

Article

Assessment of Egg Quality Across Seasons, Storage Durations, and Temperatures in Commercial Laying Hens

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Abstract

Egg quality plays a crucial role in determining shelf life, consumer acceptability, and economic value in commercial egg production systems. This study evaluated the effects of season, storage temperature, and duration on internal and external egg quality. A total of 256 freshly laid eggs were collected during winter and spring, and stored at four temperatures (0 °C, 10 °C, 20 °C, and 30 °C) for 0, 10, 20, and 30 days. The experimental design was a 2 × 4 × 4 factorial design (season × temperature × duration), with 128 eggs collected each in both seasons. Each treatment combination included 8 eggs (2 eggs × 4 replicates). External quality (egg weight and shell thickness) and internal quality (yolk and albumen height, width, pH, Haugh units, and yolk colour) parameters were evaluated at 10-day intervals. Egg weight significantly decreased ($p < 0.05$) from 67.67 g on Day 0 to 59.39 g on Day 30. Similarly, shell thickness decreased ($p < 0.05$) from 40.00 mm to 36.00 mm over the same period. Yolk pH increased from 6.68 to 7.16 ($p < 0.05$), and albumen pH rose ($p < 0.05$) from 7.30 to 7.60, particularly at higher storage temperatures (20 °C and 30 °C). Yolk and albumen heights decreased significantly ($p < 0.05$), from 2.03 cm to 1.23 cm and 6.65 cm to 3.88 cm, respectively, indicating structural degradation. Yolk width increased from 2.58 cm to 3.49 cm ($p > 0.05$), and albumen width expanded ($p < 0.05$) from 5.33 cm to 9.21 cm, with a notably greater spread observed at 30 °C (14.68 cm). Haugh unit values declined markedly from 98.46 to 60.00 over 30 days ($p < 0.05$), indicating a significant deterioration in internal egg quality. Seasonal effects were also evident: spring eggs had greater shell thickness (40.60 mm vs. 38.45 mm in winter; $p = 0.01$) and brighter yolk colour, whereas winter eggs had higher yolk pH values (6.47 vs. 6.28; $p = 0.009$), and superior yolk and albumen heights. These findings indicate that storage beyond 10 days, particularly above 20 °C, compromises egg quality and that seasonality significantly affects multiple quality parameters. Cold storage and seasonally optimized management strategies are recommended to preserve egg integrity and marketability in commercial poultry systems.

Keywords: egg quality; storage duration; temperature; season; poultry



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1. Introduction

Eggs are globally regarded as a highly nutritious, affordable, and digestible source of animal protein, providing essential amino acids, lipids, vitamins, and minerals [1,2].

Their dense nutritional composition supports food and nutrition security, particularly in developing countries. As consumer awareness increases, there is a growing demand for high-quality eggs that meet specific sensory, nutritional, and hygienic expectations [3]. As a result, egg quality has become a key determinant of market value, consumer satisfaction, and profitability in the poultry industry.

Egg quality is assessed using external and internal quality parameters. External parameters include shell cleanliness, texture, thickness, shape, and weight, factors that influence mechanical integrity and transportability [4,5]. Internal parameters such as albumen height, yolk firmness, yolk index, pH, and Haugh unit reflect egg freshness and functional quality [6,7]. These internal characteristics decline rapidly after laying due to physicochemical changes like albumen thinning and pH elevation [8,9].

Multiple genetic and environmental factors influence egg quality, including breed, age, diet, ambient temperature, and storage duration [10]. Among these, season, storage time, and temperature are especially significant due to their direct effects on egg physiology and preservation. Seasonal variations, particularly temperature, humidity, and photoperiod, affect hen metabolism, feed intake, and laying performance [7,11]. Heat stress during hot seasons has been shown to reduce feed intake, leading to decreased egg weight and shell thickness [12] (Souza et al., 2021). Empirical data suggest that eggs laid during cooler seasons exhibit higher Haugh units, firmer albumen, and stronger shells than those laid during hot periods [7,13] (Samson et al., 2024; Tesakul et al., 2025).

Storage conditions further influence egg quality. High ambient temperatures and prolonged storage are associated with increased albumen liquefaction, yolk flattening, and pH shifts, all of which diminish egg freshness and processing value [14]. Seasonal changes can also impact nutrient absorption, yolk pigmentation, and vitamin D synthesis due to variations in feed intake and sunlight exposure [15,16]. Cold conditions and shorter daylight hours, common in winter, may affect hen metabolism and egg composition. With year-round consumer demand for premium eggs (a term used to describe eggs that are perceived to be of higher quality than standard or conventional eggs, based on specific attributes), optimizing these conditions and/or practices is essential to maintaining quality across seasons.

Despite the importance of these factors, limited studies have evaluated their combined effects on commercial production settings in South Africa. This study aims to assess how season, storage duration, and temperature interact to influence key egg quality parameters, providing insights for optimizing poultry management and egg handling practices.

2. Materials and Methods

2.1. Ethical Considerations and Study Area

The study was conducted in accordance with the guidelines of the Animal and Research Ethics Committee of the University of Fort Hare (Approval number: IKU02SDWA01/24/A). All procedures involving animals adhered to both institutional and international standards for the ethical care and use of experimental animals. The experiment took place in the Animal Products Laboratory of the Department of Livestock and Pasture Science, University of Fort Hare, Alice Campus, in the Eastern Cape Province of South Africa.

The Eastern Cape experiences moderate temperatures across its four distinct seasons—winter, spring, summer, and autumn. Winter (May to August) typically presents cool and dry conditions, with coastal temperatures ranging from 7 °C to 20 °C (45 °F to 68 °F), while inland and mountainous areas may experience colder spells due to occasional cold fronts. Spring (September to November) is characterized by a gradual rise in temperature and increased humidity, with average daytime temperatures reaching the low 20 s

Celsius (around 70 °F). These moderate but seasonally distinct climatic conditions provide a relevant environmental framework for evaluating the effects of seasonal variation on egg quality.

2.2. Source of Materials and Experimental Design

A total of 256 freshly laid eggs from White Leghorn laying hens (30 weeks into production) [17] were collected from Fort Cox Research Farm, Middledrift, Eastern Cape Province, South Africa. The laying hens at Fort Cox Research Farm were 30 weeks of age at the time of egg collection, corresponding to mid-lay peak production. Birds were housed in environmentally controlled layer cages, following standard commercial practices for White Leghorn hens in research settings. The cages allowed individual nesting and feeding, and birds were exposed to a 16L:8D photoperiod. All hens were fed a nutritionally balanced commercial layer diet formulated to meet or exceed [18] requirements, containing approximately 17% crude protein, 2750 kcal/kg metabolizable energy, 3.8% calcium, and 0.45% available phosphorus. The ration composition remained unchanged throughout winter and spring seasons, eliminating diet as a confounding factor in evaluating seasonal effects on egg quality. Feed and water were provided ad libitum, and no history of disease or vaccination stress was reported during the egg collection period. Egg sampling was conducted during two distinct climatic seasons: winter (July–August 2024) and spring (September–October 2024). Since no on-site meteorological data were recorded, daily ambient temperature and relative humidity during the study period were obtained from the South African Weather Service for Middledrift. During winter, recorded temperatures ranged from approximately 6.8 °C to 16.9 °C, while in spring, they ranged from 17.5 °C to 25.6 °C. The relative humidity ranged from 48% to 72% across both seasons.

The experiment followed a factorial design ($2 \times 4 \times 4$), with two seasons (winter and spring), four storage temperatures (0 °C, 10 °C, 20 °C, and 30 °C), and four storage durations (0, 10, 20, and 30 days), with 128 eggs collected each in both seasons. Freshly laid eggs (0 days) served as the control. Each treatment combination included 8 eggs ($2 \text{ eggs} \times 4 \text{ replicates}$), totalling 256 eggs. The storage temperatures were selected to simulate common egg handling environments, refrigeration (0 °C and 10 °C), ambient spring storage conditions (20 °C), and heat-stressed summer scenarios (30 °C), thus reflecting real-life farm and informal market storage practices.

Controlled temperature storage was maintained using digital laboratory-grade egg incubators (Model: Brinsea Ova-Easy Advance Series II, Weston-super-Mare, UK) and precision thermoelectric refrigeration chambers (Model: BMG-250, BioMed Instruments, Johannesburg, South Africa). Each unit was equipped with an integrated digital thermostat and monitored using external digital data loggers (Testo 175 T2, Titisee-Neustadt, Germany) with a temperature resolution of ± 0.1 °C and an accuracy of ± 0.5 °C.

Throughout the 30-day storage period, daily temperature readings were recorded, and temperature fluctuation was maintained within ± 1.0 °C for each treatment group. Eggs were placed on cardboard trays and rotated gently every 48 h to mimic commercial storage handling. Storage was conducted in temperature-controlled incubators with stable humidity (~65%) and no light exposure, simulating ideal storage conditions in commercial practice. The eggs were randomly assigned to four groups, each corresponding to a different storage temperature: 0 °C, 10 °C, 20 °C, and 30 °C. Within each temperature group, eggs were stored for 0, 10, 20, or 30 days.

2.3. Egg Quality Measurement

Egg quality assessments were conducted on Day 0 (fresh), Day 10, Day 20, and Day 30 for each treatment group. Eggs were allowed to equilibrate to room temperature

(approx. 22 °C) for one hour before measurement to eliminate the effects of condensation or thermal shock.

Egg weight (g) was recorded using a digital precision balance (Precisa 1212 M SCS, Precisa Instruments, Dietikon, Switzerland). Yolk width and albumen width (mm) were measured using a digital Vernier calliper (QLR VCL150, Pierre Vernier, France). Yolk colour was determined using the Roche Yolk Colour Fan (DSM Nutritional Products, Kaiseraugst, Switzerland). Yolk and albumen pH were assessed using a calibrated digital pH meter (pH 8+ DHS, XS Instruments, Modena, Italy), with electrodes rinsed among samples to avoid cross-contamination. Shell thickness (mm) was measured at the blunt end, equator, and pointed end using a screw micrometre (9SM127M, James Watt, London, UK), and the average was recorded. Albumen height (mm) was measured using a tripod micrometre, and Haugh units (HU) were computed using the formula:

$$HU = 100 \log(H - 1.7W^{0.37} + 7.6)$$

where H is albumen height and W is egg weight.

All measurements were conducted under standardized laboratory conditions with consistent lighting and were performed by the same trained personnel to minimize observer bias. Instruments were calibrated weekly using standard weights and buffers. Quality control samples (reference eggs stored under standard conditions) were included to verify measurement consistency.

2.4. Statistical Analysis

Data were analyzed using the PROC MIXED procedure in SAS version 9.4 (SAS Institute Inc., Cary, NC, USA, 2012), with storage temperature, storage duration, and season included as fixed effects, and replicates as random effects. Interactions between factors were tested (e.g., temperature $\times$ time, time $\times$ season), and least significant difference (LSD) tests were used for post hoc mean comparisons at $p < 0.05$. The normality of residuals and homogeneity of variances were tested using Shapiro–Wilk and Levene’s tests, respectively. Where necessary, data were transformed to meet model assumptions. Seasonal climatic data (e.g., daily average temperature and humidity) were retrieved from the South African Weather Service for contextual interpretation.

3. Results

Although the interaction between storage time and temperature was analyzed, it did not yield statistically significant effects ($p > 0.05$) on any of the measured egg quality parameters. Therefore, interaction terms were excluded from the final presentation of results for clarity and interpretability.

3.1. Effect of Storage Time and Temperature on the External and Internal Egg Quality

The effects of storage time and temperature on external egg quality parameters are presented in Table 1. A drop in egg weight was observed as storage duration increased, decreasing from 67.67 g on Day 0 to 59.39 g on Day 30 ($p < 0.05$). Similarly, egg weight decreased with increasing storage temperature. While eggs stored at 0 °C and 10 °C did not differ ($p > 0.05$), those stored at 20 °C showed lower weights than those stored at 10 °C, and this trend continued with further weight loss at 30 °C ($p < 0.05$).

Shell thickness followed a similar pattern of deterioration over time, decreasing from an initial value of 40 mm on Day 0 to 36 mm on Day 30 ($p < 0.05$). With respect to storage temperature, eggs stored at 0 °C had thicker shells than those stored at 10 °C ($p < 0.05$). However, the differences in shell thickness between 20 °C and 30 °C were not significant ($p > 0.05$).

Table 1. Effects of storage time and temperature on external egg quality.

Sources		Egg Weight (g)	Shell Thickness (µm)
Period (day)	0	67.67 ^a	40.00 ^a
	10	63.51 ^b	37.51 ^b
	20	60.78 ^c	36.78 ^c
	30	59.39 ^d	36.00 ^d
SEM		0.76	0.40
<i>p</i> -value		0.02	0.11
Temperature (°C)	0	61.10 ^a	38.66 ^a
	10	60.71 ^a	37.00 ^b
	20	57.97 ^b	35.75 ^c
	30	56.01 ^c	35.71 ^c
SEM		0.872	0.46
<i>p</i> -values		0.018	0.012

^{a,b,c,d} Means with different superscripts down the column are significantly different ($p < 0.05$); SEM: standard error of mean.

The effects of storage time and temperature on internal egg quality parameters are presented in Table 2. Yolk pH increased progressively with storage duration, rising from 6.68 on Day 0 to 7.16 on Day 20 ($p < 0.05$). However, the yolk pH of eggs stored for 20 and 30 days showed no significant difference ($p > 0.05$). Similarly, the yolk pH increased with rising temperature, reaching a maximum of 7.60 at 30 °C and a minimum of 6.81 at 0 °C ($p < 0.05$). Albumen pH followed a similar trend, with values increasing from 7.47 (Day 0) to 8.16 (Day 30) ($p < 0.05$). Likewise, with temperature increases, the albumen pH rose from 7.35 (0 °C) to 7.60 (30 °C) ($p < 0.05$).

Table 2. Effects of storage time and temperature on internal egg quality.

Sources	Parameters									
	Yolk PH	Albumen PH	Yolk Colour	Yolk Width (mm)	Albumen Width (mm)	Yolk Height (mm)	Albumen Height (mm)	Air Cell Width (mm)	Air Cell Height (mm)	Haugh Units
Period (day)	0	6.68 ^c	7.47 ^a	11.00 ^a	2.58 ^a	5.33 ^a	2.03 ^a	1.00 ^a	0.13 ^a	98.46 ^a
	10	7.02 ^b	7.77 ^b	10.88 ^a	2.66 ^a	7.90 ^a	1.50 ^b	0.76 ^b	0.51 ^b	71.23 ^b
	20	7.17 ^a	8.08 ^c	10.67 ^b	3.38 ^b	8.77 ^b	1.33 ^c	0.48 ^c	0.87 ^c	63.47 ^c
	30	7.16 ^a	8.16 ^c	10.38 ^c	3.49 ^b	9.21 ^b	1.23 ^d	0.46 ^c	1.14 ^d	60.00 ^d
SEM		0.10	0.11	0.14	0.27	0.50	0.09	0.06	0.08	2.70
<i>p</i> -value		0.500	0.150	0.120	0.140	0.230	0.180	0.030	0.040	0.060
Temp (°C)	0	6.81 ^c	7.35 ^c	10.93 ^a	2.60 ^a	5.83 ^a	1.83 ^c	0.73 ^a	0.77 ^a	86.60 ^a
	10	6.71 ^c	7.48 ^c	10.77 ^a	2.65 ^a	5.84 ^a	1.80 ^c	0.68 ^a	0.72 ^a	77.63 ^b
	20	7.34 ^b	7.86 ^b	10.58 ^b	3.13 ^b	8.15 ^b	1.10 ^b	0.52 ^b	0.94 ^b	60.22 ^c
	30	7.60 ^a	9.33 ^a	10.40 ^c	4.32 ^c	14.68 ^c	0.63 ^a	0.25 ^c	1.47 ^c	35.12 ^d
SEM		0.11	0.15	0.16	0.31	0.58	0.10	0.07	0.10	3.12
<i>p</i> -values		0.004	0.000	0.117	0.026	0.000	0.000	0.008	0.002	0.006

^{a,b,c,d} Means with different superscripts down the column are significantly different ($p < 0.05$); SEM: standard error of mean.

The yolk colour decreased ($p < 0.05$) over the 30-day storage period, dropping from a maximum value of 11.00 to 10.83. Likewise, increasing storage temperature also affected the yolk colour, with values decreasing from 10.93 at 0 °C to 10.49 at 30 °C. The yolk colour of eggs stored at 20 °C and 30 °C differed significantly ($p < 0.05$), while those kept at lower temperatures did not show significant variation.

Yolk width increased gradually ($p < 0.05$) with storage time, from 2.58 cm on Day 0 to 3.49 cm on Day 30. Likewise, with increasing temperature, the yolk width increased from 2.60 cm at 0 °C to 4.32 cm at 30 °C ($p < 0.05$). Albumen width expanded with both storage time and temperature, rising from 5.33 cm on Day 0 to 9.21 cm on Day 30 and from 5.83 cm at 0 °C to 14.68 cm at 30 °C ($p < 0.05$), respectively.

Yolk height decreased steadily ($p < 0.05$) as storage duration increased, from 2.03 cm on Day 0 to 1.23 cm on Day 30. A similar trend was observed with the increase in temperature, where yolk height decreased from 1.83 cm at 0 °C to 0.63 cm at 30 °C ($p < 0.05$). Similarly,

the albumen height and Haugh units decreased ($p < 0.05$) with the increase in storage days and temperature. In contrast, air cell width and height increased ($p < 0.05$) with increase in storage days, and temperature.

3.2. Effect of Season on the External and Internal Egg Quality

The effect of season on external egg quality parameters is presented in Table 3. An increase in shell thickness was observed with the transition from winter (38.45) to spring (40.60) ($p < 0.05$). However, the influence of season on egg weight was not significant ($p > 0.05$).

Table 3. Effect of season on external quality of eggs.

Parameters	Means	SEM	<i>p</i> -Value
Shell thickness (μm) winter	38.45 ^b	0.74	0.017
Shell thickness (μm) spring	40.60 ^a	0.42	
Egg weight (g) winter	64.49	0.99	
Egg weight (g) spring	66.07	0.73	

^{a,b} Means with different superscripts down the column are significantly different ($p < 0.05$); SEM: standard error of mean.

The effect of season on internal egg quality parameters is presented in Table 4. Yolk pH was higher in winter (6.47) compared to spring (6.28) ($p < 0.05$). In contrast, the effect of season was not significant ($p > 0.05$) on the albumen pH. Yolk height and yolk width were greater in winter ($p < 0.05$), whereas albumen height and albumen width were greater in spring ($p < 0.05$). Air cell height was higher in winter, while air cell width, Haugh unit, and yolk colour were higher in spring ($p < 0.05$).

Table 4. Effects of seasons on internal egg quality.

Parameters	Means	SEM	<i>p</i> -Value
Yolk pH (Winter)	6.47 ^a	0.06	0.009
Yolk pH (Spring)	6.28 ^b	0.04	
Albumen pH (Winter)	7.43	0.05	0.202
Albumen pH (spring)	7.52	0.05	
Yolk height mm (Winter)	2.11 ^a	0.03	0.000
Yolk height in mm (Spring)	1.92 ^b	0.04	
Albumen height mm (Winter)	0.76 ^b	0.03	0.014
Albumen height mm (Spring)	0.89 ^a	0.04	
Yolk width mm (Winter)	2.47 ^a	0.05	0.003
Yolk width mm (Spring)	2.27 ^b	0.04	
Albumen width (Winter)	5.24 ^b	0.18	0.041
Albumen width mm (spring)	5.72 ^a	0.14	
Air cell height mm (Winter)	0.44 ^a	0.02	0.000
Air cell height mm (Spring)	0.27 ^b	0.02	
Air cell width mm (Winter)	0.23 ^b	0.02	0.028
Air cell width mm (Spring)	0.30 ^a	0.02	
Haugh units (Winter)	87.09	2.02	0.152
Haugh units (Spring)	91.26	2.02	
Yolk colour (Winter)	10.60 ^b	0.21	0.000
Yolk colour (Spring)	11.95 ^a	0.18	

^{a,b} Means with different superscripts down the column are significantly different ($p < 0.05$); SEM: standard error of mean.

4. Discussion

The interaction between storage duration and temperature was not significant across all measured parameters. This suggests that the effects of time and temperature on egg qual-

ity occurred largely independently, with no synergistic or antagonistic influence observed when both factors were combined. Nonetheless, this does not preclude the possibility of significant interactions under more extreme or prolonged storage conditions, and future studies could explore this further using broader experimental ranges.

4.1. Effect of Storage Duration and Temperature on Egg Quality

The findings from this study confirm that prolonged storage time and elevated temperatures negatively impact on the external and internal quality of eggs. A consistent reduction in egg weight was observed as storage duration and temperature increased. This trend is consistent with prior reports by [19–21], who documented that water loss through the eggshell's pores during storage contributes to weight decline. Eggs stored at higher temperatures lost weight more rapidly, supporting previous studies that linked elevated storage temperatures with accelerated moisture loss [22,23]. In warmer climates like South Africa, especially in informal markets or regions with limited refrigeration, such weight loss could lead to downgrading in size-based grading systems and reduced market value.

Shell thickness also declined over time and with temperature, though the absolute change was moderate. This aligns with [24,25], who observed deterioration in eggshell strength and thickness under suboptimal storage conditions. This may be due to the weakening of the shell matrix over time and increased shell permeability, as reported by [26,27]. Although shell thinning appeared gradual, it reflects measurable structural deterioration with implications for egg integrity, especially mechanical damage, microbial contamination, and economic loss during transport and marketing.

The results of this study revealed a consistent increase in both yolk and albumen pH with prolonged storage time and rising temperatures. This trend aligns with earlier reports by [12,14,28], who noted that prolonged storage leads to CO₂ loss and protein degradation, ultimately raising the pH of egg components. Temperature effects were also evident, with the highest yolk and albumen pH recorded at 30 °C, indicating accelerated biochemical changes under warm storage conditions. These increases in pH can be attributed to several interrelated biochemical processes. Upon oviposition, the albumen is mildly alkaline (pH ~7.6–8.0), while the yolk is closer to neutral (~6.0–6.2). As storage progresses, CO₂ diffuses through the eggshell pores, especially from the albumen, resulting in a shift in the bicarbonate buffering system and a gradual rise in pH [29]. This pH increase in the albumen promotes osmotic transfer of water into the yolk, which contributes to yolk dilution and a corresponding increase in yolk pH. Furthermore, storage temperature significantly influences the rate of these biochemical changes. At elevated temperatures (20–30 °C), enzymatic reactions and protein denaturation (particularly of yolk proteins such as lipovitellin and phosvitin) occur more rapidly, leading to the release of ammonia and other basic nitrogenous compounds that further elevate yolk pH. In contrast, under refrigeration (0–10 °C), metabolic activities and enzymatic degradation are markedly reduced, thereby stabilizing internal egg quality and delaying the pH shift. Elevated pH levels, particularly in the albumen, are indicative of reduced freshness, altered protein structure, and potential negative impacts on functional properties, such as foaming and emulsification capacity [12,29].

Yolk colour declined with longer storage and higher temperatures. This change can be linked to pigment oxidation and moisture migration between the yolk and albumen, which causes the dilution of yolk pigments [8]. Refs. [26,30] also reported that yolk colour fades more rapidly when eggs are stored at ambient temperatures. Yolk width increased over time and with temperature, likely due to the weakening of the vitelline membrane [11,31], which allowed the yolk to absorb water and expand. A similar trend was observed for albumen width, which increased due to the thinning of the thick albumen fraction as

ovomucin degrades [32,33]. This expansion can also alter frying and visual properties, further influencing consumer perception.

Yolk and albumen heights, two sensitive indicators of freshness, declined with both storage duration and temperature. These parameters are highly responsive to protein denaturation and CO₂ loss, consistent with the findings of [4,34]. A decrease in yolk or albumen height corresponds to a drop in structural integrity, making the egg less marketable and reducing its processing potential.

Air cell size increased with storage duration and temperature, as expected. This is a classic indicator of moisture loss and is often used in freshness grading [35,36]. Lohmann Breeders [34] emphasized that air cell enlargement is a direct consequence of gas exchange, which accelerates under warm conditions.

The Haugh unit, a gold-standard metric for internal quality, showed a steady decline during storage, especially at higher temperatures. The findings mirror those of [37], and [26], who established that CO₂ loss, albumen thinning, and protein degradation collectively lower Haugh values over time.

4.2. Effect of Season on Egg Quality

Seasonal variations also influenced egg quality, with measurable differences between winter and spring. Spring-laid eggs exhibited thicker shells, likely due to improved calcium metabolism and reduced thermal stress. This supports [38,39], who reported that moderate ambient temperatures enhance calcium absorption and deposition in the shell gland. Conversely, winter-related cold stress may compromise shell quality. Although eggs laid in spring weighed slightly more than those in winter, the difference was not statistically significant. This is consistent with the findings of [40], who argued that egg weight is more dependent on hen age and diet than season alone.

Yolk pH was higher in winter, possibly reflecting greater CO₂ loss in cooler, drier air, which promotes internal alkalinity. This aligns with, who observed that cold ambient temperatures and associated humidity fluctuations can influence pH dynamics. However, no seasonal difference was detected in albumen pH, which supports the assertion by [26] that pH variation is more dependent on storage duration than external temperature. Yolk height and width were greater in winter, indicating that lower ambient temperatures may help to preserve membrane strength and structural cohesiveness. This observation agrees with the results of [4,38,40], who found enhanced yolk structure under thermoneutral or cooler environmental conditions.

Albumen height and width, however, were superior in spring. Lusk and Akter attributed this to longer photoperiods and improved metabolic efficiency during spring, which may enhance albumen protein synthesis and quality.

Air cell parameters showed mixed seasonal effects. Winter eggs had taller air cells, possibly due to faster moisture loss through thinner shells, as proposed by [37]. Conversely, spring eggs had wider air cells, which could reflect subtle differences in shell porosity or ambient humidity during laying and early post-lay storage [38].

Finally, spring eggs exhibited a more vibrant yolk colour. This may result from improved dietary intake and longer sunlight exposure, which are known to influence pigment metabolism and deposition in egg yolks. Enhanced feed intake during spring also promotes better nutrient absorption, contributing to brighter yolk pigmentation.

5. Conclusions

This study highlights the significant impact of season, storage time, and temperature on egg quality. Storing eggs at 0 °C effectively preserves internal quality and extends shelf life, mitigating deterioration associated with prolonged storage. Seasonal fluctuations, if

unmanaged, can negatively affect egg quality, underscoring the need for environmental control in both production and post-harvest handling. While the findings support temperature regulation as a practical intervention for maintaining egg quality and reducing waste, further research is recommended to assess the long-term effects of storage on nutritional and microbiological parameters.

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