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The Effect of Housing Environment on Physical Egg Quality of White Egg Layers

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Abstract: Currently, the egg industry is experiencing a shift in demand for eggs from cage-free environments. This study aims to evaluate the egg quality parameters of white eggs laid in several different housing environments utilized in the industry. Egg quality parameters from battery cages, barren colony cages, enriched colony cages and cage-free pens were compared. Overall, most egg quality parameters were found to be different across housing environments. Battery cages produced the heaviest eggs and eggs with the highest Haugh unit ($p < 0.05$). Cage-free hens produced eggs with the darkest yolks, lowest Haugh units, strongest shells and highest solids percentage compared to other environments ($p < 0.05$). This study did not detect differences between any housing environment in shell color, shell elasticity, vitelline membrane strength or vitelline membrane elasticity ($p > 0.05$). Moreover, this study did not detect any differences in egg quality parameters between enriched and barren colony cages ($p > 0.05$). It appears that white egg-laying hens had superior egg quality performance in caged environments and that cage-free pens only improved yolk color. Furthermore, it appears that simply adding enrichments to cages does not affect any egg quality parameters. From the results of our study, we believe that current intensive environments, such as cages, are the most beneficial for white egg layer egg quality and that as the industry moves toward cage-free, new strategies will need to be developed to preserve egg quality. More research is needed, particularly evaluating free-range environments.

Keywords: egg quality; haugh unit; housing environment; cage-free; colony cages; yolk color

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1. Introduction

From stand-alone meals to further processed foods and baking, eggs are a staple of the American diet. The United States alone produces almost 98 billion eggs a year [1]. The majority of these eggs are produced in the conventional battery cage laying system; however, the number of cage-free facilities is on the rise [2–6]. Driven by both consumer interest groups and legislation, many regions of the United States have outright banned the use and sale of eggs from battery cages [7,8]. Due to these regulations, many groceries, food services and restaurants have pledged to discontinue the use of eggs from caged environments in favor of eggs from alternative environments such as cage-free and colony cages [9–15]. Unfortunately, this will lead to higher costs, which will ultimately be passed to consumers who may not be willing to pay the increased cost if given the option [16–18]. Therefore, it is important to understand how these environments affect the quality of the eggs that are produced since egg quality can affect the end product [19].

Physical egg quality parameters may affect the quality and consumer perceptions of table eggs and, potentially, the egg products derived from them. These parameters usually include shell and vitelline membrane strength, shell color, Haugh unit, yolk color and dry egg mass. Shell strength and elasticity directly affect the chance of breakage during processing and transportation. Furthermore, eggs with stronger shells can break cleaner at the breaker plant. The vitelline membrane is important in keeping the yolk separate from the albumen. This is important as consumers prefer their yolks to remain unbroken during cooking, and strong membranes keep the yolk and albumen separate during further processing and separating. Egg weight is directly correlated to marketable egg sizes and the amount of material for further processing. Albumen height, as well as Haugh units, directly correlate to the internal egg quality (and grades) of the eggs. Both shell and yolk color are important in consumer perceptions of table eggs. Finally, whole egg solids are the amount of dry egg matter in the egg, which is important for further processing.

Interestingly, the majority of research on how the housing environment affects egg quality has been performed on brown egg layers, as seen by Pires et al.'s review paper [20]. While both brown and white egg layers are laying hens, these types of chickens are vastly different and present different egg quality parameters [21–26]. Therefore, there is a need for more information regarding how the housing environment affects the quality of eggs produced by white egg layers. Some studies indicate that the housing environment does not affect white egg layers [23,24,27–29]. However, there are a few studies that identify better egg quality parameters in intensive environments, such as conventional battery cages [21,30,31]. Even so, some studies also indicate that floor pens provide an optimal environment for white egg layers [21]. Furthermore, researchers have indicated the importance of performing similar studies across regions to avoid confounding factors such as diet, environmental and management differences [32]. Therefore, the objective of this study was to evaluate the effect of the housing environment on egg quality from modern white egg layer strains using standard North American management practices and nutrition. Based on previous research, we hypothesize that the housing environment will have no effect on the physical quality of white eggs.

2. Materials and Methods

2.1. Animals and Experimental Design

The present study was performed in conjunction with the 40th NC Layer Performance test at the North Carolina Piedmont Research Station Poultry Unit (PRS) managed by the North Carolina Department of Agriculture and Consumer Services [33]. All chicks were hatched, vaccinated, sexed, weighed and tagged at the PRS hatchery, where they were then assigned to their respective brooding and rearing environments. Four white egg layer strains were chosen based on availability and to simulate an average white egg layer. The strains that were chosen were: Babcock white (Hendrix-Genetics BV, Boxmeer, The Netherlands), Hy-Line W-36 (Hy-Line International, West Des Moines, IA, USA), Lohman LSL-Lite and the H & N "Nick Chick" (Lohmann Tierzucht GmbH, Cuxhaven, Germany). A total of 2080 hens were utilized in this study. The quality parameters measured include shell color, shell strength and elasticity, vitelline membrane strength and elasticity, egg weight, inner thick albumen height, Haugh unit, yolk color and dry egg matter (egg solids). At 17 weeks of age, these birds were moved to their respective laying houses, and the laying cycle began. The study ended at 87 weeks of age, resulting in a 70-week laying cycle. The pullet phase was performed as part of the 40th North Carolina Layer Performance Test, which can be found in the grow report [34].

2.2. Housing Environments

The conventional battery cage (CC) house was designed as a close-sided, force-ventilated, light-tight house that utilized manure belts under each tier of cages. The cages were stacked in 3 tiers, and each replicate consisted of 2 cages with 14 hens per cage (28 hens per replicate). Each cage measured 40.6 cm (16 in) high by 50.8 cm (20 in) deep by 121.9 cm (48 in) wide, thus providing 6131.6 cm^2 (6.66 ft^2) and a stocking density of 442.3 cm^2 (68.5 in^2) per bird. This study utilized 4 replicates of each strain for the CC environment for a total of 16 replicates of the CC environment. A total of 448 hens were housed in the CC environment. Birds in the cages were provided with nipple drinkers inside the cage and a trough system for feed located outside of the cage.

Similar to the CC environment, each of the two types of colony cages, the barren enrich-able colony cages (CS) and the enriched colony cages (ECS), were also housed in a force-ventilated, light-tight house and the cages were arranged in banks of 3 tiers with manure belts under each tier. Each cage was 53.3 cm (21 in) tall by 66 cm (26 in) deep by 243.8 cm (96 in) wide, thus providing 1.6 m^2 (17.3 ft^2) for 36 birds per cage at a stocking density of 445 cm^2 (69 in^2) per bird. Each cage had its own feeder located just outside of the cage and nipple waterers located at the back of the cage. The major difference between the two types of colony cages was the enrichments. The CS environment contained no enrichments and was completely barren. However, the ECS environment contained several enrichments. These enrichments included roosting bars, a scratch area and a laying area separated by curtains. These cages were designed to mimic those used in the industry. For each colony cage environment, there were 4 replicates per strain for a total of 16 replicates and 576 hens per colony cage environment.

The cage-free (CF) house was a high-rise, slat/litter floor-style house with a manure pit beneath it. Each pen measured 2.43 m $\times$ 3.05 m (8 ft $\times$ 10 ft) and had 7.4 m^2 (80 ft^2) of floor space, half of which was covered in shavings and half were slats. Each replicate contained 60 hens for a density of 1233 cm^2 (192 in^2) per bird; however, after subtracting out the amount of space that was used for the feeders, this density was 1141 cm^2 (177 in^2) per hen. Each hen was provided feeder and waterer space in accordance with United Egg Producers' guidelines and 16 cm of roosting space as well [35]. Each pen contained 12 nest boxes lined with AstroTurf for a total of 1 nest box per 5 hens. This study utilized 2 CF replicates per strain for a total of 8 replicates and 480 hens.

2.3. Feeding and Lighting Program

The hens in this study were fed a phase-feeding diet according to standard industry practices that met or exceeded National Research Council recommendations [36]. Table 1 contains the feeding phases, and Table 2 contains the dietary information. Hens in all environments followed the same phase feeding program. All environments were provided with supplemental lighting in accordance with standard industry practices.

Table 1. Feeding program of diets according to egg production rate and ad libitum consumption rate.

Rate of Production	Feed Consumption kg/100 Birds/Day	Diet Fed
Pre-production	<9.52	Pre-Lay
Pre-peak and >90%	<10.43 10.43–12.20 >12.20	Pre-Lay Pre-Peak Layer 1
90–80%	<11.29 11.29–12.20 >12.20	Layer 1 Layer 2 Layer 3
70–80%	<11.29 11.29–12.20 >12.20	Layer 3 Layer 4 Layer 5
<70%	<11.29 ≥11.29	Layer 5 Layer 6

Table 2. Ingredient composition and calculated nutrient analysis of diets fed to all hens according to the feeding program described in Table 1.

Ingredients	Pre-Lay	Pre-Peak	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
Corn	48.7	58.3	60.1	62.0	68.0	66.5	65.8	65.2
Soybean Meal	35.2	28.2	26.7	25.3	25.0	22.0	20.9	18.9

Table 2. *Cont.*

Ingredients	Pre-Lay	Pre-Peak	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
Wheat Midds	-	-	-	-	-	-	5.70	12.9
Fat (Lard)	0.55	0.50	-	-	0.83	-	-	-
Soybean Oil	2.54	1.29	1.81	1.25	0.095	-	-	-
Lysine 78.8%	-	-	-	-	-	0.11	0.005	-
D.L. Methionine	0.17	0.15	0.12	0.10	0.095	0.078	0.062	0.057
Ground Limestone	6.87	6.12	6.08	5.53	-	5.78	5.96	6.18
Course Limestone	3.87	3.50	3.50	3.75	3.97	3.75	3.75	3.75
Sodium Bicarbonate	0.11	0.10	0.10	0.15	0.11	0.10	0.10	0.10
Phosphate mono	1.21	1.07	0.90	1.30	1.26	1.09	0.99	0.82
Salt	0.39	0.32	0.29	0.25	0.31	0.26	0.26	0.24
Vit. Premix [1]	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Min. Premix [2]	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
HyD3 Broiler (62.5 mg/lb)	-	-	0.025	-	-	-	-	-
Prop Acid 50% Dry	0.055	0.05	0.05	0.05	0.053	0.05	0.05	0.05
T-Premix	0.055	0.05	0.05	0.05	0.053	0.05	0.05	0.05
0.06% Selenium Premix [3]	0.055	0.05	0.05	0.05	0.053	0.05	0.05	0.05
Choline Cl 60%	0.090	0.097	0.080	0.050	0.046	0.026	0.005	-
Avizyme	0.055	0.050	-	-	-	-	-	-
Ronozyme P-CT 540%	0.022	0.020	0.020	-	-	-	-	-
Calculated Values (%)								
Crude Protein	19.43	18.10	17.50	17.00	16.37	15.87	15.49	14.93
Calcium	4.10	4.05	4.00	3.95	3.95	4.00	4.05	4.10
A. Phos.	0.45	0.44	0.4	0.38	0.35	0.33	0.31	0.28
Total Lysine	1.10	1.00	0.96	0.91	0.87	0.91	0.80	0.75
Total Sulfur Amino Acids	0.80	0.74	0.69	0.66	0.63	0.60	0.58	0.56
ME kcal/kg	2926	2904	2860	2843	2843	2822	2800	2778

[1] Vitamin premix supplied the following per kilogram of feed: vitamin A, 26,400 IU; cholecalciferol, 8000 IU; niacin, 220 mg; pantothenic acid, 44 mg; riboflavin, 26.4 mg; pyridoxine, 15.8 mg; menadione, 8 mg; folic acid, 4.4 mg; thiamin, 8 mg; biotin, 0.506 mg; vitamin B12, 0.08 mg; and ethoxyquin, 200 mg. The vitamin E premix provided the necessary amount of vitamin E as DL-α-tocopheryl acetate. [2] Mineral premix supplied the following per kilogram of feed: 120 mg of Zn as ZnSO4H2O, 120 mg of Mn as MnSO4H2O, 80 mg of Fe as FeSO4H2O, 10 mg of Cu as CuSO4, 2.5 mg of I as Ca(IO3)2, and 1.0 mg of Co as CoSO4. [3] Selenium premix provided 0.3 ppm Se from sodium selenite.

2.4. Data Collection and Calculations

Egg quality measurements included shell strength, shell elasticity, vitelline membrane elasticity, vitelline membrane strength, egg weight, albumen height, Haugh unit (HU), yolk color, egg solids % and shell color. At 27, 35, 51, 63, 75 and 87 weeks of age all egg quality measurements were performed except for egg solids. Egg solids measurements were performed at 35, 63 and 75 weeks of age. All eggs were collected at the same time of day and placed in an egg cooler for 24 h before analysis to mimic industry conditions. Eggshell strength and elasticity were measured utilizing a TA-HDplus texture analyzer with a 250 kg load cell which measured in grams of force (Stable Micro Systems, Surrey, UK). Similarly, vitelline membrane strength and elasticity were measured utilizing a texture analyzer (TA.XTplus) with a 1 mm round-end probe and a 500 g load cell (Stable Micro Systems, Surrey, UK). Albumen height was measured at the inner thick of the egg and by using the TSS QCD System machine (Technical Services and Supplies, Dunnington, York, UK). Haugh Unit was calculated with the following equation [37]:

$$\text{Haugh Unit} = 100 * \text{Log}\ (\text{albumen height} - 1.7 * \text{egg weight} + 7.6)$$

The TSS QCD system had the feature to measure both yolk and shell color. The yolk color scanner was calibrated using the DSM company color fan, which displays yolk color from a scale of 1 to 15, also known as Roche units [38]. Shell color was determined using refractometry of black, blue and red wavelengths combined to provide a reflectivity score from 83.3% (white) to 0% (black). When analyzing whole egg solids, all 6 eggs were weighed, combined in a bag, and mixed for 30 s. A metal pan was then filled and recorded with the mixture. The mixture was then placed in a drying oven at 50 °C until dry. The pans were then taken out and weighed. Egg solids percentage was then calculated in the following manner:

$$\text{Egg solids \%} = ((\text{dw} - \text{pw}) * 100)/(\text{ps} - \text{pw})$$

where dw is dry sample and pan weight, pw is pan weight without sample and ps is pan and liquid sample weight.

2.5. Statistical Analysis

Data were analyzed utilizing JMP Pro 15.1 [39]. Multiple ANOVA was used to calculate the statistical means, while Tukey's HSD was used for multiple comparisons. For each time point and overall, the housing environment was used as the main effect. A p-value of < 0.05 was considered to be statistically significant. Furthermore, egg quality parameters were measured on 6 eggs per replicate, and the data from each replicate were averaged together (except in the case of egg solids).

3. Results

3.1. Shell Reflectivity

The effect of the housing environment on shell reflectivity can be found in Table 3. This study only found a difference in shell color between environments during the last week (week 87). During this week, CF hens laid lighter-colored eggs than CC and CS hens by 4.5% and 2.7%, respectively ($p = 0.0011$). ECS eggs were not different from the other environments during this week. There were no other differences in egg reflectivity during any other weeks of measurement or overall.

Table 3. The effect of housing environment on shell reflectivity % of white egg layers by week and overall [1].

Housing Environment	Week 27	Week 35	Week 51	Week 63	Week 75	Week 87	Overall
Conventional Cages (CC)	77.5	81.4	82.5	81.4	79.7	78.1 ^{B}	80.1
Enrichable colony cages (CS)	82.0	82.7	82.9	82.7	77.7	79.9 ^{B}	81.3
Enriched colony cages (ECS)	82.1	83.4	82.3	83.4	80.5	80.3 ^{AB}	82.0
Cage-free (CF)	82.7	82.4	83.4	82.4	81.8	82.6 ^{A}	82.6
Pooled Standard Deviation	2.028	0.655	0.345	0.655	2.72	0.625	0.606
p-Value	0.2633	0.1905	0.2086	0.1905	0.7794	0.0011	0.0524

[1] Shell color based on reflectance, with pure white having a reflectance of 83.3% and pure black having a reflectance of 0%. ^{A,B} Denotes significant differences utilizing Tukey's HSD for separation of means and alpha = 0.05.

3.2. Egg Weight

Table 4 illustrates the effect of the housing environment on egg weight (g). There were no differences in egg weight during any of the sampling weeks; however, differences were found overall between housing environments. CC eggs were found to be heavier than eggs from CS and CF environments by 1.6 g and 1.5 g, respectively ($p = 0.0004$). ECS eggs were not different from the other environments. Over time, eggs from all environments became heavier as the hen aged.

3.3. Albumen Height

Table 5 shows the effect of the housing environment on the albumen height of white eggs. This study only found differences between the housing environment during week 51 and overall. During week 51, CS eggs had lower albumen height than CC and ECS eggs by 0.70 mm and 0.63 mm, respectively ($p = 0.0494$), while the albumen height of CF eggs was no different. Overall, CC eggs had higher albumens than CS and CF eggs by 0.27 mm and 0.41 mm, respectively, and ECS eggs had higher albumens than CF eggs by

0.37 mm ($p = 0.0027$). Albumen from ECS eggs were not found to be different from CC and CS eggs, while CS eggs were also not found to be different from CF eggs as well.

Table 4. The effect of housing environment on egg weight (g) of white egg layers by week and overall.

Housing Environment	Week 27	Week 35	Week 51	Week 63	Week 75	Week 87	Overall
Conventional Cages (CC)	58.5	62.0	63.7	62.0	66.9	67.7	63.5 ^{A}
Enrichable colony cages (CS)	56.8	60.3	62.0	60.3	66.0	65.8	61.9 ^{B}
Enriched colony cages (ECS)	57.3	61.3	62.3	61.3	66.3	67.8	62.7 ^{AB}
Cage-free (CF)	57.4	61.1	61.8	61.1	64.3	66.0	62.0 ^{B}
Pooled Standard Deviation	0.600	0.595	0.612	0.595	1.078	0.785	0.303
p-Value	0.2117	0.212	0.1261	0.212	0.5726	0.1406	0.0004

^{A,B} Denotes significant differences utilizing Tukey's HSD for separation of means and alpha = 0.05.

Table 5. The effect of housing environment on albumen height (mm) of white egg layers by week and overall.

Housing Environment	Week 27	Week 35	Week 51	Week 63	Week 75	Week 87	Overall
Conventional Cages (CC)	9.00	8.76	7.52 ^{A}	8.76	7.46	7.99	8.24 ^{A}
Enrichable colony cages (CS)	9.09	8.36	6.82 ^{B}	8.36	7.36	7.80	7.97 ^{BC}
Enriched colony cages (ECS)	9.15	8.71	7.45 ^{A}	8.71	7.37	7.81	8.20 ^{AB}
Cage-free (CF)	8.51	8.74	7.04 ^{AB}	8.74	6.66	7.28	7.83 ^{C}
Pooled Standard Deviation	0.170	0.185	0.214	0.185	0.193	0.235	0.082
p-Value	0.1534	0.3058	0.0494	0.3058	0.0938	0.3674	0.0027

^{A,B,C} Denotes significant differences utilizing Tukey's HSD for separation of means and alpha = 0.05.

3.4. Haugh Unit

Table 6 presents the Haugh unit information for this study. During any sampling period, no differences were identified between housing environments for the Haugh unit. Overall, however, there was a significant effect of the housing environment on the Haugh unit. CC eggs had higher Haugh units than CF eggs by 2.4. CS and ECS were not found to be different from the other environments ($p = 0.0178$).

Table 6. The effect of housing environment on Haugh Unit of white egg layers by week and overall.

Housing Environment	Week 27	Week 35	Week 51	Week 63	Week 75	Week 87	Overall
Conventional Cages (CC)	94.7	92.6	85.2	92.6	83.6	86.7	89.3 ^{A}
Enrichable colony cages (CS)	95.6	90.9	80.5	90.9	83.2	86.3	87.9 ^{AB}
Enriched colony cages (ECS)	95.6	92.4	85.2	92.4	83.4	85.0	89.0 ^{AB}
Cage-free (CF)	92.5	92.4	82.4	92.4	79.3	82.6	86.9 ^{B}
Pooled Standard Deviation	0.881	0.951	1.623	0.951	1.263	1.515	0.510
p-Value	0.1494	0.4556	0.084	0.5446	0.1946	0.3989	0.0178

^{A,B} Denotes significant differences utilizing Tukey's HSD for separation of means and alpha = 0.05.

3.5. Yolk Color

The Yolk color for each environment is presented in Table 7. The housing environment was found to have a significant effect on yolk color during weeks 27, 35, 51, 63 and overall. During week 27, CC and CF eggs had darker yolks than CS and ECS eggs ($p < 0.0001$). During weeks 35, 51 and 63, only CF eggs had darker yolks than the other environments ($p < 0.01$). Similarly to the other weeks, CF eggs had overall darker yolk color overall than the other environments by 0.47 when compared to CC eggs, 0.56 when compared to CS eggs and 0.61 when compared to ECS eggs ($p < 0.0001$).

Table 7. The effect of housing environment on yolk color (Roche) of white egg layers by week and overall.

Housing Environment	Week 27	Week 35	Week 51	Week 63	Week 75	Week 87	Overall
Conventional Cages (CC)	8.00 ^{A}	7.60 ^{B}	7.23 ^{B}	7.60 ^{B}	7.81	7.75	7.67 ^{B}
Enrichable colony cages (CS)	7.75 ^{B}	7.26 ^{B}	7.35 ^{B}	7.26 ^{B}	7.95	7.91	7.58 ^{B}
Enriched colony cages (ECS)	7.69 ^{B}	7.28 ^{B}	7.32 ^{B}	7.28 ^{B}	7.77	7.94	7.53 ^{B}
Cage-free (CF)	8.25 ^{A}	8.27 ^{A}	7.81 ^{A}	8.27 ^{A}	8.13	8.10	8.14 ^{A}
Pooled Standard Deviation	0.073	0.101	0.103	0.101	0.131	0.115	0.044
p-Value	0.0001	0.0001	0.0079	0.0001	0.3705	0.3233	0.0001

^{A,B} Denotes significant differences utilizing Tukey's HSD for separation of means and alpha = 0.05.

3.6. Shell Strength and Elasticity

Table 8 presents shell strength, and Table 9 presents the shell elasticity of white eggs in different housing environments. The housing environment had a significant effect on shell strength during weeks 27, 51 and 63. During week 27, CC eggs had stronger shells than CS and ECS eggs ($p < 0.0001$). At weeks 51 and 63, CF eggs had stronger shells than CC and CS eggs ($p = 0.0002$ and $p = 0.0119$, respectively). Overall, CF eggshells were stronger than CS and ECS eggs by 273.8 g/mm and 259 g/mm, respectively ($p = 0.0131$). The housing environment did not influence the shell elasticity of white eggs either overall or during any sampling week (Table 9).

Table 8. The effect of housing environment on shell strength (N/mm^2) of white egg layers by week and overall.

Housing Environment	Week 27	Week 35	Week 51	Week 63	Week 75	Week 87	Overall
Conventional Cages (CC)	51.18 ^{A}	45.93	39.04 ^{B}	34.33 ^{AB}	42.79	40.53	42.30 ^{AB}
Enrichable colony cages (CS)	44.60 ^{B}	45.48	38.52 ^{B}	33.07 ^{B}	43.79	39.49	41.58 ^{B}
Enriched colony cages (ECS)	47.30 ^{B}	46.27	43.06 ^{AB}	36.00 ^{AB}	42.62	39.64	41.73 ^{B}
Cage-free (CF)	47.77 ^{AB}	50.10	48.19 ^{A}	42.10 ^{A}	40.57	36.88	44.27 ^{A}
Pooled Standard Deviation	1.002	1.233	1.360	1.914	1.194	1.258	0.546
p-Value	0.0001	0.1459	0.0002	0.0119	0.4348	0.4066	0.0131

^{A,B} Denotes significant differences utilizing Tukey's HSD for separation of means and alpha = 0.05.

Table 9. The effect of housing environment on shell elasticity (mm) of white egg layers by week and overall.

Housing Environment	Week 27	Week 35	Week 51	Week 63	Week 75	Week 87	Overall
Conventional Cages (CC)	2.36	1.98	1.96	1.95	2.09	2.02	2.06
Enrichable colony cages (CS)	2.41	2.08	2.05	1.98	1.81	2.08	2.07
Enriched colony cages (ECS)	2.30	2.10	1.81	2.26	2.06	2.22	2.12
Cage-free (CF)	2.35	2.27	2.03	1.75	1.89	1.82	2.01
Pooled Standard Deviation	0.078	0.098	0.096	0.248	0.108	0.125	0.053
p-Value	0.758	0.3733	0.2845	0.5436	0.1927	0.2897	0.6685

3.7. Vitelline Membrane Strength and Elasticity

Vitelline membrane strength is reported in Table 10. Table 11 contains vitelline membrane elasticity based on the environment for white eggs. This study did not find any difference in vitelline membrane strength overall or during any time point. The housing environment did not have an effect on membrane elasticity for any time point or overall.

Table 10. The effect of housing environment on vitelline membrane strength (N/mm^2) of white egg layers by week and overall.

Housing Environment	Week 27	Week 35	Week 51	Week 63	Week 75	Week 87	Overall
Conventional Cages (CC)	0.0231	0.0194	0.0192	0.0191	0.0204	0.0198	0.0202
Enrichable colony cages (CS)	0.0236	0.0204	0.0201	0.0194	0.0178	0.0204	0.0203
Enriched colony cages (ECS)	0.0226	0.0206	0.0178	0.0222	0.0199	0.0218	0.0208
Cage-free (CF)	0.0230	0.0223	0.0199	0.0172	0.0185	0.0178	0.0198
Pooled Standard Deviation	0.00076	0.00096	0.00093	0.00243	0.00106	0.00123	0.000520
p-Value	0.758	0.373	0.285	0.546	0.290	0.290	0.669

Table 11. The effect of housing environment on vitelline membrane elasticity (mm) of white egg layers by week and overall.

Housing Environment	Week 27	Week 35	Week 51	Week 63	Week 75	Week 87	Overall
Conventional Cages (CC)	4.00	3.68	3.53	3.40	2.48	3.27	3.56
Enrichable colony cages (CS)	4.24	3.67	3.48	3.51	2.28	3.34	3.59
Enriched colony cages (ECS)	4.19	3.78	3.18	3.35	3.61	3.66	3.63
Cage-free (CF)	3.77	4.21	3.64	2.96	3.49	2.97	3.51
Pooled Standard Deviation	0.150	0.162	0.176	0.230	0.240	0.213	0.082
p-Value	0.2248	0.2084	0.3736	0.4190	0.7584	0.2640	0.8176

3.8. Egg Dry Matter (Egg Solids)

Table 12 contains information about the effect of the housing environment on whole egg solids. The housing environment had a significant effect on egg solids during week 75 (the last week it was measured), where CC eggs had a higher percentage of egg solids than ECS eggs by 0.7% (p = 0.0237). Overall, CF eggs had a higher percentage of egg solids than ECS eggs by 0.7%, while the other environments were not different (p = 0.0144).

Table 12. The effect of housing environment on whole egg solids percentage of white egg layers by week and overall.

Housing Environment	Week 35	Week 63	Week 75	Overall
Conventional Cages (CC)	24.5	24.3	24.9 ^{A}	24.5 ^{AB}
Enrichable colony cages (CS)	24.4	24.5	24.3 ^{AB}	24.4 ^{AB}
Enriched colony cages (ECS)	24.4	23.7	24.2 ^{B}	24.1 ^{B}
Cage-free (CF)	25.2	24.2	24.9 ^{AB}	24.8 ^{A}
Pooled Standard Deviation	0.24	0.23	0.20	0.14
p-Value	0.1916	0.1211	0.0237	0.0144

^{A,B} Denotes significant differences utilizing Tukey's HSD for separation of means and alpha = 0.05.

4. Discussion

The housing environment was found to have an effect on several egg quality parameters. While extensive research has been performed using brown egg layers to compare housing environments, there is limited research related to white egg layers [26]. Furthermore, researchers have demonstrated major differences between brown and white egg layer performance and egg quality. [21–25]. Therefore, brown egg layer studies would not be applicable for comparison against white egg layers as physical egg quality parameters between white and brown egg layers are very different [21,22,25,26].

The housing environment influenced several egg quality traits. Starting with shell color using reflectivity, the housing environment had an effect on shell color only at the end of the study, where cage-free hens had the lightest eggs. Nutrient recycling in the extensive systems may have caused these color variations. When looking at shell reflectivity, it is important to note that a pure white egg will have a reflectivity of 83.3%. Consumers prefer eggshells closest to this 83.3% reflectivity as consumers prefer white eggs to be as white as possible [40]. Unfortunately, it is not yet understood what level of difference in shell reflectance consumers can perceive in eggshells. Interestingly, the present study seems to be unique in its measurement of shell reflectivity in white egg layers. Many studies evaluate brown egg color and reflectivity in relation to the housing environment; however, it seems that studies evaluating egg quality of white egg layers in various housing environments lack measurement of shell color or reflectivity [41–43].

Overall, we identified that CF eggshells were stronger than eggshells from both colony cages. Interestingly, at the first sampling date, CC eggshells were stronger than colony cage eggshells, and at weeks 51 and 63, CF eggshells became stronger than other environments. We did not identify any differences in eggshell elasticity between treatments. Stronger eggshells are more desirable by consumers, producers and further processors [44,45]. Eggs that have stronger shells tend to break less during transportation [44,45]. Philippe et al. [29] and de Oliveria et al. [46] found no difference between ECS and CC systems, which confirms the findings of the present study. Hidalgo et al. [30] found CF eggs at the grocers had weaker shells than their caged counterparts, although the authors did not identify the egg color of the eggs chosen. Eggshell strength can be dependent on several aspects of the egg. While shell thickness was not measured for this study, it can be hypothesized that the weaker eggs could have had thinner eggshells. Research has also indicated that differences in eggshell-breaking strength may be caused by differences in eggshell mineral content, which should be further investigated in a subsequent study [47]. Furthermore, it is well known that chickens will practice coprophagic behaviors, thereby potentially consuming extra minerals and vitamins [48–50]. Therefore, we also hypothesize that CF hens reabsorbed vitamins and minerals through their feces by this behavior which caged hens would not have the ability to do.

Haugh unit is a measure of the internal freshness of the egg and is a function of egg weight and albumen height [37]. Higher Haugh units are correlated with superior internal egg quality [37]. Haugh unit has also been shown to be directly related to internal egg grades as well (USDA AA, A, and B internal grades) [51]. The present study found overall effects on albumen height, egg weight, and Haugh unit. In general, eggs from conventional cages had higher egg weights and Haugh units, while eggs from the cage-free environment had lower egg weights and Haugh units. Furthermore, while the Haugh unit was not affected, the ECS environment had smaller eggs and lower albumen than the other environments as well. We also saw differences overall and no differences in the individual weeks between environments when looking at the Haugh unit and egg weight. This could be due to the larger sample size, as the overall calculation was based on all of the data, shrinking the overall standard error. Several other studies confirm our findings, such as Singh et al. [21], who found that caged eggs had higher albumens than cage-free eggs, Sharma et al. [24] and Philippe et al. [29] found no difference in Haugh Unit between ECS and CS environments. However, Barbosa Filho et al. [28] found no difference in egg quality between caged and cage-free hens. Singh et al. [21], Barbosa Filho et al. [28] and Al-Awadi et al. [52] also found no significant difference in egg weight between caged and cage-free eggs, which disagrees with our findings. These differences could be due to the strain utilized, as the most modern study from this group is almost 20 years old, and the genetics of the laying hen has improved greatly since then [53]. Sharma et al. [24] and Philippe et al. [29] found no difference between both types of colony cages, which is in agreement with our findings.

Yolk color, measured by the DSM color fan, was affected by the housing environment. Yolk color is important as darker yolks are typically regarded as superior across the globe [54]. Eggs from the CF environment exhibited darker yolks than eggs from other environments. Furthermore, adding enrichments to the colony cages did not affect the yolk color. These results are consistent with Singh et al. [21], who discovered that CF eggs had darker yolks than CC eggs, and Philippe et al. [29], who found no difference between colony cages. However, these results are also inconsistent with Hidalgo et al. [30], who found lighter yolks in CF eggs. Yolk color is typically highly affected by the feed that the hens consume; however, in this study, there was no difference in the feed between treatments. Philippe et al. [29] found that in aviaries, which had access to litter substrates, the hens had darker yolks. Philippe et al. [29] also hypothesized that the yolks were darker due to the litter that the hens may have consumed. Furthermore, according to Singh et al. [21], high egg production can negatively influence yolk color, which may be the case for the present study as well. Therefore, in future research, yolk, liver and fat pad carotenoid levels should be measured, and behavior analysis could also identify litter-eating behaviors as well.

The housing environment was found not to affect vitelline membrane strength (except for week eighty-seven, where CF eggs had stronger membranes) or elasticity. Consumers and further processors prefer stronger vitelline membranes [55]. Consumers prefer the yolk and the albumen to be separate during some cooking activities [55]. Moreover, further processors prefer the yolk to stay intact when separating from albumen, as small amounts of yolk can reduce the functional properties of the albumen leading to financial losses [55]. Measuring the housing environment's effect on vitelline membrane parameters of white eggs appears to be a novel contribution of this study as most current research lacks this information. However, in a study performed by Jones et al. [56], CF white eggs purchased in a grocery store showed weaker vitelline membranes than conventional caged eggs, although these eggs had the oldest retail age. While this study did not show any differences in vitelline membrane properties, further research in housing environments and vitelline membrane characteristics will need to be performed to confirm these findings.

Finally, this study found that CF eggs had a greater amount of egg dry matter than ECS eggs overall. Egg dry matter percentage is important for further processing as it directly corresponds to the amount of dry product that can be produced per egg. This can directly affect the profitability of further processed eggs as a higher solids percentage yields more dry egg product when further processed [57]. Hidalgo et al. [30] found no difference between CC and CF egg dry matter percentage, which agrees with the findings of the present study. Philippe et al. [29] found that CS and ECS eggs did not differ in their dry matter percentage, which confirms the findings of this study.

5. Conclusions

From the results of this study, it appears that white egg layers have more desirable egg quality traits in conventional cages; however, for some traits, the cage-free environment also performed well. It was observed that colony cages tended to yield poorer egg quality for white egg layers. Furthermore, it did not appear that simply adding enrichments improved egg quality. While we are unsure if the differences observed will have an effect on consumer perceptions, we do know that the amalgamation of differences seen may have an additive effect on consumer perception and cause these eggs to retain higher quality levels as they move through the marketing system. Therefore, when choosing a housing environment based solely on egg quality, we recommend conventional cages for white egg layers as these provide the most optimal egg quality parameters. Further research should be conducted to evaluate aviary environments as well as the free-range environment. Furthermore, evaluating stress, welfare, behavior, and reproductive tract morphology parameters can provide insight into the differences between production systems. Finally, a microbiological analysis of the egg interior, shell exterior and cloaca could also provide valuable food safety information.

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