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Evolution of Industrial Quality Parameters of Wheat during Storage in White and Colored Silo Bags: A Field-Scale Study

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Abstract: Over the past two decades, the silo bag system has gained popularity for storing grains and by-products under hermetic conditions. However, the impact of higher temperatures in the outer grain layer on key industrial parameters, such as wheat baking quality, remains insufficiently understood. Traditional silo bags are black on the inside and white on the outside to reflect sunlight, but colored bags, recently introduced to the market, absorb more heat, potentially warming the grain and causing damage. This study aimed to assess the effect of grain strata and bag color on grain temperature and quality under field conditions. Results showed a significant surface temperature increase in colored bags compared to white ones, approximately 3 °C, which affected the temperature of the peripheral grain layer. Moisture content slightly increased (0.2 percentage points) in the outer grain layer. However, many industrial quality parameters (protein content, P/L, W, and loaf volume) and the germination test for wheat, showed no significant differences between colored and white bags or between different strata after 120 days of storage, although the falling number increased and wet gluten decreased. These findings suggest that, despite surface temperature differences, the overall industrial quality of wheat remains unaffected by external bag coloration. The influence of ambient temperature on the peripheral layer was estimated to affect approximately 5–10% of the grain mass, indicating that adverse impacts on grain quality may go unnoticed without implementing stratified sampling techniques.

Keywords: silo bag; wheat; industrial quality; seed viability; grain storage

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1. Introduction

The silo bag, also known as a grain bag, sausage bag, or silo bolsa, represents an innovative hermetic grain storage solution crafted from a plastic liner. Resembling a cylindrical tube, these bags come in various lengths and diameters, with the most common dimensions being approximately 60 m in length and 2.7 m in diameter. Remarkably, they boast a substantial holding capacity, capable of storing approximately 200 metric tons (T) of grains such as corn, wheat, barley, or soybean [1].

The use of silo bags for storing dry grains evolved from their use for anaerobic storage of chopped forages in the mid '90s in Argentina [2]. This novel storage system was massively adopted by the entire agricultural sector of the country, including farmers, grain elevators, grain processing industries, and even ports. In 1997, less than 1 million T per year of different grains were stored in silo bags in Argentina; a few years later, in 2003, this figure increased to more than 10 million T; and since 2015, between 40 and 55 million T are being stored [1]. Today, silo bags are used for storing feed grains, industrial grains, specialty grains, organic grains, seeds, and other products of different kinds [3–6]. Silo bags have garnered widespread adoption not only in Argentina but also in over 50 countries across diverse climatic zones. From tropical regions like Brazil, Colombia, Ecuador, and

Central America, to temperate climates found in Australia, South Africa, Chile, the United States, and Turkey, as well as cold climates represented by Canada, Russia, Ukraine, and others, silo bags have proven their versatility and effectiveness in safeguarding grain stocks worldwide [7].

Throughout storage, the interplay between grain temperature, moisture content (MC), and internal atmosphere significantly influences biological activity, thereby impacting the quality of the grain. The temperature of the grain within the bag at any given moment is contingent upon various factors, including its initial temperature at the time of bagging (with diminishing influence over time), solar radiation exposure, heat emissions from biotic respiration, and thermal exchange with the ambient air and the soil upon which the bag is laying [8]. Previous studies have established key insights regarding temperature dynamics. Firstly, the temperature at the top grain layer (0.1 m depth) follows the distinctive pattern of the ambient air temperature, reaching its maximum at noon and minimum during the early morning [5,9]. The daily temperature oscillation decreased with the grain depth, being not noticeable at 0.4 m from the surface [10]. Secondly, bulk grain temperature decreases from summer to winter and rises from winter to summer, gradually aligning with the prevailing ambient temperature of each season [5,6,9–11].

Temperature fluctuations lead to corresponding variations in equilibrium relative humidity (r.h.). Consequently, near the surface of the bag, there is a notable daily oscillation of equilibrium r.h., whereas towards the center of the bag, this variability remains relatively stable [9]. The dynamics of heat and moisture transfer during grain storage in silo bags were investigated using modeling techniques. It was determined that temperature oscillations in the external layer, coupled with the temperature differential between the top layer and the bulk of the bag, facilitated the migration of moisture from the core of the grain mass towards the uppermost layer [8]. This finding holds significance as pronounced moisture migration poses a heightened risk of localized grain spoilage and deterioration in grain quality. Studies conducted across different grains and storage conditions, including barley [10], peanuts [12], and sunflowers [5], have provided evidence of moisture migration. This suggests that grains with slightly elevated moisture content (experiencing high equilibrium r.h. conditions) and those with bulkier characteristics are more likely to exhibit the phenomenon of moisture migration. On the contrary, empirical studies [5,11,13] and simulation research [8] have suggested that storing dry grain (with an equilibrium r.h. below 65%) does not result in discernible moisture migration within a storage duration of up to one year.

While previous studies have demonstrated the efficacy of silo bags in preserving commercial grain quality over extended periods of storage time [1], a thorough comprehension of the interplay between heightened temperature conditions in the outermost layer of grains, coupled with potential moisture migration, and their impact on critical industrial metrics—such as wheat baking quality and seed viability—remains incomplete.

Traditional silo bags typically feature an internal black and an external white coloration, strategically chosen to optimize solar radiation reflection. However, recent market innovations have introduced externally colored silo bags, intended to distinguish products based on specific attributes. For instance, pink bags symbolize support for breast cancer research [14]. It is well-established that darker surfaces, such as pink plastic, absorb more solar energy, resulting in higher temperatures, whereas lighter surfaces, like white plastic, reflect more light, leading to lower temperatures. Consequently, pigmented liners possess an increased capacity to absorb solar radiation, thereby elevating temperatures within the outermost layer of stored grain.

Consequently, while substantial evidence supports the notion that grains can be stored in silo bags without significant quality issues, certain findings suggest a potential negative impact on the outer layer. The variables contributing to quality degradation include the manifestation of thermal amplitude, which, over time, induces increased humidity within the surface layer due to migration from internal layers, thereby fostering a localized increase in biological activity. Moreover, direct temperature effects are noteworthy, as specific quality attributes may be compromised upon surpassing certain temperature thresholds. This latter consideration assumes particular significance with the advent of pigmented liners for silo bags on the market, which could potentially elevate temperatures to levels detrimental to certain wheat quality attributes, such as the functional properties of proteins or seed viability. Collectively, these aspects still need to be comprehensively evaluated under full-scale field storage conditions to provide appropriate management recommendations to silo bag users. As a result, the main goals of this field-scale investigation were: (1) to evaluate the effect of temperature fluctuations on the industrial quality of wheat across various strata within the silo bag; and (2) to assess the consequences of externally coloring the outer layer of the silo bag on grain temperature and its subsequent implications for industrial quality.

2. Materials and Methods

The silo bags utilized in this study were standard bags commonly employed by farmers. These silo bags are engineered to exhibit a blend of mechanical properties, including puncture resistance, tear resistance, elasticity, and ductility. These properties are achieved by incorporating a combination of nonlinear low-density polyethylene (NLDPE) and linear low-density polyethylene (LLDPE) in their construction. The plastic liner, typically 230 microns thick, comprises 3–5 layers. As previously mentioned, the outermost layer typically contains titanium dioxide to impart a white color, thereby reflecting most solar radiation, while some innovations incorporate pigments in this layer for marketing purposes. However, the innermost layer always includes a black pigment to prevent translucency. Additional additives confer ultraviolet light protection and enhance sliding properties during the grain bagging process, among other functional characteristics [15]. No published data exists regarding the heat transfer coefficient for silo bag liners. However, an internal company report suggests that the thermal conductivity of low-density polyethylene is approximately 0.34 W/(m K) at 20 °C. The gas permeance of the liner is crucial for the effective application of modified and controlled atmosphere treatments. Permeance is defined as the gas transmission rate relative to the difference in gas partial pressure across the liner. Gas permeability of a new silo bag liner was measured in field conditions, obtaining permeance values of 8.29×10^{-3} and 91.95×10^{-3} $m^3/(d\ m^2\ atm)$ for O_2 and CO_2, respectively, assuming a thickness of 235 microns [16]. No specific water vapor permeability coefficients have been reported for silo bag films. Nonetheless, for reference, a permeance of 16.17 $g/(m^2\ d\ atm)$ was reported for a 230-micron-thick LDPE film [17]. Practically, this level of water vapor permeance is sufficiently low to prevent significant grain moisture variation during storage.

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The field study took place on commercial farms in the Tandil area, located in the southeastern part of Buenos Aires province, Argentina. It began during the summer crop harvest season (December–January) and continued until the typical selling period, which is approximately 120 days later. Wheat (*Triticum aestivum* L.) was harvested on each farm and immediately transferred from the combine or auxiliary grain cart directly into bags with moisture content (MC) levels of approximately 12%. Overall, on all farms, the grain was in excellent condition, without evidence of mold or insect activity. The experiment was structured as a completely randomized block design across 5 different farms or locations. Each farm grew different wheat varieties for the trial, potentially impacting the results. Additionally, varying agronomic conditions at each farm could also influence the outcomes. To account for these differences, the experimental design treated each farm as a separate block in the analysis.

The study focused on factors such as bag colors (white and pink), different grain layers within each bag (periphery and interior), and sampling dates (0, 30, and 120 days). The silo bags used were standard white and pink ones (IPESA SA, Argentina), each with a diameter of 2.7 m and a length of 60 m, capable of holding approximately 200 metric tons of wheat. At each location, one pink and one white bag were placed side by side for direct comparison (Figure 1). A total of 60 samples (5 farms × 2 colors × 2 layers × 3 dates) were collected for quality assessments, except for the germination test, which included an additional sampling at 200 days, totaling 80 samples.

Figure 1. Experimental site showing paired white and pink silo bags used in the field trial.

The bags were assembled according to INTA recommendations [18] in an elevated, clean field (free of rocks, stubble, and weeds), to prevent tears at the base of the bag and with a slight slope to prevent the entry of rainwater. Furthermore, bag sealing was performed using a heat-sealing device (La Pipiola, Buenos Aires, Argentina). Although the airtightness of the silo bag was not assessed in the current study, it has been documented that a silo bag constructed by an experienced user (as the one in this study) following standard precautions can achieve high levels of tightness [19]. This is evidenced by a pressure decay test (PDT) duration exceeding 5 min, appropriate for conducting controlled atmosphere treatments [20].

Grain samples were collected with a torpedo probe, inserting it towards the bottom and center of the bag. Sampling was conducted in two strata, one upper, aiming to take a layer of approximately 0.05 m below the surface of the bag (exposed to external temperature fluctuation), and the other covering the rest of the bag's profile. One sampling location per bag was considered, approximately at the center along the bag length. Grain samples were placed in double plastic bags, hermetically sealed, and immediately sent for analysis.

In a pair of white and pink bags from one location, temperature was registered every hour with integrated data loggers (Hobo, Onset Computer Corporation, Bourne, MA, USA) inserted with a wooden stick at 0.05 and 0.80 m from the surface. An additional data logger was placed outside, on the bag surface, to register ambient temperature conditions (sheltered from direct solar radiation). Additionally, the temperature at the surface of the plastic linear was measured with an infrared thermometer (TFA, Flash III, Germany) at standardized radial locations of the white and pink bags. Temperature readings on the liner were consistently taken at noon to minimize the impact of sunlight variations throughout the day. Carbon dioxide concentrations were measured approximately every two weeks at the grain sampling location of each bag using a portable gas analyzer (Silcheck, Junín, Argentina) [21].

The wheat quality tests were carried out at the Laboratory of Industrial Grain Quality of the Chacra Experimental Integrada Barrow (Ministerio de Desarrollo Agrario—Instituto Nacional de Tecnología Agropecuaria) in Tres Arroyos, Buenos Aires, Argentina. The equipment and procedures used for each quality parameter were extensively described in a previous study [22], and are summarized as follows: grain test weight (kg/hl) was determined using a Schopper device (SAGPyA 1262/04). Wheat protein (%) was assessed using rapid methods based on near-infrared transmittance (NIRT) (Foss, DS 2500). Moisture content (%) was determined by initial milling followed by drying at 130 ± 3 °C under normal pressure in an oven with forced air circulation (Ionomex, Argentina) for 1 h (IRAM 15850: 2009). Falling number (s) was measured to assess flour alpha-amylase activity, indicative of fermentative capacity during baking (Falling Number, Mod. 1400) (IRAM 15.862:2003). Wet gluten (%) was determined using a glutomatic system (Perten Instruments, Stockholm, Sweden), followed by assessing gluten characteristics using a gluten index centrifuge (IRAM 15.864-2:2013). The alveograph test measured the resistance to deformation and extensibility of dough test pieces with a certain thickness, generating alveograms that indicate deformation energy (W) and the tenacity/extensibility ratio (P/L) determining dough equilibrium (Chopin Technology, Alveograph Model MA95, Villeneuve-la-Garenne, France) (IRAM 15.857:2012). The loaf volume was determined by making a standardized bread and measuring its volume with the rapeseed (*Brassica campestris* L.) displacement method.

Germination tests were carried out at the Seed Quality Lab of the Instituto de Innovación para la Producción Agropecuaria y el Desarrollo Sostenible (INTA-CONICET) at Balcarce, according to the International Seed Testing Association recommendations [23]. Briefly, 400 seeds from each sample were sown in four trays (100 seeds each) in moist river sand and placed in plastic bags to prevent drying. The trays were placed in a chamber with alternating temperatures (20–30 °C, 16–8 h) and a photoperiod of 8 h light and 16 h darkness for 7 days. At the end, normal seedlings were counted, and the results were expressed as a percentage of the total seeds sown.

Statistical analysis was conducted using the R program [24]. An analysis of variance (ANOVA, α = 0.05%) was conducted for quality parameters. Model assumptions were assessed using diagnostic plots. The germination rate (binomial distribution) was analyzed through a generalized linear model, followed by a deviance analysis (α = 0.05%). Post-hoc comparisons of means were performed using Tukey's test.

3. Results

3.1. Temperature of the Plastic Liner

The liner temperature was significantly influenced by storage time and bag color, with no observed interaction between these factors. On average, the external liner temperature of pink bags (30.2 °C) was 3 °C higher than that of white bags (27.1 °C) (Table 1). The impact of storage time on temperature was also evident in Table 1, showcasing a decline in the temperature measured on the liner surface from 39.1 °C in January to 10.0 °C in June.

Table 1. Temperature measurements of the plastic liner in silo bags, captured using an infrared thermometer at midday, compared between white and pink bags across various dates, and farms. Capitalized letters indicate significant differences within bag color and small letters within storage time ($\alpha = 0.05$).

Level	Mean	SE	Group
Color of the bag			
White	27.1	0.944	A
Pink	30.2	0.944	B
Storage time			
January	39.1	0.968	a
February	38.0	1.400	ab
March	32.6	0.479	b
April	18.7	2.266	c
June	10.0	0.960	c

3.2. Ambient and Grain Temperature Evolution

During storage, the ambient temperature reached its peak approximately mid-day and reached its lowest point at sunrise, as depicted in Figure 2. Over time, from early summer (January) to early winter (June), the average ambient temperature decreased from 25 °C to approximately 5 °C. Similarly, the temperature at the outermost layer of the grain (grain periphery 0.05 m) followed the same daily temperature pattern as the ambient (note that the "ambient" temperature line is overlapped with the "grain periphery" temperature). The peripheral grain layer of the pink bag was notably more influenced by the ambient temperature than the grain in the white bag. However, within the bag (at a depth of 0.80 m), the temperature of the grain did not fluctuate daily but steadily decreased from 37 °C in summer to slightly below 20 °C in winter for the pink bag and from 32 °C to 20 °C in the white bag. The initial differences in grain temperature between the pink and white bags (37 °C and 32 °C, respectively) could be attributed to variations in the initial grain temperature at harvest. Although both bags were filled on the same day, differing ambient temperatures throughout the day resulted in varying temperatures in the harvested grain.

The impact of liner color on grain temperature was investigated by obtaining the maximum daily temperature from the dataset illustrated in Figure 2, and a comparison was made between the ambient temperature and the grain temperature at the peripheral layer for the white and pink bags, revealing that the maximum temperature of the grain at the peripheral layer of the pink bag was similar to the ambient temperature (22.7 °C and 23.3 °C, respectively), while the peripheral grain layer in the white bag was approximately 3 °C colder (19.9 °C), as shown in Table 2.

Table 2. Average maximum daily temperature during storage measured at the exterior (ambient) and at the grain periphery (0.05 m inside the grain mass) of the white and pink silo bags. Different letters indicate significant differences ($\alpha = 0.05$).

Color	Position	Mean	SE	Group
White	Periphery	19.9	0.438	A
Pink	Periphery	22.7	0.438	B
Exterior		23.3	0.438	B

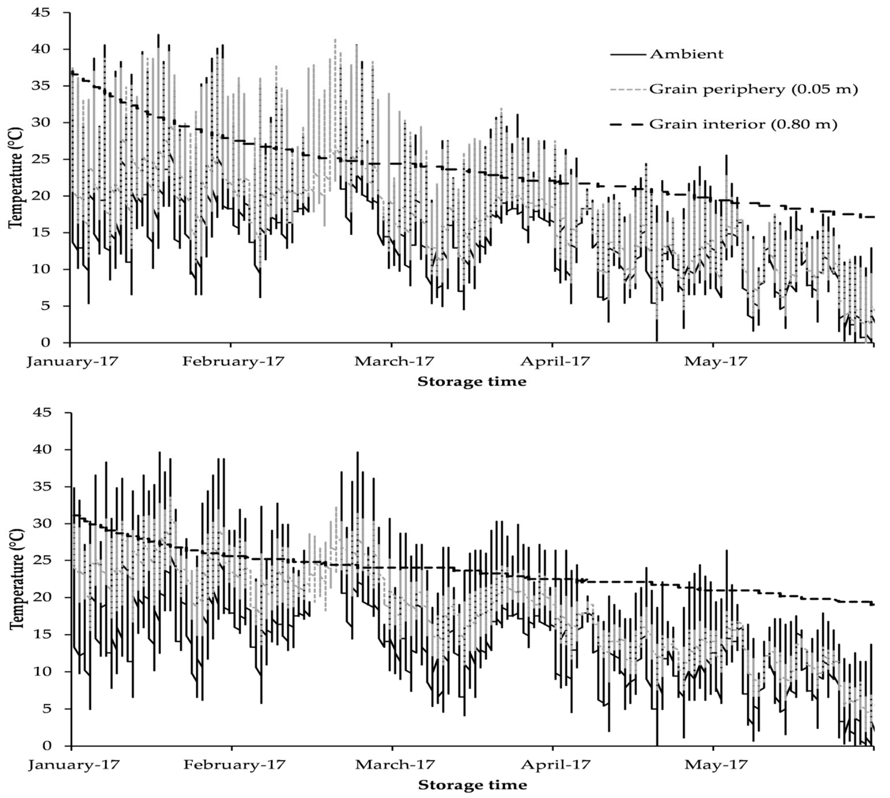

Figure 2. Temperature changes throughout the seasons in wheat silo bags with pink (**top**) and white (**bottom**) liners at the upper grain layer (grain periphery 0.05 m), the interior of the silo bag (grain interior 0.80 m), and the ambient temperature.

3.3. Carbon Dioxide Concentration

The evolution of the internal atmosphere was similar in both bag colors (Figure 3). During the first two weeks of storage, CO_2 concentrations in all bags remained below 3%, subsequently increasing steadily with storage time until April, reaching average values of approximately 6 in the white bags and 8% in the colored bags, with some absolute values reaching 15%. From April to June, CO_2 concentrations gradually decreased to approximately 5%.

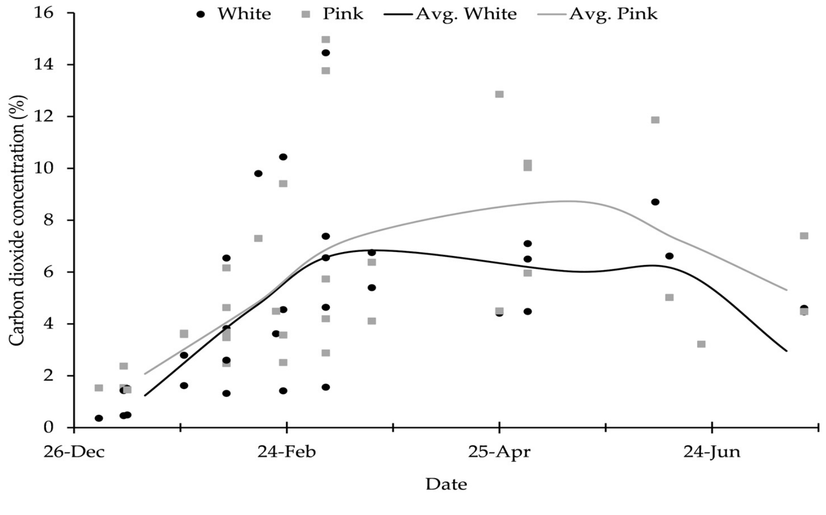

Figure 3. Carbon dioxide concentration in white and colored silo bags containing dry wheat. Dots represent individual measurements, and lines indicate the average values for each month across all bags of the same color.

3.4. Industrial Quality

Bag color did not adversely affect any of the examined quality parameters, while stratum had only a minor influence on moisture content, leading to a slight increase of 0.2 percentage points. The duration of storage had a significant impact solely on the wet gluten percentage and falling number. The wet gluten percentage remained stable during the initial 30 days but declined from 24.6% to 22.4% between days 30 and 120. Conversely, the falling number consistently increased from 376 sec to 421 sec from day 0 to day 120. All other parameters, including test weight, protein content, W value, P/L ratio, loaf volume, and germination test, remained unchanged throughout the strata and storage period (Table 3).

Table 3. Effect of strata and storage time on quality parameters of wheat stored in silo bags. Different letters indicate significant differences ($\alpha = 0.05$) within the same quality parameter and factor.

Parameter	Factor	Level	Mean	SE	Significance
Moisture content	Stratum	Interior	11.3	0.17	A
		Periphery	11.5	0.17	B
Falling number	Time	0	376	4.6	A
		30	407	4.6	AB
		120	421	7.8	B
Wet gluten	Time	0	24.8	0.72	A
		30	24.6	0.72	A
		120	22.4	0.72	B
Test weight			80.3	0.17	
Protein			10.9	0.17	
W			223.9	8.96	
P/L			2.2	0.15	
Loaf volume			506.4	6.35	
Germination test			97.1	0.22	

4. Discussion

4.1. Liner Temperature Evolution

As expected, the temperature of the plastic liner was significantly influenced by storage time. This temperature change results from heat exchange with ambient air and solar radiation. Over the transition from summer to fall and winter, both ambient temperature and solar radiation decreased, causing a reduction in the plastic liner temperature inside the silo bag from 39.1 °C in January to 10.0 °C in June.

Bag color also affected the liner temperature, with pink bags showing an average external liner temperature 3 °C higher than white bags. This temperature difference is due to the higher solar radiation absorption of pink bags caused by their pigment composition, contrasting with the greater solar radiation reflection seen in white bags. While there was no interaction observed between bag color and time, the temperature difference between white and colored bags remained consistent throughout the seasons, albeit with a slight reduction in the temperature gap towards winter.

Previous research has extensively compared solar radiation absorption between plastic liners with colored pigments and white colors [25–27]. These studies have highlighted that pigments with high near-infrared solar absorptance contribute to temperature increases. Conversely, white or clear pigments with high near-infrared solar reflectance minimize temperature increases. Notably, white pigments such as titanium dioxide (TiO_2), which gives the standard silo bag its white color, are known for their high solar reflectance properties [27], effectively maintaining cooler temperatures in the standard white silo bag liner compared to other pigments used for coloration.

4.2. Grain Temperature Evolution

The grain temperature at the periphery of pink bags closely followed ambient temperatures, while grains in white bags remained slightly cooler. These findings suggest that grains stored in colored bags may experience a higher temperature regime, particularly at the outermost layer, compared to those stored in white bags. This temperature difference can be critical for storing products where temperature significantly influences quality parameters, such as seed viability [28,29].

The outermost grain layer, located at a depth of 0.05 m from the silo bag surface (grain periphery), experiences daily temperature fluctuations influenced by ambient conditions. However, these fluctuations decrease with increasing grain depth, becoming imperceptible at the center of the silo bag (at 0.80 m depth). This observation aligns with findings from previous studies conducted under various grain types and climate conditions [1,30]. Consistent with earlier research, our study shows that grain temperature follows a seasonal pattern reflecting changes in ambient temperature. Specifically, temperatures decreased from 25 °C to approximately 5 °C at the peripheral layer as summer transitioned to winter. Similarly, temperatures within the bag's interior (at 0.80 m depth) decreased from above 30 °C (after bagging) to below 20 °C over the same period. These findings emphasize the influence of external environmental conditions on grain temperature dynamics within the silo bag, a crucial consideration when extrapolating results to regions with different temperature regimes.

4.3. Industrial Quality

The industrial quality of grains is influenced by various factors, such as genotype, climate during growth, agronomic practices, and storage conditions [31]. Specifically, grain moisture content, relative humidity, temperature regimes, and storage duration play crucial roles in determining industrial grain quality. While differences in temperature were observed in the outer layer of the pink bag, the bag's color did not significantly impact any wheat quality parameters. Strata did exhibit a minor but noteworthy effect on moisture, leading to an increase of 0.2 percentage points. Previous research has shown that temperature differences between the outer and inner sections of the bag prompt moisture movement from the grain core toward the upper layer [1]. The moisture content of the grain, coupled with temperature fluctuations and storage time, are critical factors determining the extent of moisture stratification [6,8]. In our study, the initially low level of moisture prevented significant moisture migration. However, a more noticeable increase in moisture in the outer grain layer would be expected if the grain had an initial higher moisture content (i.e., 14%), was stored for longer than 120 days, or was exposed to higher temperature fluctuations.

After 120 days of storage, most wheat quality parameters were not negatively impacted; in fact, their values either remained stable or slightly increased. The only parameters that were adversely affected were falling numbers and wet gluten content. The safe storage moisture content for wheat is approximately 14% [32]. In the present study, the storage conditions maintained a moisture level of approximately 12%, which is well below the threshold for microbial activity. Barley's respiration rate under these storage conditions (moisture content of approximately 12% and temperature between 15 and 35 °C) ranges from 0.0451 to 0.5461 mg CO_2/(kgDM day) [33]. Given the similar composition of wheat and barley, it can be inferred that the respiration rate of wheat is likely similar to that of barley. A dry matter loss of 0.1% was considered the threshold for commercial damage to wheat, and if stored wheat is to be used as seed, the approximate limit for safe storage is 0.04% [34]. Achieving a 0.04% dry matter loss under the present study conditions would take more than 450 days [33]. The low respiration rate and consequently low dry matter loss imply that no significant changes in physical or compositional parameters should be expected during storage.

The slight increase in moisture within the upper grain layer, combined with the modest temperature impact discussed earlier, helped avoid negative effects on quality parameters. The industrial and rheological properties of wheat, such as W, P/L, and loaf volume, remained unchanged during storage. These findings align with previous studies on dry wheat stored in silo bags [5]. Likewise, there was no notable change observed in the germination results, with values remaining unaffected (>98%) after 200 days. A similar study was carried out for barley storage, and no effect on seed viability was observed either. Seed viability, closely tied to enzyme activity in the embryo, is among the most sensitive parameters to harsh storage conditions [28]. Prior studies have consistently shown that storing wheat and barley in silo bags at approximately 12% moisture does not negatively affect seed viability [5,13,35], highlighting the feasibility of using silo bag technology for malting barley and seed storage. It is noteworthy that no adverse effects on quality were specifically noted in the outer grain layers (no layering effect).

However, contrasting results were observed for the falling number, which increased, suggesting a change in enzymatic activity related to starch degradation during storage. Additionally, wet gluten decreased, indicating potential damage to the structural function of wheat proteins. Similar trends were observed in studies evaluating storage time in metal bins [36], where the authors hypothesized that the cause was the fluctuation in moisture and temperature during storage. The effect on falling numbers disagrees with the lack of effect on germination, since both parameters are related to enzymatic activity. However, previous studies suggested that the germination test sometimes does not have enough sensitivity to detect small changes, and a vigor test could have been more appropriate [28]. The decrease in wet gluten content, on the contrary, is more difficult to explain since it implies changes in the structure of the protein. Usually, these changes occur at a higher moisture content and temperature regime than the one observed in the present study [31]. Furthermore, one might have expected changes in the alveograph results (W, P/L) and loaf volume to correspond with the reduction in wet gluten content, but this was not observed. Therefore, another plausible explanation is that the decrease in wet gluten could be attributed to a sampling or methodological error.

It is important to note that in the present study, wheat was stored dry, substantially below the threshold for biological activity. Higher moisture content could increase susceptibility to temperature damage, potentially impacting temperature-sensitive parameters [29,30]. Another critical point to consider is that while this study encompassed most of the summer period with its high-temperature regime, it was limited to a duration of 120 days. These aspects are vital for extrapolating information about grain storage in silo bags to regions with higher temperature regimes, significantly wider temperature fluctuations, or considerably longer storage periods.

4.4. Carbon Dioxyde Evolution

The CO_2 concentration inside the silo bags exhibited a similar pattern in both white and colored bags. The initial rise in CO_2 concentration was attributed to accumulated respiration, which elevated CO_2 levels, thereby creating a modified atmosphere. The concentration inside the silo bags reflects a dynamic equilibrium between the respiration rate (CO_2 generation) and the permeability rate (CO_2 loss to the ambient) [1]. Consequently, the CO_2 concentration plateaued at approximately 6–8% in April. There was a slight tendency for higher readings in the colored bags, approximately 2 percentage points higher, which could be attributed to increased biological activity resulting from the higher temperature in the peripheral layer (Table 2). As storage continued into winter and the temperature of the stored grain decreased (Figure 2), the respiration rate declined [37], resulting in a lower equilibrium CO_2 concentration of approximately 3–5% by the end of June. A previous study reported similar CO_2 concentration values in wheat silo bags rated as being in good condition [38]. Therefore, based on the CO_2 readings, it can be inferred that the average grain condition in the silo bags of the present study was good, with no substantial effect on the quality expected. Conversely, in February, some individual CO_2 values reached 15% (Figure 3), likely due to localized spots of increased biological activity from water leakage through a perforation in the liner [38]. This water leakage was sufficient to alter the internal atmosphere but did not affect the overall grain quality.

4.5. Practical Implications

The results of this study have significant practical implications for the monitoring of silo bags. The border effect, marked by greater temperature fluctuations and potentially harmful daily maximums, might extend 0.05–0.10 m into the grain mass, affecting between 5% and 10% of the volume (estimation assumed that the silo bag is a cylinder with a diameter of 2.7 m, with 70% of its surface exposed to ambient air fluctuations and 30% in contact with the soil). Consequently, sampling the entire grain mass with a standard probe might not detect quality issues, as the affected portion of grain is minimal and would be diluted in the average sample. To effectively monitor storage conditions and promptly detect quality losses, it is recommended to perform differential sampling by separating the upper stratum (5–10 cm) from the rest of the grain. This approach is particularly important in warm weather conditions, especially when the quality attribute that needs to be preserved is sensitive to heat damage, such as seed viability or the functional properties of proteins.

4.6. Future Research Recommendation

Based on the results of the present study, it was determined that pigmented bags absorb a greater amount of solar radiation, leading to a differential increase in temperature in the outer layers of the grain. To accurately quantify the extent of this differential radiation absorption in colored bags, it is recommended to conduct laboratory-scale tests under controlled conditions. Additionally, further studies should investigate the impact of this differential radiation absorption on the properties of the liner. The current study also confirmed a differential temperature regime in the grain of the peripheral layer, with maximum temperature peaks higher than those in the grain at the center of the bag. Furthermore, these maximum temperature peaks were higher in pigmented bags. Despite this, no negative effects on grain quality were observed under the field-scale study conditions, except for an increase in falling number values and a reduction in the quantity of wet gluten. To further elucidate this aspect, it is proposed to conduct controlled laboratory studies on grains under conditions that replicate the various scenarios within the bag. Specifically, this involves replicating the temperature cycle experienced by the peripheral layer and contrasting it with the constant temperatures inside the bag. This investigation should also consider different moisture contents to establish a correlation between storage conditions (temperature regime and moisture content) and the industrial quality of wheat. These correlations could be incorporated into an existing heat and moisture transfer model for silo bags [8]. This enhanced model can be used to evaluate the effects of different storage scenarios, including varying grain conditions and climatic influences, on the quality of stored wheat in silo bags. Finally, in relation to field scale studies, future research should explore more challenging temperature regimes and longer storage periods to gain insights into long-term grain quality preservation in silo bags.

5. Conclusions

The conclusion of this field study highlights the impact of temperature fluctuations and external bag coloring on grain temperature and industrial quality for wheat stored in silo bags. Despite minor temperature differences in the pink bag’s peripheral layer, grain quality parameters remained largely unaffected. The study emphasizes the importance of maintaining a low initial moisture content to mitigate adverse quality effects during storage. While industrial and rheological wheat properties remained stable, falling numbers and wet gluten content showed changes. Notably, seed vigor remained unaffected, indicating potential suitability for the malting barley and seed industries. The effect of ambient temperature on the peripheral layer was estimated to influence between 5 and 10% of the grain mass, suggesting that negative effects on grain quality may not be detected unless differential sampling by strata is implemented.

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