Original Article
Food Science and Technology

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

DOI: https://doi.org/10.5327/fst.00275

Manual and automated aeration strategies during storage of sunflower grains in silos

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Abstract

The objective of this study was to identify the influence of manual and automated aeration strategies guided by thermometry systems with thermocouples and digital sensors, respectively, on the quality of sunflower grains stored at different heights in a metal silo. The experiment was conducted in a storage unit in two vertical metal silos. Aeration in these silos was manually coordinated in the silo containing thermocouples and automated in the silo with a digital thermometry system. In addition to the grain mass temperature data, the quality of the sunflower grains was monitored for 90 days of storage at three heights in the silo (upper, middle, and lower thirds). The aeration strategies influenced the temperature of the grain mass and, consequently, the quality of the stored product, especially its moisture content. No influence of aeration strategies was identified for protein content, oil content, and iodine content of the oil of the stored sunflower grains. Automation of aeration contributes to making use of better climatic conditions to carry out the process, compared with the manual system used. The aeration strategies adopted (cooling and conservation) were efficient in reducing grain mass temperature in the automated process. The silo with automated aeration showed better conservation of the quality of the stored sunflower grains. The silo with manually controlled aeration showed an 11.55% reduction in grain moisture content. Grains stored in the middle third of the silo tend to have better quality.

Keywords: *Helianthus annuus* L; thermometry; sensors; thermocouples.

Practical Application: Better conservation of the quality of the stored sunflower grains.

1 INTRODUCTION

During the post-harvest of grains, the set of techniques adopted must ensure the quality of the product, and these include drying and aeration of stored products. Aeration aims to keep the temperature of the grain mass and relative humidity of the intergranular air at optimal levels, in order to promote a safe equilibrium moisture content in the product (Lopes & Steidle Neto, 2019; Panigrahi et al., 2020).

Aeration is carried out by blowing external air into the silo; hence, attention must be paid to the differences between grain mass temperature and external temperature. Therefore, the local climate affects aeration management, that is, aeration strategies are largely influenced by climate change (Lopes & Steidle Neto, 2019).

To perform aeration, one must take advantage of the best external air conditions to make the process economical and preserve the quality of the product (Panigrahi et al., 2020). In the state of Goiás, Brazil, the storage of sunflower grains begins in winter, in the second half of June, a period characterized by long nights and low temperatures and relative humidity. Cold periods at the beginning of the storage of this product should be taken advantage of to preserve its quality (Li et al., 2020) since the storage of sunflower grains usually extends until the Brazilian summer season.

Monitoring grain mass temperature during storage is important to enable the correct management of aeration. This monitoring can be carried out through cables containing thermocouples or digital sensors. The operation of an aeration system can be manual or automated with the use of controllers and/or thermostats that consider temperature and relative humidity as parameters (Steidle Neto & Lopes, 2015).

With the airflow from upward aeration, grains present in the lower third of the silo tend to cool first, as this region is closer to the air intake ducts (Li et al., 2020). Air distribution during aeration must be homogeneous, as process uniformity is affected by duct spacing, airflow rate, grain column height, intergranular porosity, impurity content, physical properties, and compaction of the grain mass (Goneli et al., 2020; Panigrahi et al., 2020; Rocha et al., 2020).

Uneven aeration can lead to excessive drying in regions near the air outlets and be inefficient for other areas inside the silo (Binelo et al., 2019). Changes in grain mass temperature should be monitored during storage, as they may indicate the formation of heat pockets, due to changes caused by insects and

Received: Feb. 6, 2024.
Accepted: Oct. 3, 2024.
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Conflict of interest: nothing to declare.
Funding: Instituto Federal Goiano (Process Number: 23218.003584.2023-20), PROCER, CARAMURU, EMBRAPII, CAPES, FAPEG, FINEP and CNPq (Process Number: 310222/2021-4).

microorganisms, and increased respiratory rate of the grains, thus directly affecting the quantity and quality of the stored product (Mohapatra et al., 2017).

Considering the importance of aeration under safe conditions for grain storage, the objective of this study was to identify the influence of manual and automated aeration strategies guided by thermometry systems with thermocouples and digital sensors, respectively, on the quality of sunflower grains stored at different heights in a metal silo.

2 MATERIAL AND METHODS

2.1 Aeration management

Sunflower grains were stored in the 2018/19 season from June to November 2019, totaling approximately 130 days. Approximately 6,000 tons of sunflower grains were divided into two vertical metal silos in a grain storage unit in the municipality of Morrinhos, Goiás, Brazil.

Each of the silos was composed of a specific thermometry system, and the grain mass temperature data were used in the aeration management. One of the silos was equipped with a thermometry system containing 100 thermocouples divided into nine cables; considering the total volume of the silo of 8,466.81 m^3, there is one reading point for every 84.7 m^3 of grains. The other silo with the same volume was equipped with 128 digital sensors divided into nine cables, with one sensor for every 66.0 m^3 of grain. Thus, the number of thermometry points used in this study was within the minimum limit required by Normative Instruction No. 29, which requires at least one point for every 150 m^3 of volume (Brasil, 2011).

Each of the silos had two centrifugal fans with forward-curved blades driven by a three-phase motor with a power of 26 hp (19.12 kW), enabling an air flow (specific flow rate) of approximately 0.05 m^3 min^{-1} ton^{-1} of grain. The silos used were flat-bottomed, containing the area of the aeration ducts spread inside the silo. Aeration was manually programmed by timers in the silo containing thermocouples and automated in the silo with a digital thermometry system. In addition to the grain mass temperature data, the environmental data of temperature and relative humidity were monitored by means of a weather station to show the favorable climatic conditions for implementing the aeration strategies.

Initially, the first 40 days of storage were intended for the simultaneous filling of the silos, and, at the same time, aeration was adopted to cool the grain mass since the local winter promoted favorable conditions for applying this management. The fans were turned on when the external temperature was between 3 and 4°C lower than the average internal temperature, of the grain mass, as well as under conditions of no rainfall and except during peak energy hours, between 5:30 pm and 8:30 pm.

In the second half of August, the aeration strategy was changed in order to conserve the sunflower grains; the conditions described in the aeration management for cooling were used, and the difference between the external air temperature and the average internal temperature was reduced to 3°C for the actuation of the system. In addition, two other conditions, namely, the sensible heating of the external air when passing through the fans and the hygroscopic equilibrium of the sunflower grains, were added to the conditions of the intergranular air, avoiding excessive drying and rewetting.

This aeration strategy was maintained during the 90 days of storage of the sunflower grains, during which time the quality of the product was monitored. Climatological data and the quantitative data of fan operating time were recorded and used to justify the changes in grain mass temperature and any changes in the quality of the product.

2.2 Thermometry

The two metal silos have cylindrical bodies and a conical top, with a diameter of 22 m and a total height of 26.44 m. For the experiment, only the cylindrical part of the silos, approximately 20 m high, was used for the storage of sunflower grains, corresponding to an approximate volume of 7,675 m^3. One of the silos had a thermometry system with thermocouples separated by nine cables in the silo, containing meters vertically spaced from each other every 1.8 m per cable. The other silo had a thermometry system with digital sensors, which were divided into nine cables inside the silo, spaced every 1.5 m along the cable (Figure 1).

Changes in grain mass temperature were monitored for 90 days of sunflower storage. In order to evaluate the effects of the change in grain mass temperature, 2 m of grains stored in the upper layer were disregarded in both silos, thus totaling an experimental area of 18 m, which was divided into three regions of 6 m in height each, called thirds: upper, middle, and lower. The different thirds of each silo were compared with each other during storage.

The experimental replicates were composed of thermometry data grouped in 10-day periods by storage time, each of which consisting of 30 days, that is, each block had an average grain mass temperature in a period of 10 days for each third of the two silos, except for the time zero, at which the thermometry of the previous 30 days was not used, and only the grouped values of 3 days prior to the beginning of the experiment were considered.

2.3 Grain quality

Grain quality was monitored over a period of 90 days, related to the time of use of the aeration strategy for grain conservation. Samples were collected per third, throughout the storage at 0, 30, 60, and 90 days from the beginning of the aeration strategy aimed at grain conservation. Samples were collected in the three-thirds (upper, middle, and lower) of each silo, separately. In the upper third, the samples were collected at a depth of 2.1 m, at five points located near the thermometry pendulums, forming a composite sample, with the aid of a three-stage manual sampler. In the middle third, to obtain the composite sample, the grains were also collected at five points near the thermometry pendulums, at a depth of 10.0 m, using a pneumatic probe. In the lower third, the samples were collected using a pelican sampler that collected the grains at the three outlets of the screw conveyors, used in the unloading of the grains, with samples collected within an interval of 30 s to form the sampling blocks.

For each collection, approximately 5.0 kg of grains were taken, and then, the samples were homogenized and reduced to 1.0 kg in a Boerner divider. The grains were analyzed for moisture content, bulk density, oil and protein content, and chemical quality of the extracted oil. During the analysis of the samples, the presence of live insects and structures of microorganisms perceptible to the naked eye were evaluated.

Moisture content was determined using the oven method at 105 ± 3°C for 24 h (Brasil, 2009), with 10 g per sample. Bulk density, expressed in kg m^{-3}, was determined using a hectoliter weight kit, in a volume of one liter. Crude protein was determined by the method that consists of determining total nitrogen (Silva & Queiroz, 2002). Oil was extracted in the Soxhlet apparatus, and its quality was determined by means of the acidity index, iodine index, and peroxide index (IAL, 2008).

2.4 Statistics

Data of thermometry and quality of the stored grains were evaluated in a 2 × 3 × 4 factorial scheme, corresponding to two silos with different aeration strategies: manual (thermocouple thermometry system) and automated (digital thermometry system), three regions per silo (thirds: upper, middle, and lower), and four storage times (0, 30, 60, and 90 days) in a randomized block design. For general characterization of the grain mass, the effect of the interaction between the aeration strategies (manual and automated) and the storage time was also evaluated, in a 2 × 4 factorial scheme. The data were analyzed by analysis of variance, and the means were compared by the Tukey test, adopting a significance level of 5%.

3 RESULTS AND DISCUSSION

Under the conditions programmed to carry out aeration for cooling, the process was performed for 111 h in the silo with an automated system and for 73 h in the silo with manually controlled aeration, that is, 34% less than in the silo with an automated system. This difference is justified by the use of an automated process in the silo, due to the presence of sensors, whose system programming establishes that the aeration management is dynamic and takes advantage of the potential of the ambient conditions to aerate the grains.

It is worth pointing out that at the beginning of storage, the average temperature of the stored grains was 20.1 ± 0.73 and 18.8 ± 0.86°C, with maximum temperatures of 27.1 and 29°C at some points in the grain mass in the silos with automated and manual systems, respectively, validating the need for cooling the grains in both silos to safe levels of temperature and moisture content (Steidle Neto & Lopes, 2015). At the end of the aeration management period aimed at cooling the grains, it was observed that the average temperature of the grain mass in the silo with an automatic controller was 17.25 ± 1.23°C, representing a decrease of 2.8°C in the average temperature of the stored product during the aeration period. In the manually operated silo, the cooling process was less efficient since the final average grain temperature was 21.47 ± 0.40°C, representing an average increase of 2.67°C in the grain mass.

This contradictory result shows that the aeration process coordinated by employees in the storage unit was less precise and not dynamic in the sense of taking advantage of the best conditions for aeration during the storage period. Heating of the grains in the aeration management may be attributed to the employee paying attention only to the presence of heating points and not considering the average temperature of the stored product in the decision to turn on the fans. In addition, when activated, the silo fans with thermocouples remained on during the entire night (00:00 to 07:30 h), periods that were not always favorable to perform aeration and can induce an unnecessary expenditure of electricity.

During the supervised storage period, using aeration management for grain conservation, the mean external temperature

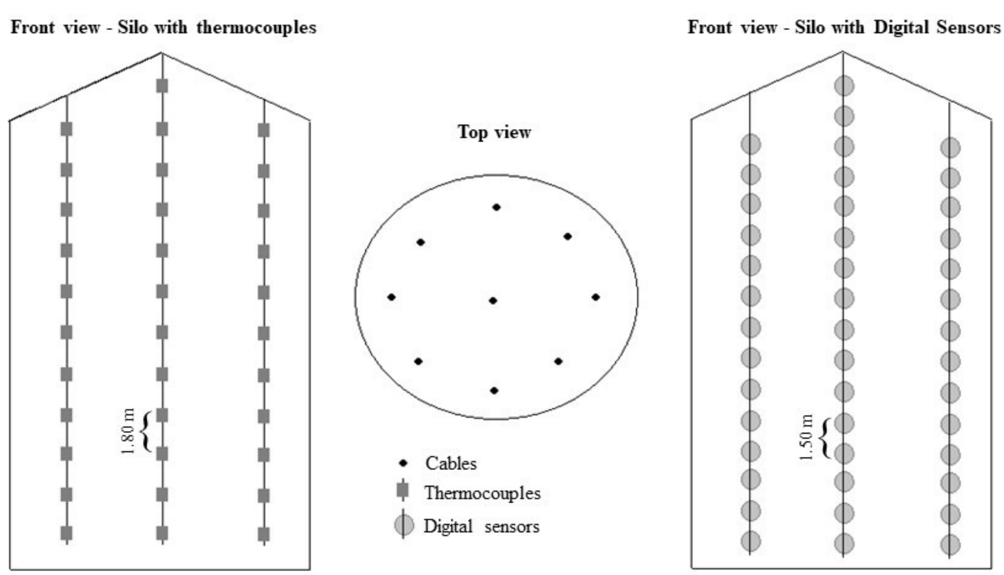

Figure 1. Thermocouple and digital thermometry systems in metal silos.

and relative humidity were 25.67 ± 4.19°C and 55.94 ± 22.02, respectively (Figure 2A). The climatic conditions of the external air proved to be favorable for aeration during the second fortnight of storage in the automated silo. During this period, the fans of this silo were activated for 3:24 h, at night, when the lowest air temperatures were observed, after which the conditions were not favorable to carry out the proposed aeration strategy.

It can be seen that the 15:24 h of aeration performed in the automated silo was sufficient to maintain the temperature of the grains during the first 30 days of storage (Figure 2A), and the mean temperatures during this period did not differ from each other. After this period, the product was heated (Figure 2A), reaching an average final temperature of 19.68 ± 0.28°C, with a total heating of 2.43°C in the grain mass during this 90-day storage period. With these results, it is possible to validate the efficiency of the aeration strategies adopted for this silo since the average temperature of the sunflower grains was lower than their initial temperature, equal to 20.1 ± 0.73°C when aeration began to be performed to cool the product.

Figure 2A shows that silos with manual aeration showed an increasing linear behavior in grain mass temperature. This behavior is due to the absence of conservation aeration during this storage period. As the aeration process in this silo was manual, some night periods favorable to performing the aeration process were not taken advantage of. The average temperature of the sunflower grains stored in this silo was 27.15 ± 1.42°C, indicating an increase of 5.69°C during the monitored storage period. Considering the initial temperature during cooling aeration, the increment was 8.36°C since the beginning of storage.

During the entire storage period, the silo with automated aeration had a lower temperature than the silo with manually controlled aeration (Figure 2A), and the same result could be observed in the upper third (Figure 2B), middle third (Figure 2C), and lower third (Figure 2D) of these silos. Regarding the thermometry in these regions of the silo, there is a similarity in the behavior compared with the average of the silo (Figure 2A); for the upper and lower thirds (Figure 2B and 2D) of the automated silo, the temperature remained constant during the first 30 days,

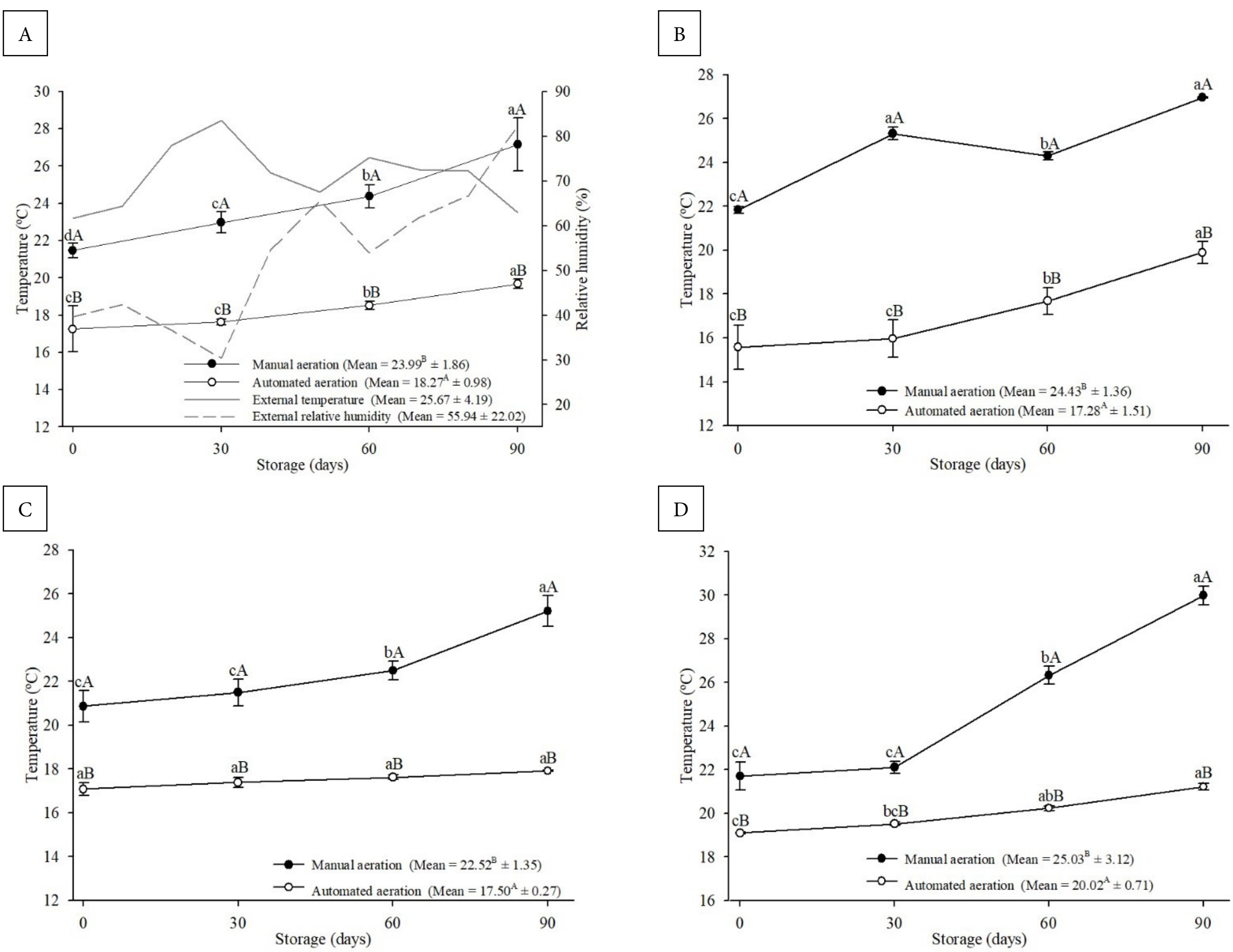

Figure 2. (A) External temperature and relative humidity, average temperature of the mass of sunflower grains stored in metal silos with manual and automated aeration strategy; (B) average temperature of the sunflower grain mass in the upper third of the silos during storage; (C) average temperature of the sunflower grain mass in the middle third of the silos during storage; (D) average temperature of the sunflower grain mass in the lower third of the silos during storage. Means followed by the same lowercase letter for each aeration strategy throughout storage and the same uppercase letter between the aeration strategies for each time do not differ from each other at a 5% significance level.

with a subsequent increase in the remaining 60 days of storage. Considering the three regions (Figure 2B–2D) in the manually controlled silo, the temperature increased throughout storage, as shown in Figure 2A.

The middle third of both silos showed the lowest mean temperature (Figure 2C), 17.50 ± 0.27 and 22.52 ± 1.35°C for the silo with sensors and for the silo with thermocouples, respectively. This behavior shows that the middle third of the silo better preserves grain temperature, due to the low thermal conductivity of the grains, not exchanging heat easily (Bragantini, 2005). The automated silo maintained a constant temperature during the 90 days of storage in the middle third, and for the silo with manually controlled aeration, there was an average heating of the grains of 1.51 ± 0.56°C after 30 days of storage.

Heat pockets were observed during the last 45 days of storage in the lower third of the silo, whose aeration was manually coordinated, with a temperature of 36.22 ± 1.70°C, and in the last fortnight in the middle third of this silo, with a temperature peak of 30.67 ± 3.27°C. The average temperature went from 22.11 ± 0.28 to 29.98 ± 0.42°C in the lower third in the last 45 days of storage (Figure 2D), which represents an approximate heating of 7.87°C in the grain mass. During the last 15 days, the average temperature in the middle third of this silo ranged from 22.50 ± 0.43 to 25.22 ± 0.71°C (Figure 2C). These heating zones can result from increased respiration of the grains and the presence of insects and microorganisms (Mohapatra et al., 2017).

No insects were identified in the grain samples; however, in the last collection, fungal structures were observed in the grain mass coming from the lower and middle thirds of the manually controlled silo, but no microbiological analyses were performed to classify these microorganisms. The presence of microorganisms may be associated with increased grain mass temperature and respiratory activity of sunflower grains (Mohapatra et al., 2017). It is worth pointing out that the aeration process was not performed during this period, as the average temperature in the silo ranged from 24.37 ± 0.62 to 27.16 ± 1.42°C, whereas the mean temperature and relative humidity of the external air were 25.01 ± 1.00°C and 70.31 ± 8.01%, respectively (Figure 2A). In other words, the climatic conditions did not favor the operation of the fans to cool the grains since there is a sensible heating of approximately 2°C of the air when it passes through the fan blades.

When evaluating the different regions within the same silo, it is not possible to observe a concrete trend in the thermometry data for the first 30 days of storage (Table 1). In the manually controlled silo, the upper third has a higher average grain temperature when compared with the other thirds; the opposite result is observed in the same period for the silo with sensors, in which the upper third showed a lower temperature. Grain temperature uniformity in silos is an important indicator of aeration performance (Li et al., 2020).

The uneven temperature at the beginning of storage in the manually controlled silo may be associated with the aeration

Table 1. Temperature (°C), moisture content (% w.b.), bulk density (ASM, kg m^{3}), and peroxide index (meq O_2 kg oil^{-1}) of sunflower grains stored for 90 days in silos with manually controlled aeration (silo 1) and silo with automatic aeration controllers (silo 2)*.

Time (days)	Silo	Third	Temperature (°C)	Moisture content (% w.b.)	ASM (kg m^{3})	Peroxide index (meq O_2 kg oil^{-1})
0	1	Upper	21.84a	5.45b	369.25^{a}	21.86b
		Middle	20.87b	6.64a	369.28^{a}	31.22b
		Lower	21.70ab	6.35a	366.24^{a}	57.92a
	2	Upper	15.58c	6.35b	376.84b	15.34b
		Middle	17.08b	6.70a	383.51^{a}	37.18a
		Lower	19.10a	6.51ab	373.94b	20.60b
30	1	Upper	25.32a	5.22c	380.15^{a}	21.76b
		Middle	21.50b	6.67a	376.22ab	14.59b
		Lower	22.11b	5.79b	371.73b	51.63a
	2	Upper	15.97c	5.93b	386.68ab	26.47a
		Middle	17.40b	6.62a	391.33^{a}	20.70a
		Lower	19.52a	6.37a	380.47b	30.40a
60	1	Upper	24.30b	4.91c	370.22^{a}	27.96a
		Middle	22.50c	6.30a	368.81^{a}	26.48a
		Lower	26.32a	5.78b	371.55^{a}	26.73a
	2	Upper	17.69b	5.67c	380.54b	29.63a
		Middle	17.63b	6.60a	393.35^{a}	24.80a
		Lower	20.24a	6.07b	365.86c	30.12a
90	1	Upper	26.26b	5.22b	365.57ab	38.80a
		Middle	25.22c	6.23a	370.42^{a}	30.00a
		Lower	29.98a	4.89c	359.59b	27.71a
	2	Upper	19.90b	6.10b	373.06b	26.66a
		Middle	17.92c	6.63a	390.28^{a}	24.43a
		Lower	21.22a	6.34ab	369.77b	20.68a

*Means followed by the same lowercase letter in the column for each silo at a given time do not differ from each other at a 5% significance level.

time, which was shorted in this silo and may have led to reduced cooling of the grains in the upper third (Table 1). In addition, the upper third has greater resistance to the passage of air due to the larger column of grains, which may have resulted in uneven aeration. As the depth of the grains decreases, there is a reduction in static pressure and greater ease for the passage of air; in addition, factors such as impurity content, airflow, and physical properties affect the static pressure and consequently the distribution of air (Goneli et al., 2020). At 60 and 90 days of storage (Table 1), the middle third had the lowest average grain temperature, and the lower third had the highest average in both silos.

Regarding the moisture content (Table 1), higher values were observed in the grains stored in the middle third of both silos from 30 days of storage, which may be associated with the maintenance of mild temperatures in this region inside the silo (Figure 2C). The automated silo had a lower mean temperature (Figure 2A) and, consequently, a higher average moisture content, 6.32 ± 0.27% (w.b.), along the entire storage period (Figure 3A). Low temperatures also minimize the risks associated with grain deterioration and dry matter losses (Lopes & Steidle Neto, 2019).

During storage, there was a reduction in moisture content at 30 and 60 days (Figure 3A) compared with the other times in the silo with automated aeration; however, the moisture content at the end of storage did not differ from the moisture content at the beginning of the monitored storage, although a reduction of 2.61% was observed. The moisture content of the grains in the manually controlled silo (Figure 3A) decreased linearly throughout storage, a result that was simultaneously proportional to the increase in temperature in this silo, and there was a linear increase in temperature during the period (Figure 2A). The mean moisture content in this silo was 5.79 ± 0.56% (w.b.), and the grains stored in this silo in general showed a reduction of up to 11.55% during storage.

Reductions in moisture content in stored products are directly proportional to the decrease in the total mass of stored

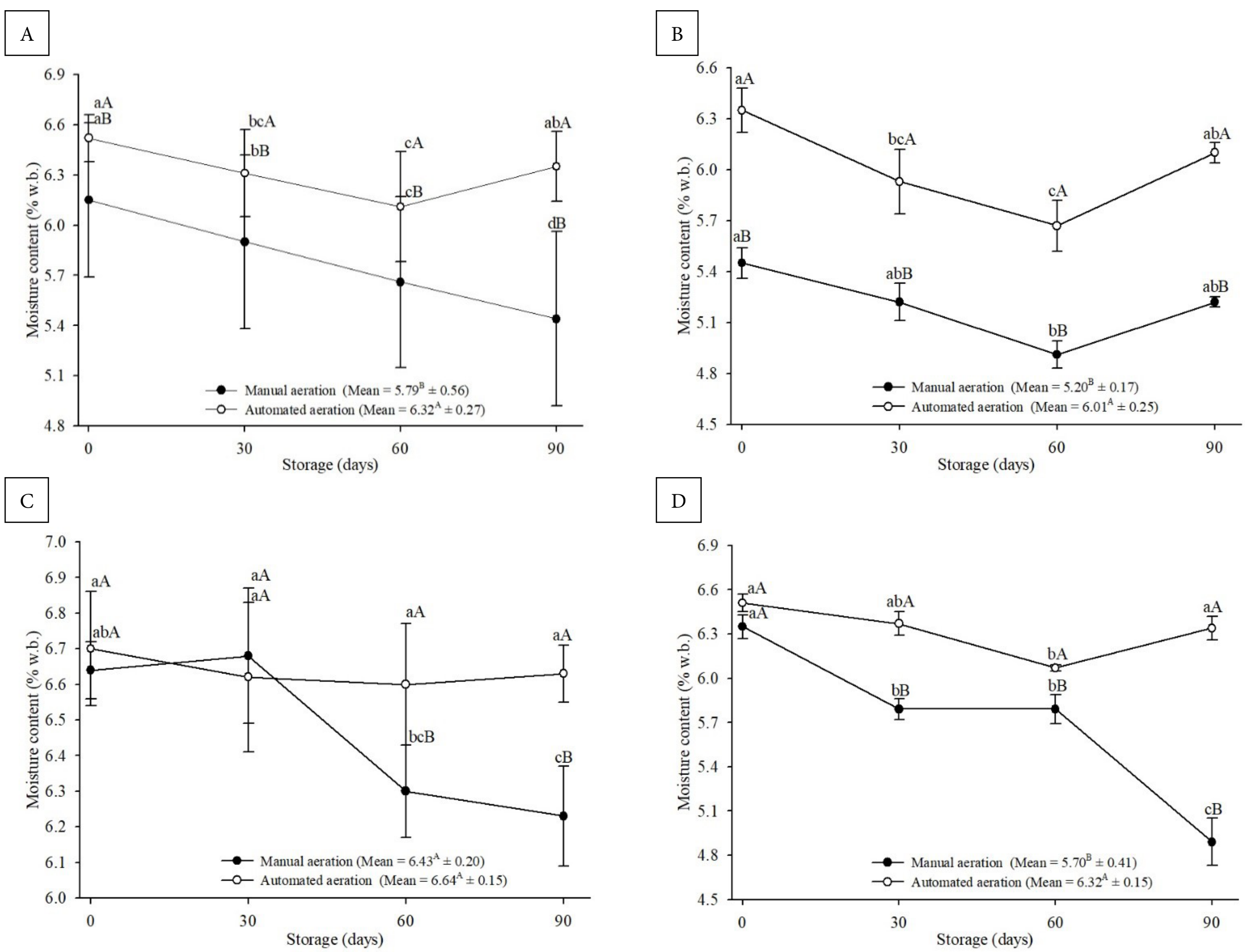

Figure 3. (A) Moisture content (% w.b.) of sunflower grains stored in metal silos with manual and automated aeration strategy. (B) Moisture content (% w.b.) of sunflower grains in the upper third of the silos during storage. (C) Moisture content (% w.b.) of sunflower grains in the middle third of the silos during storage. (D) Moisture content (% w.b.) of sunflower grains in the lower third of the silos during storage. Means followed by the same lowercase letter for each aeration strategy throughout storage and the same uppercase letter between the aeration strategies for each time do not differ from each other at a 5% significance level.

products. The reduction in moisture content with the increase in grain mass temperature was expected since, without aeration, the air around the grains would reach the equilibrium of temperature and relative humidity in a few days, reducing the equilibrium moisture content of the grains with the increase in temperature, for a constant relative humidity (Othman et al., 2017).

Regarding moisture content in the different thirds of the silo, it was observed that in the silo with automated aeration, the moisture contents were predominantly higher in all regions during storage, except for the initial moisture content in the lower and middle thirds, as well as the moisture content at 30 days in the middle third, which did not differ between the silos (Figures 2B, 2C, and 2D). These results indicate that the conditions of relative humidity of the intergranular air promoted a similar hygroscopic equilibrium in these grains since the temperature in these regions during the mentioned period differed (Figure 2C and 2D). Hygroscopic equilibrium is the phenomenon in which the temperature and relative humidity of the intergranular air influence the gain or loss of water in the product (Bustos-Vanegas et al., 2018; Campos et al., 2019; Mallek-Ayadi et al., 2020).

Reduction in moisture content was observed at 30 and 60 days for grains stored in the upper third of both silos (Figure 3B); however, the final moisture content of the grains of both silos did not differ from the moisture content of the grains at the beginning of storage. Grains stored in the middle third of the automated silo maintained their moisture content throughout the storage period (Figure 3C), the same behavior described for temperature in this silo (Figure 2C). Also, in the middle third, reductions in the moisture content of the grains were observed at 60 and 90 days of storage in the silo with manually controlled aeration, during which time there was an increase in grain mass temperature (Figure 2C).

The moisture content at the end of storage in the middle third of the manually controlled silo was 6.18% lower than the initial moisture content (Figure 3C), and this reduction in moisture content occurred due to the formation of heat pockets in the last fortnight of storage in this region of the silo, favoring the reduction of moisture content. The final moisture content also differed from the initial moisture content for grains stored in the lower third of the silo (Figure 3D). There was a reduction of 22.99% in the moisture content in this silo, which is justified by the increase of grain temperature in this region, approximately 7.87°C.

In the lower third, there was a reduction in moisture content at 60 days of storage in the automated silo (Figure 3D); however, in the following 30 days, there was an increase in moisture content, not differing from the moisture content at the beginning of storage. Such an increase is characteristic of changes in intergranular air, promoting the hygroscopic equilibrium of the grains (Campos et al., 2019). In relation to the grains stored in the lower third of the silo with thermocouples, there was a reduction in their moisture content during the first 30 days (Figure 3D), and this moisture content remained stable during the following 30 days, decreasing at the end of storage, as previously discussed.

Regarding the values of bulk density, which are presented in Figure 4 and Table 1, the silo with automated aeration stands out from the manually controlled silo, with overall averages of 380.47 ± 7.68 kg m^{-3} and 369.94 ± 4.23 kg m^{-3}, respectively (Figure 4A). From 60 days of storage (Table 1), higher values of bulk density were determined mainly for grains stored in the middle third of both silos, 389.62 ± 3.70 and 371.26 ± 3.41 kg m^{-3} for silos with automated and manual aeration, respectively (Figure 4C). This result may be associated with better conservation of the grains in this third, especially in relation to the moisture content (Figure 3C). Reduction of specific mass due to a decrease in moisture content has been reported for sunflower seeds (Smaniotto et al., 2017).

During the first 30 days of storage, there was an increase in the values of bulk density of the grains in both silos in general (Figure 4A), in the upper third (Figure 4B), and in the lower middle third (Figure 3C), with no significant increase in the lower thirds (Figure 3D). As no increase in the moisture content of the stored grains was observed during this period (Figure 3), the increase in specific mass observed at 30 days in both silos may be associated with sample heterogeneity or with instrumental or random factors during the execution of the test.

In the different thirds of the silos during storage, higher values of specific mass were observed in grains stored in the automated silo (Figure 4B–4D), which is directly related to the higher moisture contents (Smaniotto et al., 2017) obtained in the same silo (Figure 3B–3D), except for grains stored in the lower third of this silo at 60 days (Figure 4D), for which there was no intrinsic factors to be related to the high reduction in the bulk density observed in samples collected at this location in the silo.

It is worth pointing out that despite the predominant variation in the bulk density of the grains during storage, there was no difference in this variable when comparing the grains at the beginning and end of storage, both for the grains in general and for the grains evaluated in the three regions of the silos (Figure 4). It is important to highlight that the reduction in moisture content observed in the silo with manually controlled aeration (Figure 3) did not affect the bulk density of the sunflower grains. This behavior may be associated with a proportional reduction in the volume of the grains with the loss of mass (water) since when the moisture content influences the bulk density, this occurs because the change in mass is not directly proportional to the change in the volume of the grains (Bajpai et al., 2019).

The quality of the oil extracted from the stored grains is shown in Table 1 and Figure 5 through data related to the peroxide index. Table 1 shows that from 30 days of storage onward, this index stabilizes in the different thirds of the silo with automated aeration, not differing from each other, until the end of storage, and a similar result was observed from 60 days onward in the silo with thermocouples. Thus, for this variable, there was no evidence of a region inside the silo standing out for its conservation since the three regions proved to be efficient throughout the storage.

When evaluating the effect of grain storage in the two silos, it was observed that the peroxide index of the oil differed between the silos at the beginning and at the end of storage

(Figure 5A); oils extracted from grains stored in the silo with manually controlled aeration showed higher values for this index (31.39 ± 10.51 meq O_2 kg oil^{-1}). These results corroborate the temperature changes experienced by the grain mass of this silo, initially during the aeration management aimed at cooling; the grain mass heated up, exposing the product to a temperature increase of 2.67°C. Popa et al. (2017) defined that temperature has the greatest influence on the oxidation of sunflower oil, consequently leading to high peroxide values.

The values determined for the peroxide index in the present study exceeded the limit recommended in the Codex Alimentarius (1999) specifications for refined oil, which limits this index to 10 meq O_2 kg oil^{-1}. However, it should be noted that the oil extracted in the present study refers to the crude oil extracted from the whole grain. According to Lamas et al. (2018), crude sunflower oil must be refined before consumption in order to remove compounds that affect the sensory characteristics and stability of the product such as free fatty acids, color pigments, phospholipids, metals, and waxes. Many of these components are present in the seed coat, which was not removed for oil extraction in this study (Aluyor et al., 2009; Tinto et al., 2017).

The silo with automated aeration showed a lower average value for peroxide index, 25.58 ± 5.74 meq O_2 kg oil^{-1}, and similar results were observed in oils from grains stored in the lower third of the same silo. In general, the automated silo also showed lower average values for this index (Figure 5A), at 30 and 90 days of storage (Figure 5D). Such behavior was not observed for the oils from grains of the upper third (Figure 5B), except for the oil extracted at the end of storage and the middle third (Figure 5C), as the values obtained for this index did not differ between the silos during storage.

The oil extracted from grains stored in the upper third of the silo with automated aeration (Figure 5B) showed stability in terms of peroxide content, and the values did not differ from each other during storage. Such stability is also observed when evaluating all the grains of the automated silo (Figure 5A). Stability of this index is visualized during the first 60 days of grain storage in the silo with manually coordinated aeration

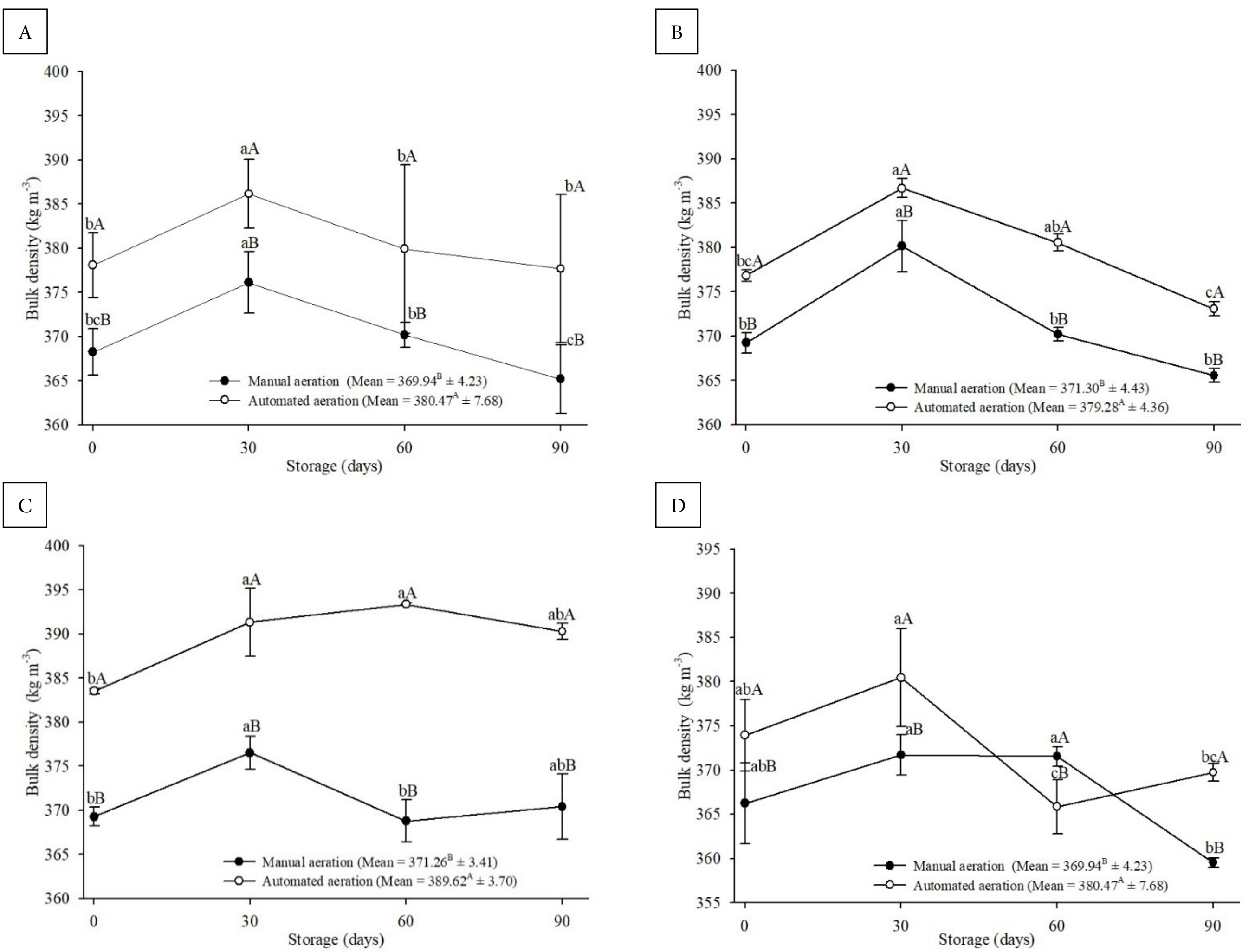

Figure 4. (A) Bulk density (kg m^{-3}) of sunflower grains stored in metal silos with manual and automated aeration strategy. (B) Bulk density (kg m^{-3}) of sunflower grains in the upper third of the silos during storage. (C) Apparent specific mass (kg m^{-3}) of sunflower grains in the middle third of the silos during storage. (D) Bulk density (kg m^{-3}) of sunflower grains in the lower third of the silos during storage. Means followed by the same lowercase letter for each aeration strategy throughout storage and the same uppercase letter between the aeration strategies for each time do not differ from each other at a 5% significance level.

(Figure 5B). At the end of storage, there was an increase in this index, which may be associated with instability in grain mass temperature (Figure 2B), with a sequence of increase, reduction, and increase in temperature, possibility resulting in lipid oxidation, which occurs through a set of autocatalytic reactions that produce many new compounds (Marmesat et al., 2009). When comparing the oils at the beginning and end of grain storage, differences between them were observed only in the upper third of the manually controlled silo (Figure 5).

Peroxide indices of oils extracted from the middle third of both silos decreased during the first 30 days of storage (Figure 5C), with some stability in the remaining storage period. In relation to the oil from grains stored in the lower third (Figure 5D), the peroxide index did not differ during the storage of the grains in the silos with automated aeration. On the other hand, there was a high increase in the peroxide index at 30 days of storage for the oil extracted from grains stored in the silo with manually controlled aeration, which is not attributed to the storage conditions, as the grains heated up in this region of the silo from 60 days onward (Figure 2D). Figure 5D shows that after 60 days, the peroxide index decreases and stabilizes until the end of the storage of these grains. The oxidation process is complex and dependent on the intensity of light and temperature (Popa et al., 2017). The alteration of the values obtained in the present study may be associated with the exposure of the grains and the extracted oil to ambient temperatures and light during the experiment.

Regarding the crude protein content (%) (Figure 6A), no influence of the evaluated treatments was identified, regardless of the manual or automated aeration strategy adopted in the silos, location of the grains inside the silo, and storage time. The crude protein contents determined for sunflower grains did not differ, with an average value of 16.34 ± 0.44%. It can be inferred that the average temperature of the grain mass was not sufficient to favor the denaturation of the protein content. Crude protein contents of unprocessed sunflower grains were

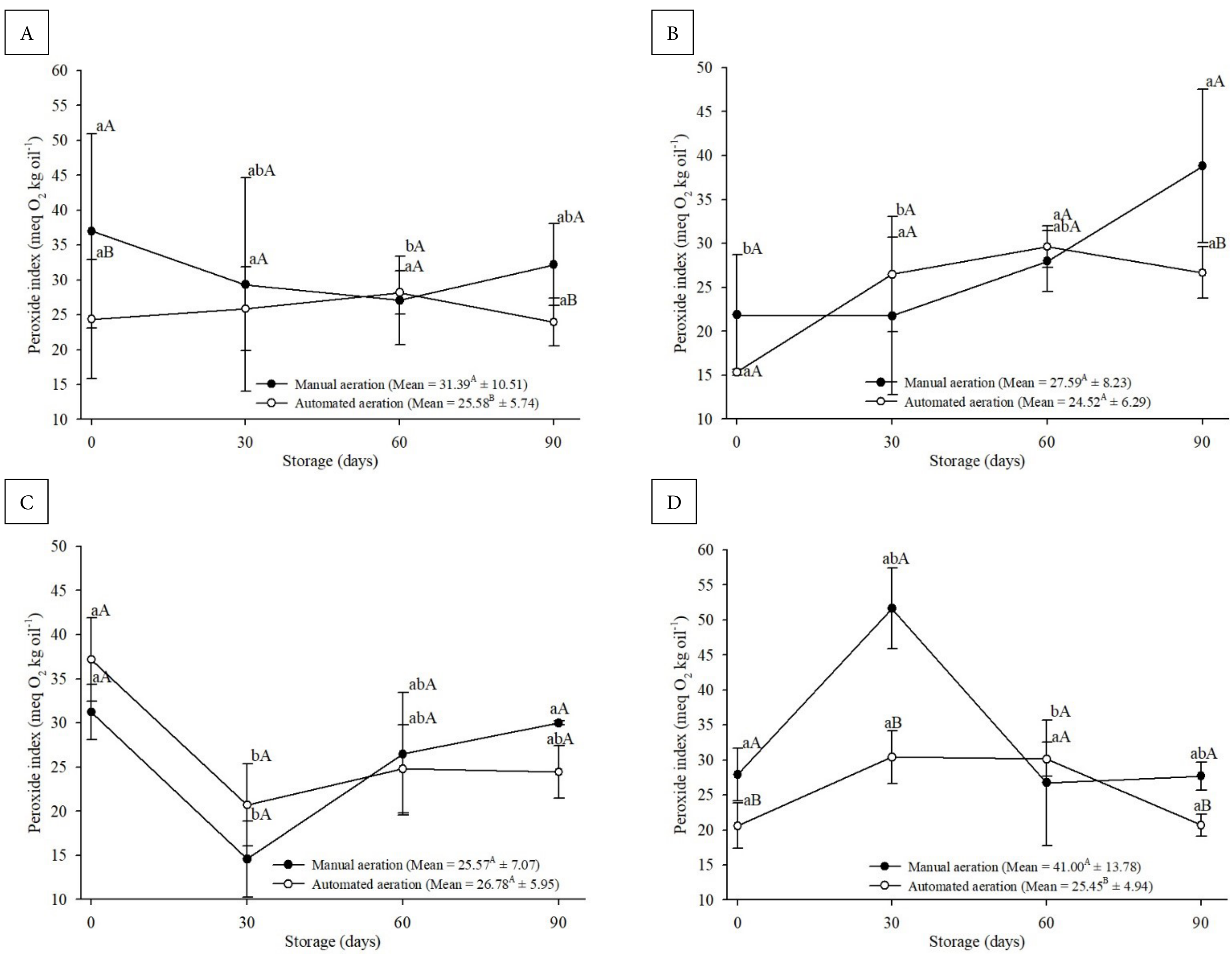

Figure 5. (A) Peroxide index (meq O_2 kg oil^{-1}) of sunflower grains stored in metal silos with manual and automated aeration strategy. (B) Peroxide index (meq O_2 kg oil^{-1}) of sunflower grains in the upper third of the silos during storage. (C) Peroxide index (meq O_2 kg oil^{-1}) of sunflower grains in the middle third of the silos during storage. (D) Peroxide index (meq O_2 kg oil^{-1}) of sunflower grains in the lower third of the silos during storage. Means followed by the same lowercase letter for each aeration strategy throughout storage and the same uppercase letter between the aeration strategies for each time do not differ from each other at a 5% significance level.

reported in the literature ranging from 17.09 to 27.02%, and for dry grains, this variation was between 12.10 and 20.28%; hence, it is possible to notice a reduction of protein content in dry grains with temperatures above 60°C (Adesina, 2018; Nascimento et al., 2018), a temperature range used for drying sunflower grains in storage units in Brazil.

Storage time had effects on oil content (%) (Figure 6B), acidity index (mg KOH g oil^{-1}) (Figure 6C), and iodine index (mg I_2 100 g oil^{-1}) (Figure 6D), that is, for these variables, the location of the grains inside the silo neither influenced the results nor was there any difference for these factors in the manual and automated aeration strategies, except for the acidity index (Figure 6C).

Regarding oil content (%), an increase was observed at 30 days of storage, which may have occurred due to the heterogeneity of the material. Sunflower grains contain between 24 and 52% of oil (Grunvald et al., 2014), and in the present study, the variation was from 39.45 ± 1.46% to 43.80 ± 1.42%. This difference may be associated with the different origins of the grains stored in the silos in relation to cultivars and regions. It can be observed that the oil contents decreased throughout storage, not differing from the oil content at the beginning of the period, as well as at 30 days. The reduction in oil content during storage is due to the respiratory activity of the grains, which consequently consumes and oxidizes reserve structures (Araujo & Barbedo, 2017). Different storage environments did not influence the lipid content of sunflower seeds (Abreu et al., 2013); however, a reduction in oil content was observed during the 12-month period. Coradi et al. (2017) indicated that there is a reduction in the lipid content of sunflower grains when the storage temperature increases from 20 to 30°C and relative humidity decreases from 60 to 40%, conditions that were not observed in the present study (Figure 2).

For the acidity index of the oil extracted from the stored sunflower grains, a reduction was observed at 60 days compared with 30 and 90 days of storage. However, the value found at 60 days did not differ from that of the oil extracted from the grains at the beginning of storage. The determined acidity index showed constant behavior during storage, compared with the index at the beginning of storage. Regarding the aeration strategies, in the silo with automated aeration, there was a lower

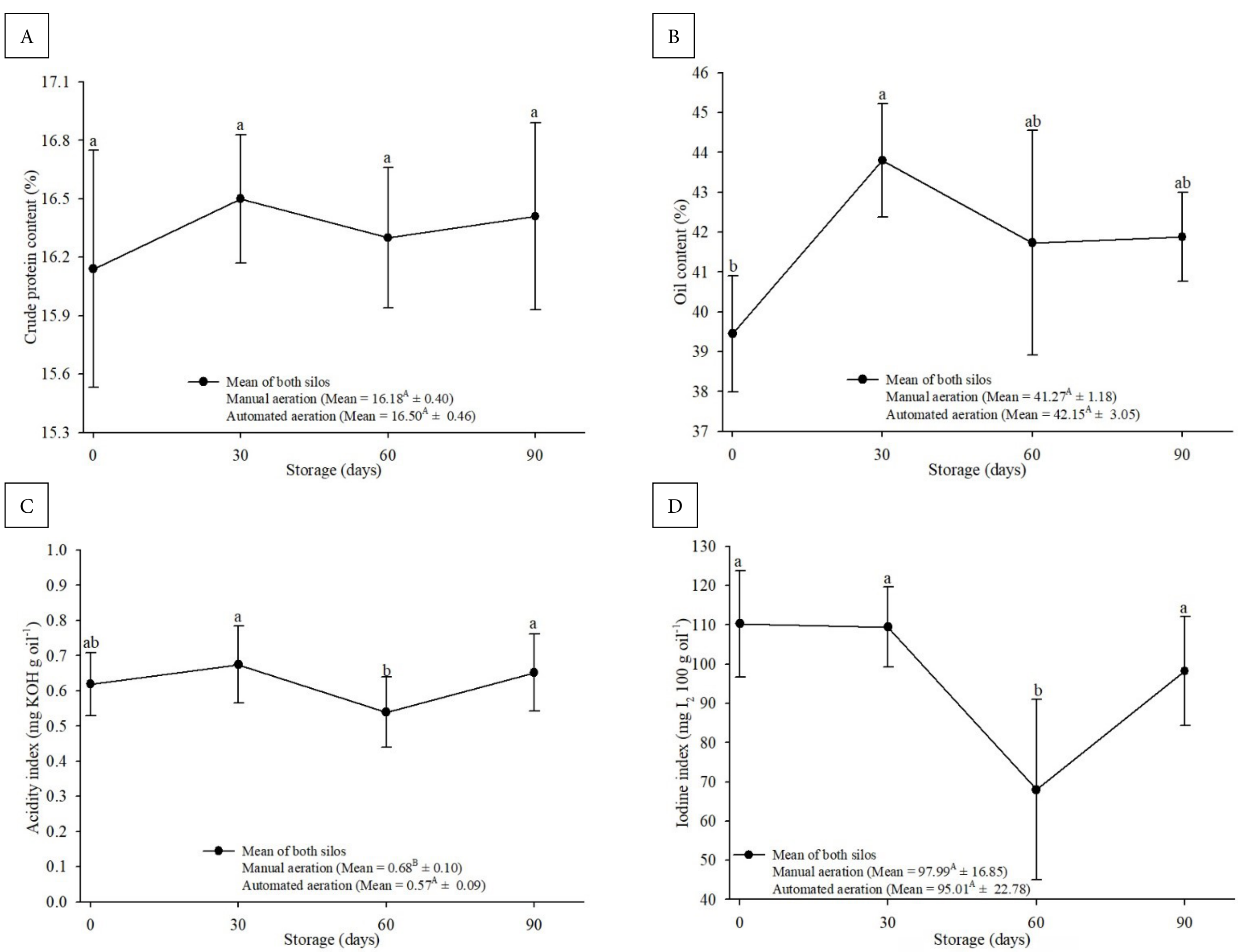

Figure 6. (A) Crude protein content (%), (B) oil content (%), (C) acidity index (mg KOH g oil^{-1}), and (D) iodine index (mg I_2 100 g oil^{-1}) of sunflower grains stored in metal silos with manual and automated aeration strategy. Means followed by the same lowercase letter between the aeration strategies for each time do not differ from each other at a 5% significance level.

value, 0.57 ± 0.09 mg KOH g oil^{-1}, when compared with the silo with manually controlled aeration, 0.68 ± 0.10 mg KOH g oil^{-1}, a difference that can be explained by the difference in the average temperature of the grains (Figure 2A). The influence of the increase in storage temperature on the increase in the acidity values of sunflower oil has been reported by Coradi et al. (2017) and Moureu et al. (2016).

The crude oil extracted from grains in the silo with manually controlled aeration showed an acidity index higher than the limit of 0.6 mg KOH g oil^{-1} for refined oils (Codex Alimentarius, 1999), indicating the need for processing. The mean acidity index during grain storage was also higher than the recommended limit, 0.62 ± 0.04 KOH g oil^{-1} (Figure 6C). Regarding the iodine index, the mean values were lower than those established for refined oils by the Codex Alimentarius (1999), of 118–141 mg I_2 and 100 g oil^{-1} (Figure 6D).

There was a reduction in the iodine index of the oil extracted from stored grains at 60 days of storage (Figure 6D); however, at the end of storage, the iodine index did not differ from the initial value. Therefore, the reduction in the iodine index can be attributed to intrinsic and extrinsic factors of the product. A decrease in iodine value is an indication of lipid oxidation (Naz et al., 2004). Influence of relative humidity on iodine index values during storage is described by Ajith et al. (2015), who found the highest index of lipid unsaturation of cashew nuts in storage with a relative humidity of 57%.

4 CONCLUSION

Using a thermometry system equipped with digital sensors contributes to automated aeration management. Automation of aeration contributes to making use of better climatic conditions to carry out the process, compared with the manual system used. The aeration strategies adopted (cooling and conservation) were efficient in reducing grain mass temperature in the automated process. The silo with automated aeration showed better conservation of the quality of the stored sunflower grains. The silo with manually controlled aeration showed an 11.55% reduction in moisture content. Grains stored in the middle third of the silo tend to have better quality.

ACKNOWLEDGMENTS

To the Instituto Federal Goiano (Process Number: 23218.003584.2023-20), PROCER, CARAMURU, EMBRAPII, CAPES, FAPEG, FINEP, and CNPq (Process Number: 310222/2021-4) for the indispensable support to conducting this study.

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