sensores de umidade relativa do ar intergranular atrelados a sensores digitais de temperatura no sistema de termometria de silos armazenando grãos de soja. Duas amostragens de grãos de soja no terço superior, médio e inferior do silo foram analisadas para a temperatura da massa de grãos, umidade relativa do ar intergranular, teor de água de equilíbrio estimado conforme dados coletados e teor de água dos grãos amostrados. Realizou-se a comparação do teor de água obtido a partir das medições dos sensores usando a equação do equilíbrio higroscópico e pela determinação através do método da estufa. O teor de água de equilíbrio estimado pelos dados fornecidos pelos sensores não diferenciou pelo teste de Tukey ($p \leq 0.05$) do teor de água determinado pela estufa. Os sensores digitais de temperatura e umidade relativa do ar demonstraram-se eficientes, visto que contribuem para estimativa do teor de água de equilíbrio com precisão satisfatória.

Palavras-chave: atividade de água, higroscopicidade, modelagem matemática

---

• Ref. 280005 – Received 25 Oct, 2023
* Corresponding author - E-mail: osvresende@yahoo.com.br
• Accepted 18 Mar, 2024 • Published 29 Apr, 2024
Editors: Toshik Iarley da Silva, Carlos Alberto Vieira de Azevedo & Leda Rita Dantonino Faroni

Introduction

During the grain storage period, in which the products must have the ideal and uniform moisture content, it is essential to control the air conditions present in the intergranular space, thereby ensuring aeration (Oliveira et al., 2007; Steidle Neto & Lopes, 2015). According to Normative Instruction N°. 29, dated June 8, 2011 (MAPA, 2011), storage units must be equipped with a thermometry system, under adequate operational conditions.

For Bica et al. (2021), monitoring the temperature of the grain mass is important to ensure that strategies are performed to avoid heating the grains and thus guarantee their integrity. It is clear that there is a great influence of relative air humidity on the behavior of stored grains, including their safety. This occurs because the grains are hygroscopic materials (Granella et al., 2019; Fonseca et al., 2020; Bessa et al., 2021).

Normative Instruction N°. 29 (MAPA, 2011) does not establish the need to monitor the relative humidity of the intergranular air in the silos. However, by monitoring the relative air humidity inside the silos associated with the temperature of the grain mass, it is possible to promote aeration management considering the equilibrium moisture content of the grains.

The use of digital temperature and relative air humidity sensors in soybean grain silos has proven to be a superior alternative to the traditional thermometer system. Over time, thermocouple sensors can become inaccurate, which is a reality for many storage units where numerous silos have malfunctioning cables or provide unreliable data (Plumier & Mayer, 2021).

The integration of these sensors into the Internet of Things concept allows for continuous and real-time monitoring (Ayres et al., 2021). Recent studies demonstrate the economic value and operational effectiveness of these solutions, contributing to the improvement of grain storage management and providing crucial information for farmers, storage facilities, and other stakeholders in the agricultural sector (Schiavon et al., 2019; Ayres et al., 2021; Lopes et al., 2022). Therefore, the objective in this study was to assess the efficiency and applicability of intergranular relative air humidity sensors linked to digital temperature sensors in the thermometry system of silos storing soybeans.

Material and Methods

Soybeans from producers in the state of Goiás, Brazil, were used. The grains were harvested by grain harvesters and transported by trucks to the storage unit located in the municipality of Morrinhos – GO, Brazil (17° 43’ 41.8” S and 49° 03’ 51.5” W, at altitude of 840 m).

The grains went through the pre-processing process, drying and cleaning and were stored in vertical metal silos at ambient temperature. The circular silo was 22 m in diameter, with 22 rings measuring 0.917 m, which resulted in a cylinder of 20.19 m in height and 26.44 m in total height.

During storage, the grain mass temperature and intergranular relative air humidity were monitored using digital sensors. The temperature sensor consists of an NTC thermistor and the humidity sensor is of the HR202 type. The thermometry system present in the silo was composed of 128 digital temperature sensors, with the structure consisting of nine cables distributed strategically and homogeneously throughout the silo (Figure 1). The thermometry cables are special cables with four layers of protection, featuring a mechanical braided steel frame with a PE 70C ST3 covering. The composite side cables were composed of eight pendulums featuring 14 digital temperature sensors in each of them, 16 temperature sensors were installed in the central cable, totaling 128 temperature reading points.

From these 128 sensors, 26 were mixed sensors, with the ability to obtain intergranular temperature and relative air humidity readings; these sensors were uniformly arranged in 5 cables (Figure 1). The mixed sensors were distributed in four lateral cables and one central cable, containing five sensors on each side cable, and the central cable was composed of six mixed sensors. In each cable, the mixed digital sensors were vertically spaced 4.5 m apart, containing a mixed sensor every 295 m^3, and the temperature sensors were spaced 1.5 m apart, with a temperature sensor at approximately 60 m^3.

During the study, a total of 72.21 hours of aeration were conducted to facilitate the cooling and preservation of the grains. The fans were activated when both the internal and external thermometry systems identified opportune moments for aeration without compromising the grains. Conditions deemed suitable for aeration were when the external temperature was between 3 and 4 °C lower than the average internal temperature of the grain mass, and when there was no precipitation, except during peak energy consumption hours, between 5:30 and 8:30 p.m.

The grain mass temperature and intergranular relative air humidity values were obtained for four days prior to the collection of product samples, with information being extracted from the sensors in three periods of the day, at

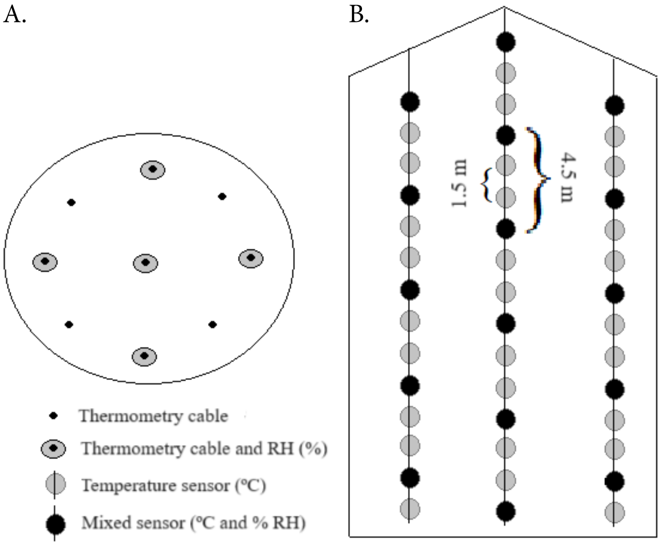

Figure 1. Organizational diagram of digital thermometry containing mixed temperature and relative air humidity (RH) reading sensors. Top view of the cable distribution (A) and vertical view of the distribution of sensors in the cables (B)

6 a.m., 2 and 8 p.m. The 4-day interval was adopted so that the grains reached hygroscopic equilibrium. The silo was divided into three regions (thirds) in order to separate the grain mass according to height (upper, middle and lower).

Evaluations were performed using only data from the mixed sensors, which measure temperature and relative air humidity; the other temperature sensors were not considered for this analysis. The upper third consisted of a set of six sensors, grouped into three pairs, representing the replicates. The middle third included nine sensors, with three replicates assembled using data from three sensors in each one. For the lower third, the same scheme as the upper third was adopted, as there were also six sensors in this third.

To obtain the average temperature and relative air humidity in each sensor, during the sampling period, reading data from four days prior to sample collection were considered, using data from three periods per day, as previously described, totaling 12 readings for each sensor. The averages of the equilibrium moisture content estimated by the system were obtained in the same way. The system estimates the equilibrium moisture content from the hygroscopic equilibrium moisture content equation (Eq.1), using intergranular temperature and relative air humidity data, that is, for the same points where the mixed sensors are located, with the estimated equilibrium moisture content, and these are then selected.

Eq.1 represents the Modified Henderson model (ASABE, 2007) used by the sensor system to estimate the equilibrium moisture content of stored soybeans. When the grains are in hygroscopic equilibrium, the intergranular relative air humidity will be equal to the water activity in decimal.

$$\mathrm{Xe} = \left[\frac{\left(\ln\left(1 - \mathrm{aw}\right) \right)}{\left(-0.00031 \times \left(\mathrm{T} + 66.60300 \right) \right)} \right]^{\frac{1}{1.7459}} \quad (1)$$

where:

Xe - equilibrium moisture content, % d.b.;
a_w - water activity, decimal; and,
T - temperature, °C.

To determine the equilibrium moisture content, the grains were collected twice with an interval of 15 days between collections in the upper, middle and lower thirds. In the upper third, samples were collected at a depth of 2.5 m, at five random points, forming a composite sample, with the aid of a grain sampler.

In the middle third to obtain the composite sample, the grains were also collected at five random points; they were removed at a depth of 10 m with the aid of a pneumatic probe. In the lower third, samples were taken with the help of a pelican sampler that collected the grains at the three exits of the screw conveyors, used to unload the grains, collecting samples within 30 s to compose the sample blocks.

For each third and collection, approximately 5 kg of grains were removed, and the samples were homogenized and reduced to 1 kg in a Boerner-type homogenizer. Moisture content was determined by the oven method at 105 ± 3 °C for 24 hours (MAPA, 2009), with 10 g per sample, in three replicates, for each third at each sampling time.

The two methods of evaluating equilibrium moisture content were compared: the moisture content estimated by the system based on sensor readings using Eq. 1 and the moisture content determined experimentally by the oven method based on sample collection (MAPA, 2009). For this, the comparison between the two samples was disregarded, and the replicates were then formed by the readings of the sensor groups for each third, as previously described.

Due to the occurrence of two sampling periods, these were added to the average calculation. In other words, after obtaining the average of the sensor groups per replicate, the average between the same replicates of the two sampling periods was calculated, thus obtaining the overall average per replicate.

In addition to the comparison between the methods for evaluating the equilibrium moisture content, the influence of the location of the grains (upper, middle and lower) was assessed, separately and in correlation with the method for evaluating the moisture content.

To characterize the equilibrium moisture content as a function of temperature and intergranular relative air humidity, a 2 x 3 factorial scheme was set up, with three replicates, with 2 samples and 3 silo thirds (upper, middle and lower), in a randomized block design, analyzing grain mass temperature, intergranular relative air humidity, equilibrium moisture content estimated by the sensor system and moisture content determined by the oven method (105 ± 3 °C for 24 hours), during sampling.

Regarding the comparison of the estimation and determination of moisture content, the experiment followed the 2 x 3 factorial scheme, with 2 methods of evaluating moisture content (estimated by the sensor system and determined by the oven method) and 3 silo thirds (upper, middle and lower), and the equilibrium moisture content data were compared between the different treatments. The data were analyzed using analysis of variance, with the means compared using the Tukey test ($p \leq 0.05$), using Sisvar 5.8 version (Ferreira, 2019).

Results and Discussion

No sampling effect was observed for grain mass temperature, intergranular relative air humidity, equilibrium moisture content estimated by the sensor system using Eq.1, and equilibrium moisture content determined by the oven method. No interaction effects of the factors sampling x third were observed, for all variables analyzed. For the third factor, that is, location of the grains in the silo, a difference was observed using the F test for all variables.

The average temperature of soybean grain mass in the analyzed period was 25.71 °C, and this did not differ between samplings (Table 1). The average intergranular relative air humidity in the analyzed period was 71.01%, with an estimated average grain moisture content of 13.77% d.b., both not differing as a function of the sampling time. For the moisture content experimentally determined in the collected grains, it was observed that it did not diverge during the sampling period (oven method), with an average of 14.10% d.b., which indicates a possible state of hygroscopic equilibrium in the period (Corrêa et al., 2014).

Table 1. Average values of temperature (°C), relative air humidity (RH, %), estimated equilibrium moisture content (EEMC, % d.b.) and determined equilibrium moisture content (DEMC, % d.b.) of samples of stored soybeans in different thirds in a vertical silo

Sampling	Temperature (°C)	RH (%)	EEMC	DEMC
			(% d.b)	
First	26.45 a	71.18 a	13.81 a	14.14 a
Second	24.97 a	70.84 a	13.72 a	14.06 a
Third	Temperature	RH	EEMC	DEMC
Upper	28.43 a	68.03 b	12.45 c	14.59 a
Middle	25.11 ab	70.78 ab	13.76 b	13.67 c
Lower	23.59 b	74.73 a	15.10 a	14.04 b

Equal letters in the same column for Sampling or Third do not differ from each other by the Tukey test ($p \leq 0.05$)

In Table 1 it is possible to analyze the effect on the behavior of the analyzed variables depending on the arrangement of the grains in the silo, through the different thirds. It is observed that temperature in the upper third was 20.5% higher than that of grains stored in the lower third; opposite behavior was seen for intergranular relative air humidity, in which the highest average intergranular relative air humidity was observed in the lower third, while the upper third had lower value.

Lower temperature in the lower third can be explained by the fact that it is the first portion of grains through which air from aeration through insufflation passes, that is, making these grains more susceptible to cooling than the grains in the middle and upper thirds. This fact is not harmful to grain preservation, in fact, it may even contribute to the formation of convective air currents inside the silos (Silva et al., 2000). This occurs due to lower static pressure in the lower third compared to the other thirds (Goneli et al., 2020).

The difference in intergranular relative air humidity in the different thirds of the silo can be justified by the movement of the air current by convection (natural and forced), that is, the air inside the silo is not static, as circulation occurs in the silo due to the difference in density between hot and cold air, a phenomenon known as convective currents (Silva et al., 2000). When cases occur inside the silo as seen in Table 1, in which the temperature of the upper third is higher than those of the other thirds, the hot air from this region tends to be directed towards the others, whose temperatures are lower.

The difference between air temperature and grain mass temperature causes air cooling and, consequently, an increase in intergranular relative air humidity (Sauer, 1992). For Devilla et al. (2004), differences in temperature can promote the migration of moisture from areas of high temperatures to areas of low temperatures.

Table 1 shows the effect of the variables temperature and intergranular relative air humidity to estimate the moisture content through Eq. 1; grains stored in the three thirds differed from each other, and it is possible to notice a greater effect of the RH variable, since the highest estimated moisture content was obtained for grains located in the lower third, followed by those in the middle and upper thirds.

When analyzing the determined moisture content, it was observed that the result was not the same; the upper third had grains with higher moisture content, followed by the lower third and finally the middle third. According to Côrrea et al. (2014) and Durks et al. (2019), grains stored in large volumes remain in constant search of hygroscopic equilibrium with the surrounding air.

Regarding the comparative analysis between the equilibrium moisture content estimated by the sensor system through Eq. 1 (EEMC) and the experimentally determined (oven method - DEMC) moisture content, it was possible to observe that only the moisture content evaluation method, individually, was not significant by the Tukey test. The same did not occur for the moisture contents in the different thirds, which differed. There was a difference in the interaction between the moisture content assessment method and third in the silo.

When analyzing the methods for evaluating the moisture content in the different thirds, difference was observed only in the upper third, where the estimated equilibrium moisture content was lower (12.45% d.b.) than the experimentally determined equilibrium moisture content (14.59% d.b., Table 2). When analyzing each moisture content assessment method for the different thirds, it was observed that the experimental moisture content (oven method) did not differ in the different thirds, while for the estimated moisture content, grains stored in the upper third had lower value.

The estimate of the moisture content for the upper third (Table 2) may have had an error, since the values are different from the other moisture content values, estimated and experimental (oven method). It should be noted that the moisture content estimated by the sensor system is obtained from the mathematical estimate of the correlation between data from grain mass temperature sensors and intergranular relative air humidity.

Another important issue to be raised is the heterogeneity in the physical-chemical composition of the stored grains, as the coefficients fitted in Eq.1 are specific to that material, and the difference in the chemical composition and even the physical properties of the product can compromise the estimation of the moisture content.

The fitted model coefficients are dependent on the characteristics of the product, including the chemical composition (Brooker et al., 1992), which reflects the behavior of water activity for different moisture contents and temperatures. It is known that the physical-chemical composition of soybeans can vary according to cultivar, planting and harvesting time, edaphoclimatic conditions in the field and post-harvest stages (Calçado et al., 2019; Durks et al., 2019; Hackenhaar et al., 2019; Faria Neto et al., 2022).

According to Table 1, the average temperature was 28.43 °C and the intergranular relative air humidity was 68.03%. During the analysis period, the formation of heat points was

Table 2. Average values of the moisture content of soybeans obtained from the estimation of the equilibrium moisture content (EEMC % d.b.) and through the determination of the experimental equilibrium moisture content (DEMC, % d.b.)

Third	EEMC	DEMC
	(% d.b.)	
Upper	12.45 Bb	14.59 Aa
Middle	13.76 Aa	13.67 Aa
Lower	14.90 Aa	13.92 Aa

Equal uppercase letters in the same row and equal lowercase letters in the same column do not differ from each other by the Tukey test ($p \leq 0.05$)

identified in the central area of the silo in the upper range, which led to an increase in temperature due to the presence of fine impurities in the grain mass.

To check the impurity content, samples were collected in this central range of the silo, and a proportion of 7.22% of impurities was found. In addition, the moisture content of the grains collected in this portion was determined, showing an average of 13.30% d.b., which is consistent with the average estimated in Table 2.

The presence of a high level of impurities in the upper third of the silo created a barrier for the passage of aeration air; in addition, impurities can contribute to the occurrence of insects and oxidative processes (Durks et al., 2019). The high content of impurities, above 1%, which is the limit established by MAPA (2007), over time promoted an increase in the grain respiration rate, causing the temperature of the grain mass to rise.

The period of high temperatures identified in this region of the silo was insufficient to reach the equilibrium moisture content value. According to Weber (2005), the product will not always reach equilibrium due to its physical characteristics, and for the equilibrium to actually occur in some situations, it would require an impractical amount of time; therefore, the author emphasizes that estimates may be biased.

For the moisture content determined experimentally (oven method), the values were higher (14.59% d.b.) when compared to the estimates (12.45%), that is, the product would have to go through a desorption process. It should be noted that the method used to determine the moisture content is a direct method, which quantifies the amount of water in the sample from water extraction (Moritz et al., 2012), so it shows satisfactory precision. Despite the difference in the estimated moisture content in the upper third compared to the experimental moisture content in the same third, the estimation of moisture content by the sensor system proved to be efficient, showing no difference from the experimental moisture content in general.

Considering the methods for evaluating moisture content, it is possible to infer that the estimation of moisture content using data from grain mass temperature and intergranular relative air humidity sensors proves to be efficient. Therefore, relative air humidity sensors represent a good ally for monitoring product behavior throughout storage.

Although the moisture content of the stored grains differed according to the location in the silo, the estimated and experimental (oven method) moisture contents were within the standard for commercializing soybeans, which is 12 to 13% on a wet basis (w.b.) (Durks et al., 2019), which is between 13 and 15% on a dry basis. According to Smaniotto et al. (2014), moisture content of 12% w.b. maintains higher quality soybean seeds, so this content is recommended for the safe storage of products under tropical climate conditions.

Conclusions

1. Intergranular relative air humidity sensors contribute to monitoring the behavior of the equilibrium moisture content of stored grains.

2. The equilibrium moisture content, estimated from the data provided by the sensors, did not differ from the determined (oven method) moisture content.

3. Digital temperature and relative air humidity sensors have proven to be efficient, as they contribute to estimating the equilibrium moisture content with satisfactory precision.

Acknowledgments

The authors thank the Instituto Federal de Educação, Ciência e Tecnologia Goiano, PROCER – Agrointeligência de Pós-Colheita, CARAMURU Alimentos, Empresa Brasileira de Pesquisa e Inovação Industrial, Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, Fundação de Amparo à Pesquisa do Estado de Goiás, Financiadora de Estudos e Projetos and Conselho Nacional de Desenvolvimento Científico e Tecnológico.

Literature Cited

ASABE - American Society of Agricultural and Biological Engineers. ASAE D245.6: Moisture relationships of plant-based agricultural products. Saint Joseph: ASABE, 2007.

Ayres, G. D. J.; Nascimento, J. W. B.; Francisco, P. R. M. Sistema integrado de monitoramento de produtos armazenados em silos. Campina Grande: EPTEC, 2021, 81p.

Bessa, J. F. V.; Resende, O.; Oliveira, D. E. C.; Lima, R. R.; Quequeto, W. D.; Siqueira, V. C. Adsorption isotherms and thermodynamic properties of *Carthamus tinctorius* L. seeds. Revista Brasileira de Engenharia Agrícola e Ambiental, v.25, p.696-702, 2021. https://doi.org/10.1590/1807-1929/agriambi.v25n10p696-702

Bica, M. R. R.; Pai, A. D.; Raniero, M. R.; Calca, M. V. C.; Franco, J. R. Sistema de monitoramento de temperatura em silo de armazenamento de grãos com comunicação sem fio. Braziliam Journal of Development, v.7, p.51409-51427, 2021. https://doi.org/10.34117/bjdv.v7i5.30175

Brooker, D. B., Bakker-Arkema, F. W., & Hall, C. W. Drying and storage of grains and oilseeds. Westport, 1.ed. US: The AVI Publishing Company, 1992, 462p.

Calçado, J. P.; Peluzio, J. M.; Siqueira, F. L. T.; Siqueira, G. B.; Aferri, F. S.; Tavares, A. T. Épocas de semeadura e períodos de colheita de soja visando produção de óleo e proteínas. Nativa, v.7, p.376-382, 2019. https://doi.org/10.31413/nativa.v7i4.6667

Corrêa, P.C.; Botelho, F.M.; Botelho, S. C. C.; Goneli, A. L. D. Isotermas de sorção de água de frutos de *Coffea canephora*. Revista Brasileira de Engenharia Agrícola e Ambiental, v.18, p.1047-1052, 2014. https://doi.org/10.1590/1807-1929/agriambi.v18n10p1047-1052

Devilla, I. A.; Couto, S. M.; Zolnier, S.; Silva, J. S. Variação da temperatura e umidade de grãos armazenados em silos com aeração. Revista Brasileira de Engenharia Agrícola e Ambiental, v.8, p.284-291, 2004. https://doi.org/10.1590/S1415-43662004000200018

Durks, J. M.; Botelho, F. M.; Botelho, S. C. C.; Ruffalo, S.; Hoscher, R. H. Perdas quantitativas e qualitativas em soja armazenada com aeração convencional e resfriamento artificial. Revista de Ciências Agroambientais, v.17, p.32-39, 2019. https://doi.org/10.5327/rcaa.v17i1.2861

Faria Neto, A. L.; Ramos Junior, E. U.; Lorini, I.; Mandarino, J. M. G. Efeito do retardo na colheita na qualidade de grãos de cultivares de soja. Nativa, v.10, p.47-53, 2022. https://doi.org/10.31413/nativa.v10i1.12265

Ferreira, D. F. Sisvar: a computer analysis system to fixed effects split plot type designs. Revista Brasileira de Biometria, v.37, p.529- 535, 2019. https://doi.org/10.28951/rbb.v37i4.450

Fonseca, N. N.; Resende, O.; Ferreira Junior, W. N.; Silva, L. C. M.; Andrade, E. G.; Oliveira, L. P. Isotermas de dessorção de grãos de sorgo granífero. Research, Society and Development, v.9, 466973661, 2020. http://dx.doi.org/10.33448/rsd-v9i7.3661

Goneli, A. L. D.; Corrêa, P. C.; Figueiredo Neto, A.; Kirsch, M. R. H.; Botelho, F. M. Static pressure drop in layers of castor bean grains. Engenharia Agrícola, v.40, p.184-191, 2020. https://doi.org/10.1590/1809-4430-Eng.Agric.v40n2p184-191/2020

Granella, S. J.; Bechlin, T. R.; Christ, D.; Werncke, I. Isotermas e calor isostérico de dessorção da água em sementes de trigo. Revista Engenharia na Agricultura, v.27, p.304-312, 2019. https://doi.org/10.13083/reveng.v27i4.891

Hackenhaar, N. M.; Peluzio, J. M.; Lima, M. D.; Hackenhaar, C.; Carvalho, E. V.; Afférri, F. S.; Mandarino, J. M. C. Potássio e época de semeadura em cultivares de soja para teor de óleo e proteína. Acta Iguazu, v.8, p.1-11, 2019. https://doi.org/10.48075/actaiguaz.v8i2.17552

Lopes, T. T.; Camusso, D.; Fernandes, C. L. M. F. Monitoramento do ar em ambientes de armazenamento de sementes usando internet das coisas e computação em nuvem. Revista Brasileira de Mecatrônica, v.4, p.20-47, 2022.

MAPA - Ministério da Agricultura, Pecuária e Abastecimento. Instrução normativa nº 11. Diário Oficial da República Federativa do Brasil, Brasília: MAPA, 2007.

MAPA - Ministério da Agricultura e Reforma Agrária. Secretaria Nacional de defesa Agropecuária. Regras para análise de sementes. Brasília: MAPA, 2009. 395p.

MAPA - Ministério da Agricultura, Pecuária e Abastecimento.I nstrução normativa n. 29. Diário Oficial da União, Brasília: MAPA, 2011.

Moritz, A.; Ortiz, T. A.; Souza, A.; Takhashi, L. S. A.; Zucareli, C. Comparação de métodos para a determinação do teor de umidade em grãos de milho e de soja. Revista Brasileira de Tecnologia Aplicada nas Ciências Agrárias, v.5, p.145-154, 2012. https://doi.org/10.5777/paet.v5i2.1648

Oliveira, F. A.; Khatchatourian, O. A.; Bihain, A. Estado térmico de produtos armazenados em silos com sistema de aeração: Estudo teórico e experimental. Engenharia Agrícola, v.27, p.247-258, 2007. https://doi.org/10.1590/S0100-69162007000100019

Plumier, B.; Maier, D. Effect of temperature sensor numbers and placement on aeration cooling of a stored grain mass using a 3D finite element model. Agriculture, v.11, p.1-14, 2021. https://doi.org/10.3390/agriculture11030231

Sauer, D. B. Storage of cereal grains and their products. American Association of Cereal Chemists, 1.ed. Minnesota: Inc. St. Paul, Minnesota, 1992. 615p.

Schiavon, R. A.; Nogueira, I. S.; Borges, G. B.; Holanda, H. S.; Castro, K. K. Arduino uma tecnologia de baixo custo para termometria de grãos armazenados. Brazilian Journal of development, v.5, p.18825-18839, 2019. https://doi.org/10.34117/bjdv5n10-124

Silva, J. S.; Lacerda Filho, A. F.; Devilha, I. A. Aeração de grãos armazenados de produtos agrícolas. Viçosa: Editora Aprenda Fácil, 2000, 615p.

Smaniotto, T. A. S.; Resende, O.; Marçal, K. A. F.; Oliveira, D. E. C.; Simon, G. A. Qualidade fisiológica das sementes de soja armazenadas em diferentes condições. Revista Brasileira de Engenharia Agrícola e Ambiental, v.18, p.446-453, 2014. https://doi.org/10.1590/S1415-43662014000400013

Steidle Neto, A. J.; Lopes, D. C. Thermistor based system for grain aeration monitoring and control. Computers and Electronics in Agriculture, v.116, p.45-54, 2015. https://doi.org/10.1016/j.compag.2015.06.004

Weber, E. A. Excelência em Beneficiamento e Armazenagem de Grãos. 1.ed. Canoas: Editora Salles, 2005. 385p.