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Age-related variation and multivariate analysis of internal and external egg quality traits in ISA Brown hens

Variación relacionada con la edad y análisis multivariado de las características de calidad interna y externa del huevo en gallinas ISA Brown

Variação relacionada à idade e análise multivariada de características internas e externas de qualidade dos ovos em galinhas ISA Brown

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Abstract

This study evaluated age-related variations in internal and external egg quality traits in ISA Brown hens raised under semi-arid Algerian conditions. Hens were assessed at two production stages: 5,977 at peak lay (25-30 weeks) and 5,430 at late lay (75-80 weeks). A total of 360 eggs were collected (180 per stage), at a rate of 30 eggs per week, randomly selected at the beginning of each week. Egg weight, shell thickness, shape index, yolk and albumen indices, Haugh units, and yolk color were measured. A one-way analysis of variance (ANOVA) was used to detect age-related differences, Pearson correlation to examine interrelationships among traits, and principal component analysis (PCA) to identify general age-related patterns. Significant differences were observed between the two laying stages. Peak-lay eggs showed superior internal quality, particularly in albumen height and Haugh units, whereas late-lay eggs exhibited greater mass but reduced albumen integrity. Shell thickness and yolk shape remained relatively stable. Correlation analysis revealed stronger trait associations during peak lay, which weakened with advancing age. PCA showed contrasting age-related trends between egg size and internal quality: egg size increased with age, whereas internal quality declined, while shell- and yolk-related traits remained relatively constant. The findings of this study apply to hens up to 80 weeks of age. Further studies covering longer production cycles are recommended to determine whether these patterns persist beyond this period.

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Resumen

Este estudio evaluó las variaciones relacionadas con la edad en los parámetros internos y externos de la calidad del huevo en gallinas ISA Brown, criadas en condiciones semiáridas de Argelia. Las gallinas fueron evaluadas en dos etapas de producción: 5.977 en el pico de puesta (25-30 semanas) y 5.430 en la fase final (75-80 semanas). Se recolectaron 360 huevos en total (180 por etapa), a razón de 30 huevos por semana, seleccionados al azar al inicio de cada semana. Se midieron el peso del huevo, el grosor de la cáscara, el índice de forma, los índices de yema y albúmina, las unidades Haugh y el color de la yema. Se utilizó un análisis de varianza de una vía (ANOVA) para detectar diferencias relacionadas con la edad, la correlación de Pearson para examinar las interrelaciones entre los rasgos y un análisis de componentes principales (ACP) para identificar patrones generales asociados con la edad. Se observaron diferencias significativas entre las dos etapas de puesta. Los huevos del pico de puesta mostraron una mejor calidad interna, especialmente en la altura de la albúmina y unidades Haugh, mientras que, los huevos de la fase final presentaron mayor masa pero menor integridad de albúmina. El grosor de la cáscara y la forma de la yema se mantuvieron relativamente estables. El análisis de correlación reveló asociaciones más fuertes entre los rasgos durante el pico de puesta, las cuales se debilitaron con el avance de la edad. El ACP mostró tendencias contrastantes relacionadas con la edad entre el tamaño del huevo y la calidad interna: el tamaño del huevo aumentó con la edad, mientras que la calidad interna disminuyó, mientras que los rasgos relacionados con la cáscara y la yema permanecieron relativamente constantes. Los resultados de éste estudio son aplicables a gallinas de hasta 80 semanas de edad. Se recomiendan estudios adicionales que abarquen ciclos de producción más prolongados paraedeterminar si estos patrones se mantienen más allá de este período.

Palabras clave: fase de puesta, calidad del huevo, ACP, correlación

Resumo

Este estudo avaliou variações relacionadas à idade nos parâmetros internos e externos da qualidade dos ovos de galinhas ISA Brown criadas em condições semiáridas na Argélia. As aves foram avaliadas em duas etapas produtivas: 5.977 no pico de postura (25-30 semanas) e 5.430 na fase final (75-80 semanas). Um total de 360 ovos foi coletado (180 por etapa), à razão de 30 ovos por semana, selecionados ao acaso no início de cada semana. Foram medidos o peso do ovo, a espessura da casca, o índice de forma, os índices de gema e albúmen, a unidade Haugh e a coloração da gema. Utilizou-se uma análise de variância de uma via (ANOVA) para detectar diferenças relacionadas à idade, correlação de Pearson para examinar inter-relações entre os traços e análise de componentes principais (PCA) para identificar padrões gerais associados à idade. Foram observadas diferenças significativas entre as duas etapas de postura. Os ovos do pico apresentaram melhor qualidade interna, especialmente na altura do albúmen e na unidades Haugh, enquanto os ovos da fase final apresentaram maior massa, porém menor integridade do albúmen. A espessura da casca e o formato da gema permaneceram relativamente estáveis. A análise de correlação revelou associações mais fortes entre os traços durante o pico de postura, que enfraqueceram com o avanço da idade. A PCA mostrou tendências contrastantes relacionadas à idade entre o tamanho do ovo e a qualidade interna: o tamanho do ovo aumentou com a idade, enquanto a qualidade interna diminuiu, enquanto os traços relacionados à casca e à gema permaneceram relativamente constantes. Os resultados deste estudo são aplicáveis a galinhas até 80 semanas de idade. Estudos adicionais que incluam ciclos produtivos mais longos são recomendados para verificar se esses padrões persistem além desse período.

Palavras-chave: fase de postura, qualidade dos ovos, PCA, correlação.

Introduction

The poultry sector plays a vital role in the national economy and global food security by efficiently supplying affordable and high-quality animal protein to meet rising consumer demand. Among its products, eggs stand out for their rich nutritional profile, providing highly digestible proteins, balanced amino acids, and essential vitamins and minerals. Their easy storage, transport, and affordability make eggs a dietary staple across diverse populations. Accordingly, egg quality is a critical factor influencing market value, transport and packaging, and consumer satisfaction (Ulbad and Andre, 2024).

Egg quality is typically assessed through both external characteristics, such as shell strength, thickness, weight, and shape index, and internal traits, including albumen and yolk weight and height, Haugh unit, and yolk color. These traits are interconnected and influenced by numerous factors, including genetics, diet, housing, environmental conditions, and particularly hen's age (Zita *et al.,* 2009; Silversides and Scott, 2001; Duman *et al.,* 2016).

As commercial production systems evolve, laying cycles have been gradually extended from the traditional 72 weeks to 80 weeks or beyond (Liu *et al.,* 2018). This shift has prompted renewed interest in maintaining egg quality throughout prolonged production cycles (Arulnathan *et al.,* 2024; Molnár *et al.,* 2016) However, age-related changes—such as increased egg size, decline in albumen freshness, and reduced shell quality pose challenges for sustainability and economic efficiency (Şekeroğlu *et al.,* 2024; Biesiada-Drzazga *et al.,* 2022).

Isa Brown hens, a leading commercial layer strain, exhibit notable changes in egg quality as they age. Eggs produced at peak lay typically display optimal internal traits, whereas those laid later tend to be heavier but may exhibit diminished freshness and shell integrity (Kraus and Zita, 2019; Kim *et al.,* 2014). Despite these known trends, egg quality dynamics and interaction between internal and external factors throughout the laying phases under local conditions remain poorly documented.

This study aimed to evaluate age-related variation in internal and external egg quality traits in ISA Brown hens and to examine the relationships among traits using correlation analysis and principal component analysis (PCA).

Material and methods

Study location and housing conditions

The study was conducted at the government experimental farm of Baaraouia, Constantine, Algeria. Laying hens were housed in conventional cages, with four birds per cage, ensuring sufficient space per animal. Environmental conditions were maintained at 21-24 °C, with a 16-hour light and 8-hour dark photoperiod. The flock was managed under strict sanitary protocols, including routine cleaning, medication schedules, and vaccination programs. Hens had *ad libitum* access to clean water and were fed a commercial diet (120 g.hen^{-1}.day^{-1}) throughout the laying period until culling at 80 weeks of age.

The diet used throughout the laying period was analysed. Between 25 and 30 weeks of age, hens received a diet containing 2914.7 kcal.kg^{-1} of metabolizable energy, 16.3 % of crude protein, 4.00 % of calcium, and of 0.42 % phosphorus. During the late laying phase (75 to 80 weeks of age), the diet contained 2793.8 kcal.kg^{-1}of metabolizable energy, 14.35 % of crude protein, 3.5 % of calcium, and 0.36 % of phosphorus.

Egg Collection and Sampling

A total of 360 eggs were collected across the two laying stages (180 eggs per stage). Each week, 30 eggs were sampled. The flock consisted of 6,000 ISA Brown hens, of which 5,977 were in peak lay (25-30 weeks) and 5,430 were in late lay (75-80 weeks). The poultry house comprised five battery rows; each week, an equal number of eggs were randomly selected from different positions within each row, all eggs were individually numbered, weighed, and analysed on the day of the collection to assess both internal and external traits.

Egg quality measurements and calculations

Egg weight, shell weight, and yolk weight were measured using a precision digital scale. Albumen weight was calculated by subtracting yolk and shell weights from total egg weight. Morphometric parameters including yolk height and diameter, albumen height, egg width and length, and shell thickness (at the equator, blunt, and pointed ends) were recorded with a digital caliper. Yolk color was assessed using the DSM Roche Yolk Color Fan, measurement were used in equations to calculate the egg quality traits following established studies (Şekeroğlu *et al.,* 2024; Biesiada-Drzazga *et al.,* 2022).

- Shape Index (%) = (Egg Width / Egg Length) x100
- Yolk Index = Yolk Height / Yolk Diameter
- Albumen index= (albumen height/ (albumen length +albumen width /2)) x 100
- Yolk (albumen) Ratio (%) = (Yolk (albumen) Weight / Egg Weight) x100
- Yolk/Albumen Ratio = Yolk Weight / Albumen Weight
- Haugh Units = 100 × log (AH + 7.57 − 1.7 x EW^0.37), where AH = albumen height (mm), EW = egg weight (g)

Statistical Analysis

Data analysis was performed using PASW Statistics 18 (SPSS Inc, 2010), *t* test and Pearson's correlation coefficients were computed to assess trait distributions and interrelationships. Multivariate structure was explored with Principal Component Analysis (PCA) to explore internal and external egg quality relationships across laying phases.

Results and discussion

External and internal egg quality traits: Age-related changes

The descriptive statistics of egg quality traits (Table 1) demonstrated a progressive increase in egg weight across the production cycle, rising from 60.39 g at peak to 64.19 g at 80 weeks (p<0.001), consistent with previous reports (Roberts *et al.,* 2013; ISA Brown, 2016), and accompanied by a corresponding rise in egg surface area due to greater egg length and width, in agreement with (Abanikannda and Leigh, 2012). Conversely, the shape index declined from 78.94 % to 75.79 % (p<0.001), indicating more elongated eggs consistent with Abanikannda and Leigh (2012). While the values remained commercially acceptable, this trend may affect packaging and handling efficiency (Duman *et al.,* 2016). Shell weight increased slightly (p = 0.02), but the shell ratio decreased (p<0.001), suggesting that shell deposition continued, but it was insufficient to match the higher metabolic demand of larger eggs, a common phenomenon in extended laying cycles. Contrary to several reports of age-related thinning (Duman *et al.,* 2016), shell thickness remained remarkably consistent (0.39 vs. 0.38 mm; p= 0.49), supporting observations by Roberts *et al.* (2013), that shell deposition may stabilize in older layers under optimized conditions. Arulnathan *et al.* (2024) reported a value above 0.3 mm in all reviewed studies, which supports shell thickness quality resilience among extended lay cycles.

Table 1. External and internal egg quality traits (Mean ± SD) of ISA Brown hens at Peak (25–30 weeks) and late (75–80 weeks) production phase.

Trait	25-30 W Mean ± SD	75-80 W Mean ± SD	P value
Egg weight (g)	60.39 ± 4.01	64.19 ± 5.72	<0.001
Egg length mm	55.49 ± 1,66	58.67 ± 2.68	<0.001
Egg width mm	43.78 ± 1.47	44.41 ± 1.81	<0.001
Egg surf area cm^2	77.63 ± 4.39	83.54 ± 6.39	<0.001
Shape Index (%)	78.94 ± 2.71	75.79 ± 3.27	<0.001
Shell weight	6.05 ± 0.52	6.20 ± 0.67	0.02
Shell Ratio (%)	10.04 ± 0.74	9.69 ± 1.05	<0.001
Shell thickness	0.39 ± 0.04	0.38 ± 0.06	0.49
Yolk weight	13.98 ± 1.09	17.01 ± 2.18	<0.001
Yolk height	14.45 ± 1.05	15.42 ±1.06	<0.001
Yolk ratio	23.20 ± 1.7	26.6 ± 3.4	<0.001
Yolk index	38.09 ± 3.02	37.91 ± 3.63	0.612
Yolk colour	9.39 ± 1.02	7.78±0.83	<0.001
Albumen weight	40.34 ± 3.34	40.98 ± 5.13	0.165
Albumen height	9.26 ± 1.65	7.22 ± 1.6	<0.001
Albumen ratio	66.75 ± 1.86	63.70 ± 3.74	<0.001
Albumen index	12.50 ± 2.9	8.49 ± 2.62	<0.001
Haugh unit	95.18 ± 7.99	82.72 ± 10.52	<0.001
Album/yolk ratio	2.89 ± 0.29	2.44 ± 0.42	0.065

Yolk-related traits increased with age, as both yolk weight and yolk height rose significantly (p<0.001), while the yolk index remained stable and the yolk ratio increased (Şekeroğlu *et al.,* 2024; Roberts *et al.,* 2013; Kraus and Zita, 2019), indicating that yolk morphology is preserved despite volumetric changes. However, yolk color declined (p<0.001), possibly due to reduced carotenoid dietary or absorption in aging hens (Abanikannda and Leigh, 2012; Marzec *et al.,* 2018).

In contrast, albumen quality declined. Albumen height, index, and ratio all decreased (p<0.001), though albumen weight remained unchanged. The Haugh unit dropped from 95.18 to 82.72 (p<0.001), confirming internal degradation with age (Roberts *et al.,* 2013). Nonetheless, values remained above the commercial acceptability suggesting maintained quality under controlled conditions.

Phenotypic correlations of external and internal traits

Phenotypic correlations during peak production phase (25-30 weeks)

Internally, yolk weight was positively correlated with yolk height and yolk ratio (p<0.001), indicating that heavier yolks were more voluminous and elevated. A low correlation was reported between yolk weight and albumen weight (r = 0.236, p<0.01), while albumen weight showed a positive relationship with yolk height (p<0.05), reinforcing its association with overall egg mass, in agreement with Olawumi and Ogunlade (2007). Albumen ratio was negatively correlated with yolk ratio and weight and positively with albumen weight (p<0.001), this inverse volumetric relation is consistent with the result of Vekić *et al.* (2022).

Externally, egg weight was moderately associated with shell weight (r = 0.540), in line with Rotimi *et al.* (2022) and Adeoye *et al.* (2022). Shell weight also correlated with shell ratio (r = 0.674), but correlation of shell ratio declined with egg weight (r = –0.256), indicating thinner shells in larger eggs—an issue noted in commercial flocks (Mitrović *et al.,* 2010). Shell thickness was positively correlated with shell weight and ratio (r = 0.284 and 0.305), but not with egg weight (r = 0.025), suggesting independent regulation of shell deposition, in accordance with Ukwu *et al.* (2017). Shape index was not significantly correlated with other traits, consistent with Vekić *et al.* (2022) reaffirming its role as an independent morphological descriptor.

Across internal–external relationships, egg weight strongly predicted albumen weight (r = 0.891), while its association with yolk weight was moderate (r = 0.494), confirming findings of Olawumi and Ogunlade (2007), and Vekić *et al*. (2022). Albumen ratio increased with egg weight, indicating albumen dominance in larger eggs. Freshness traits like albumen index and Haugh unit were weakly linked to shell characteristics, consistent with Vekić *et al*. (2022), and showing their independence (Table 2).

Phenotypic correlations during late production phase (75-80 weeks)

During late lay, yolk weight maintained a strong positive correlation with yolk ratio (r = 0.762, p<0.001) and strong negative correlation with albumen ratio (r = –0.668). A weak but significant negative association with Haugh unit (r = –0.158, p<0.05) suggests that greater yolk mass may compromise albumen freshness in older hens. Still, yolk height remained positively correlated with yolk weight (r = 0.239) and albumen weight (r = 0.337), indicating preserved coordination among internal traits. Albumen weight showed a negative correlation with yolk ratio (r = –0.680), consistent with internal balancing mechanisms observed previously (Inca *et al.,* 2020).

Among external traits, egg weight retained its positive correlation with shell weight (r = 0.431), though weaker than at peak lay (r = 0.540). Notably, the negative correlation between egg weight and shell ratio strengthened in late lay (r = –0.387 vs. –0.256), suggesting increased shell insufficiency with age consistent with Padhi *et al.* (2013). The strong link between shell weight and shell ratio (r = 0.662) persisted, while shell thickness remained only weakly related to other traits and shape index continued to show no significant correlations, confirming its limited predictive value.

Internal–external trait relationships showed that egg weight remained a strong predictor of albumen weight (r = 0.908), but its correlation with yolk weight declined markedly with age (r = 0.209 vs. 0.494 at peak), reflecting a shift toward albumen dominance in older eggs. This was supported by a slightly higher inverse correlation between yolk ratio and egg weight (r = –0.422 vs. –0.406), and a slightly higher positive correlation between egg weight and albumen ratio (r = 0.477 vs. 0.434), these moderate but consistent shifts align with the patterns reported by Padhi *et al.* (2013) and Inca *et al.* (2020).

In contrast to peak lay, freshness indicators such as Haugh unit and albumen index exhibited no meaningful correlations with shell or egg size traits, confirming their physiological independence in older hens (Table 3).

In summary, egg weight remains a reliable, non-invasive predictor of albumen content across ages, but its links to yolk traits weaken with hen age and other internal traits remain poorly correlated with external features, requiring direct measurement.

Principal Component Analysis (PCA)

A principal component analysis was performed to explore the multidimensional relationships among internal and external egg quality traits across both laying phases. Six components were extracted, with the first two accounting for the majority of the variance.

The first component (FAC1), explaining 32.40 % of the total variance, was strongly correlated with internal egg quality parameters, including albumen index, Haugh unit and albumen height. During the peak egg laying phase (25-30 weeks), FAC1 scores were consistently positive, peaking at 25 weeks, indicating high albumen properties. On the other hand, at the end of the egg-laying cycle (75-80 weeks), these scores became negative, with a minimum observed at 77 weeks, reflecting a gradual deterioration of internal characteristics. This agrees with Sarica *et al.* (2012), also Udeh *et al.* (2021) highlighted albumen traits as key indicators, though they focused on genetic differences.

Table 2. Pearson correlation coefficients among egg quality traits at peak.

Traits	YR	AW	AR	HU	YH	EW	SI	SW	SR	ST
YW	.617***	.236**	-.483***	.054	.517***	.494**	.077	.119	-.183*	.060
YR		-.609***	-.917***	.010	.214**	-.406**	-.107	.265**	.009	-.031
AW			.693***	.050	.245***	.891**	.217**	.477**	-.360**	.053
AR				.050	-.145	.434**	.116	.027	-.375**	-.044
HU					.104	.073	.071	-.217**	-.132	-.152*
YH						.278**	.108	.065	-.276**	-.138
EW							.125	.540***	-.256***	.025
SI								.073	-.034**	.028
SW									.674***	.284***
SR										.305***

* p<0.05, ** p<0.01, *** p<0.001. Abbreviations: YW = yolk weight, YR = yolk ratio, AW = albumen weight, AR = albumen ratio, HU = Haugh unit, YH = yolk height, EW = egg weight, SI = shape index, SW = shell weight, SR = shell ratio, ST = shell thickness.

Table 3. Pearson correlation coefficients among egg quality traits at late phase.

Traits	YR	AW	AR	HU	YH	EW	SI	SW	SR	ST
YW	.762***	-.057	-.668***	-.158*	.239**	.209**	.026	.100	-.065	.100
YR		-.680***	-.961***	-.155*	-.047	-.422**	-.038	-.213**	.147*	.113
AW			.753***	.071	.337***	.908**	.088	.335**	-.428**	-.108
AR				.169*	.107	.477**	.054	.062	-.354**	-.165**
HU					-.060	-.072	.119	-.153*	-.087	-.004
YH						.417**	.114	.122	-.228**	-.201**
EW							.110	.431***	-.387***	-.041
SI								.005	-.087	.016
SW									.662***	.226**
SR										.268***

* p < .05, ** p < .01, *** p < .001. Abbreviations: YW = yolk weight, YR = yolk ratio, AW = albumen weight, AR = albumen ratio, HU = Haugh unit, YH = yolk height, EW = egg weight, SI = shape index, SW = shell weight, SR = shell ratio, ST = shell thickness.

The second component (FAC2), representing 24.10 % of the variance, was mainly associated with egg size and weight, with high correlations for albumen weight and total egg weight. Unlike FAC1, FAC2 scores remained relatively stable across most weeks, but showed a marked increase at 80 weeks, reflecting the larger egg size produced by hens at the end of the laying cycle. This opposite evolution between FAC1 and FAC2 highlights an important physiological compromise: while the eggs become larger with age, their iinternal characteristics degrade (Table 4) (Sirri *et al.,* 2018; Lee *et al.,* 2013).

FAC3 explained 10.44 % of the variance and was mainly associated with secondary internal quality traits such as albumen height, Haugh unit, and albumen index (Roberts *et al.,* 2013). However, it did not show a clear age-related pattern.

FAC4 explained 9.89 % of the variance, related to shell weight and thickness, showed limited age-related variation, suggesting stable shell quality, likely due to adequate calcium nutrition. FAC5, accounting for 6.85 % of the variance, associated with yolk morphology, also remained consistent, aligning with Inca *et al.* (2020) (Table 4).

The weekly distribution of PCA scores (Table 5) on Components 1 and 2 as illustrated in Figure 1, separates the two laying phases: peak-lay eggs (weeks 25-30) cluster in the upper right quadrant, indicating high internal freshness and structural integrity. In contrast, late-lay eggs (weeks 75-80) are more dispersed, with negative scores on Component 1 and increasing values on Component 2, reflecting reduced freshness and increased egg mass. These visual patterns reinforce the physiological trade-off observed with age and confirm the multidimensional nature of egg quality dynamics.

Table 4. Component matrix of egg quality traits from PCA.

Trait	FAC1	FAC2	FAC3	FAC4	FAC5	FAC6
Egg weight	-.376	.821	-.006	.026	-.090	.160
Egg surface area	-.621	.574	.118	.151	-.251	-.148
Shape index	.463	.071	.194	.193	.240	.782
Yolk weight	-.859	.045	.346	-.047	-.124	.189
Yolk ratio	-.750	-.495	.397	-.071	-.081	.113
Shell weight	-.276	.329	-.091	.810	.137	-.082
Shell ratio	.038	-.383	-.090	.827	.223	-.233
Shell thickness	-.070	-.128	-.142	.529	-.036	.094
Haugh unit	.734	.079	.558	.108	-.223	-.130
Yolk colour	.670	.006	.236	.059	-.068	.035
Albumen index	.740	.116	.526	.115	-.138	-.164
Albumen weight	.034	.931	-.177	-.057	-.063	.106
Albumen ratio	.706	.580	-.355	-.163	.015	-.043
Egg length	-.696	.431	.011	.037	-.303	-.420
Egg width	-.334	.622	.238	.266	-.100	.385
Yolk height	-.480	.427	.381	-.188	.542	-.097
Yolk index	.002	.364	.336	-.118	.749	-.291
Alb/yolk ratio	.738	.518	-.399	.016	.034	-.063
Albumen height	.698	.197	.587	.108	-.213	-.139

Table 5. Weekly mean scores for FAC1 and FAC2 across laying period.

Week	25	26	27	28	29	30	75	76	77	78	79	80
FAC1	1.35	.82	.86	.64	.43	.56	-.59	-.90	-1.19	-.91	-.49	-.57
FAC2	-.18	-.23	-.07	-.04	-.03	.15	-.29	.11	.06	-.04	.03	.52

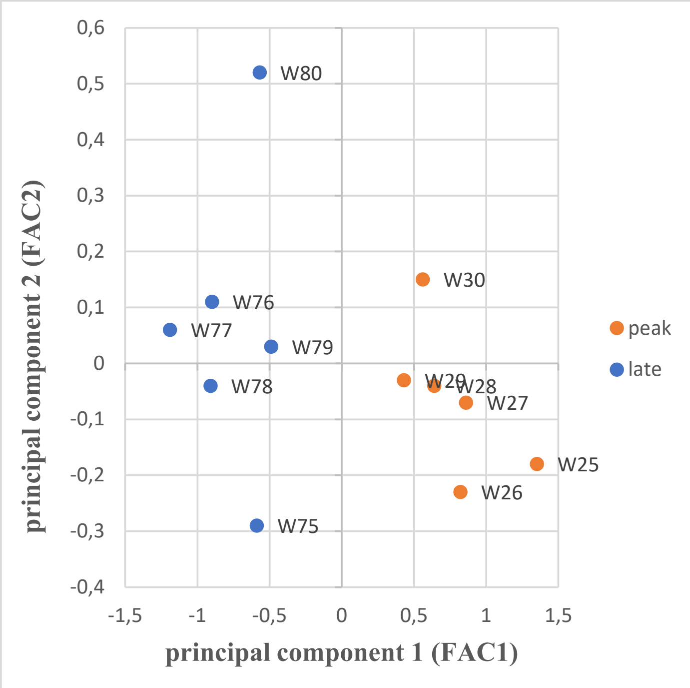

Figure 1. Weekly mean scores on principal components 1 and 2.

Conclusion

This study confirms the viability of ISA Brown hens to maintain acceptable egg quality up to 80 weeks under Algerian conditions. Despite declines in freshness-related traits with age, structural integrity remained stable, suggesting physiological adaptability. The weakening of inter-trait correlation in late lay suggests a decoupling of structural and compositional integration, reinforcing the need for direct measurement of freshness and internal quality indicators beyond surface parameters. Collectively, the results confirm that Isa Brown hens can remain productive with acceptable egg quality beyond conventional culling thresholds. Extending laying cycles under controlled environmental and nutritional conditions is feasible and may contribute to more sustainable poultry production in semi-arid regions. Future research should therefore integrate performance, welfare, and cost-benefit analyses beyond 80 weeks to guide long-term data-driven strategies for the poultry industry.

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