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Investigation of Physical Properties of Egg and shell Strength in Final Phase of Industrial Production

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ABSTRACT

Eggs are a product with high nutritional value and are a good source of protein, vitamins and essential minerals that can be an important food item in human diets. This research was conducted in a 100,000-piece industrial poultry unit equipped with smart and automatic sensors in the final phase of production (68-77 weeks). During this period, which is the stage of aging of the poultry and the end of egg production, knowing the trend of the physical properties of eggs is very important for the producer to manage the diet and analyze the cost-benefit. The parameters studied included the physical properties of eggs including weight, sphericity, shape index, section area, shell thickness, shell weight, shell percentage and shell strength. The results showed that the egg weight had an increasing trend in the final period of production, but the shell thickness and shell strength decreased significantly after week 74. Despite the significant egg length and width, the shape index was not significant. The sphericity coefficient showed that the shape of the eggs changed from cylindrical to circular. The highest eggshell strength was in week 68, at about 5.6 kg/cm², and the lowest was in week 77, at 4.5 kg/cm². According to the results of this study, the need for scientific management in the final phase of production in the laying poultry industry, taking into account changes in physical properties, is essential to prevent cracking and breakage of eggs in order to ensure profitability.

1- INTRODUCTION

Food security is increasingly becoming a critical global concern due to a range of anthropogenic factors, including climate change and the contamination of air, water, and soil, which are further exacerbated by the rapid growth of the world's population. These factors directly affect primary food production and contribute to a substantial increase in global food demand. By 2050, the global population is projected to increase from 7.7 billion to 9.2 billion, potentially resulting in a significant shortage of safe, nutritious, and high-quality food. Moreover, the global urban population is expected to account for approximately 66% of the total population, while food demand is projected to increase substantially, potentially ranging from 59% to 98% [1].

Therefore, the global production of widely consumed and nutritionally important foods, such as eggs and poultry meat, must be increased in a safe, consistent, and sustainable manner to meet the growing demand for food. Ensuring appropriate access to safe, nutritious, and readily available food is a fundamental concern in achieving food security. The primary objective of the modern food industry is to ensure food security and safety by establishing a safer, more efficient, resilient, and sustainable food supply chain extending from farm to fork. A considerable proportion of the global population is currently facing a worldwide epidemic of diet-related chronic diseases, which has stimulated increasing research into the use of food as medicine for the prevention, management, and treatment of various diseases. With the advancement of the industrial revolution and food science, researchers are increasingly focusing on enhancing targeted food properties, including high nutrient density, reduced risks of certain diseases, and improved gastrointestinal health. Such advances are intended to promote healthier lifestyles and contribute to a productive and meaningful quality of life [2].

The importance of eggs and egg-related products as one of the primary sources of dietary protein in everyday human life is indisputable. From 2010 to 2030, global egg production is projected to increase by approximately 35%, with Asia accounting for 64.8% of the total global growth [3].

Field investigations conducted to determine the prevalence of egg defects in the United States have estimated that approximately 3–5% of eggs develop cracks or become broken prior to packaging. When a large proportion of laying hens in a poultry farm are relatively old, or when significant and multiple problems occur in egg production and handling equipment, the proportion of cracked eggs may increase to as high as 10%. The proportion of dirty eggs has been reported to be slightly above 1%, whereas eggs with blood spots have accounted for approximately 1% of the total egg production [4].

Eggshells possess a hard and mechanically strong structure composed of both inorganic minerals and organic components, whose primary function is to protect the internal contents of the egg. This protective structure is the result of millions of years of evolutionary and reproductive adaptation in birds. The egg yolk and albumen exchange oxygen and moisture with the external environment through the eggshell. Consequently, any alteration in the structural integrity or physical properties of the eggshell can substantially affect the quality and stability of the egg contents. Cracks in the eggshell increase the exchange of moisture and oxygen between the internal contents of the egg and the external environment, thereby compromising the protective barrier provided by the shell [5].

Eggshell is formed as a porous biological ceramic at body temperature and within an acellular environment. This biomineralization process is considered one of the fastest calcium mineralization processes known to date. Approximately 96% of the eggshell is composed of calcium carbonate (CaCO_3), while the remaining fraction consists primarily of an organic matrix, magnesium, phosphorus, and several trace elements [6].

In one study, a shell strength of approximately 17 MPa was measured for freshly laid eggs, whereas a value of approximately 14 MPa was obtained for eggs sampled at the retail level. This reduction in shell strength was attributed to the accumulation of micro-defects in the eggshell during handling and transportation, resulting in a mechanically weaker eggshell structure [7].

The productive lifespan of laying hens is closely associated with the quality of the eggs they produce. As hens age, eggshell quality gradually deteriorates. Consequently, older

hens become less capable of consistently producing eggs with acceptable quality, ultimately contributing to the end of their productive lifespan. Therefore, eggshell quality can be considered an important factor associated with the productive longevity of commercial laying hens [8].

Numerous studies have reported that eggshell quality tends to decline as laying hens age. Eggs produced by older hens are generally larger and have thinner eggshells [9–10].

The results of a study showed that the fracture strength of eggshells produced by 58-week-old laying hens was less than half that of eggshells produced by 30-week-old hens [11].

The egg industry will face new challenges in meeting the growing demand for eggs while complying with increasingly stringent safety and quality standards [12].

The aim of the present study is to provide a comprehensive understanding of the changes in the physical properties of eggs and eggshell strength during the late stage of the laying cycle, thereby supporting appropriate management practices in commercial poultry production systems. The findings of this study may contribute to improving productivity and efficiency in the poultry industry and, ultimately, enhancing food security at the national level.

2- Materials and Methods

Fresh eggs were obtained from a commercial poultry farm located in the vicinity of Bonab County, Iran. The laying hens were maintained under standard nutritional conditions in a cage housing system. The poultry farm had a capacity of 100,000 laying hens and was equipped with automated sensors and control systems for temperature, relative humidity, pressure, carbon dioxide concentration, lighting, air velocity, and ventilation.

The egg-processing facility had a packaging capacity of 36,000 eggs per hour. The transfer of eggs from the cages to the packaging line was fully automated and performed without human intervention using canvas and cylindrical conveyor belts.

A total of 600 egg samples were selected during the final stage of commercial egg production at four hen-age stages: 68, 71, 74, and 77 weeks.

The collected eggs were stored for 5 days under controlled environmental conditions at a temperature of 20–25 °C and a relative humidity of 40–50%. Quantitative physical tests were subsequently performed using direct measurement methods, as described below.

2.1. Determination of Egg Weight

The egg weight was determined using a digital balance (Sartorius, Germany) with a precision of 0.001 g. Each egg was weighed individually, and its mass was recorded in grams.

2.2. Determination of Shape Index

To determine the shape index (SI), the length (L) and width (W) of each egg were measured using a caliper with an accuracy of 0.01 mm. The shape index was then calculated as a percentage using the following equation [13].

$$SI = \left(\frac{W}{L} \right) \times 100$$

where (W) is the maximum egg width (mm) and (L) is the egg length (mm).

2.3. Determination of Geometric Mean Diameter

The geometric mean diameter (D_g) of the eggs, expressed in millimeters, was calculated using the following equation [14].

$$D_g = \sqrt[3]{L W^2}$$

where (L) is the egg length (mm) and (W) is the maximum egg width (mm).

2.4. Determination of Sphericity

The sphericity (Ø) of the eggs, expressed as a percentage, was calculated according to the following equation [14].

$$\emptyset = \left(\frac{D_g}{L} \right) \times 100$$

where (D_g) is the geometric mean diameter (mm) and (L) is the egg length (mm).

2.5. Determination of Surface Area

The surface area (SA) of each egg, expressed in cm², was calculated using the following equation [14].

$$SA = \pi Dg^2$$

2.6. Determination of Eggshell Thickness

Eggshell thickness was measured using a dial micrometer (FHK, Japan) with an accuracy of 0.01 mm. Measurements were taken at three locations on each eggshell: the narrow end (small end), the broad end (large end), and the middle region. The arithmetic mean of the three measurements was calculated and considered the final eggshell thickness.

2.7. Determination of Eggshell Breaking Strength

Eggshell breaking strength was measured using a Japanese eggshell strength tester (Model OSK-13473, Japan), equipped with a pressure gauge with a measurement range of 0–6 kg/cm². For the measurement procedure, each egg was positioned vertically between two parallel plates of the instrument, with the load applied to the equatorial region of the egg. Compressive force was gradually applied until the eggshell fractured. At the moment of shell failure, the applied load was read from the pressure gauge and recorded as the eggshell breaking strength (Figure 1).



Fig 1. Eggshell Strength Measurement Device

commercial production are presented in Table 1.

3- Results and Discussion

The results of the evaluation of the physical properties of the eggs during the final stage of

Table 1. Effect of chicken age on physical properties of eggs

Age/ Trait	Egg weight (g)	W (mm)	L (mm)	SI (%)	D _g (mm)	Ø (%)	SA (cm ²)
68 wks	52.23 ^c	41.87 ^b	52.90 ^c	79.2	45.26 ^c	85.55 ^a	64.35 ^c
71 wks	57.38 ^c	43.05 ^{ab}	54.79 ^c	78.6	46.81 ^b	85.43 ^a	68.83 ^c
74 wks	64.07 ^b	44.65 ^{ab}	57.01 ^b	78.4	48.43 ^b	84.95 ^a	73.68 ^b
77 wks	71.58 ^a	46.61 ^a	68.63 ^a	79.6	53.02 ^a	77.25 ^b	88.31 ^a

^{a,b,c} Means within column with different superscript letters for each factor are significantly different ($p < 0.05$). wks= weeks, L= egg length, W= egg width, SI= shape index, Dg= geometric mean diameter, Φ = sphericity, SA= surface area. N= 300 intact eggs.

3.1. Physical Properties of Eggs

The effect of hen age on egg weight was statistically significant, and the results showed that egg weight increased with increasing hen age (Figure 2). As shown in Figure 1, during the period from 68 to 74 weeks of age, the eggs

were classified as large and extra-large. However, after 74 weeks of age, egg weight exceeded 70 g. At this stage, the larger egg size makes packaging more difficult and increases the risk of mechanical damage during handling and processing. Therefore, continuation of egg production beyond 74 weeks of hen age may not be economically feasible.

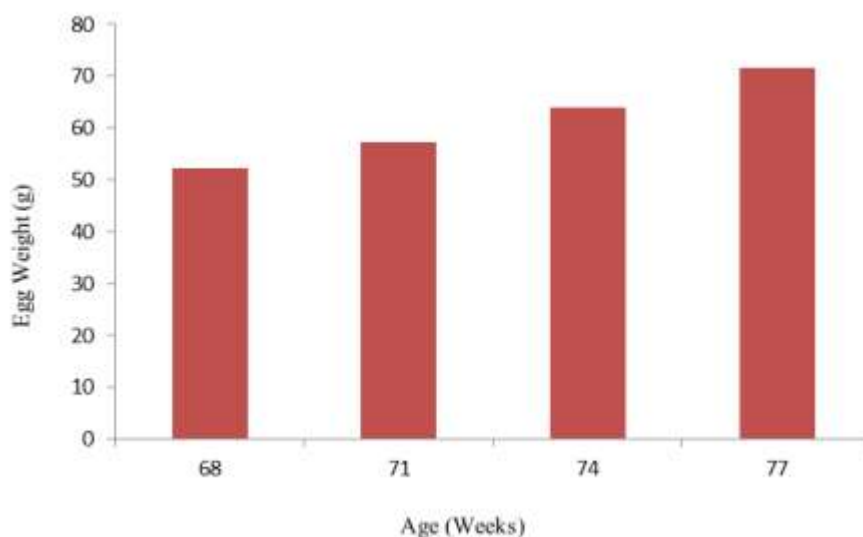


Fig 2. Effect of Chicken Age on Egg Weight at Final Phase of Production

According to Table 1, the dimensional characteristics of the eggs, including length and width, differed significantly across the age range investigated; however, the shape index, which represents the ratio between these two parameters, did not differ significantly. The results reported in [15] showed that the shape index decreased with increasing hen age, declining from 0.79 to 0.76%. The findings of [16] also confirmed a decrease in the shape index as hen age increased.

The results for sphericity indicated that the eggs tended to change in shape during the final stages of production, shifting from a more cylindrical form toward a more spherical form. The

specific surface area of the eggs also increased significantly over time.

Egg weight is an appropriate indicator of egg size and is an important parameter in the commercialization of eggs, as consumers generally prefer larger eggs. However, one of the major challenges facing the poultry industry is the production of larger eggs with sufficient structural integrity to withstand handling and transportation. Since an increase in egg weight is associated with reductions in eggshell strength and thickness [17], it was therefore necessary to evaluate differences in eggshell properties according to hen age.

3.2. Physical Properties and Breaking Strength of the Eggshell

The results of the evaluation of the physical properties and breaking strength of the eggshells during the final stage of commercial egg production are presented in Table 2.

Table 2. Effect of chicken age on physical properties of eggshell

Age/ Trait	T (μm)	SW (g)	S (%)	Strength (Kg/cm^2)
68 wks	377 ^a	7.1 ^b	9.5 ^{ab}	5.6 ^a
71 wks	352 ^b	7.4 ^{ab}	9.2 ^b	4.7 ^b
74 wks	363 ^{ab}	7.8 ^a	9.9 ^a	4.9 ^b
77 wks	349 ^b	7.5 ^{ab}	9.6 ^{ab}	4.5 ^b

^{a,b} Means within column with different superscript letters for each factor are significantly different ($p < 0.05$).

wks= weeks, T= shell thickness, SW= shell weight, S%= shell percentage. N= 300 intact eggs.

The effect of hen age on eggshell thickness was statistically significant, indicating that eggshell thickness decreased with increasing hen age.

Despite a slight increase at 74 weeks of age, the overall trend in eggshell thickness was downward (Figure 3).

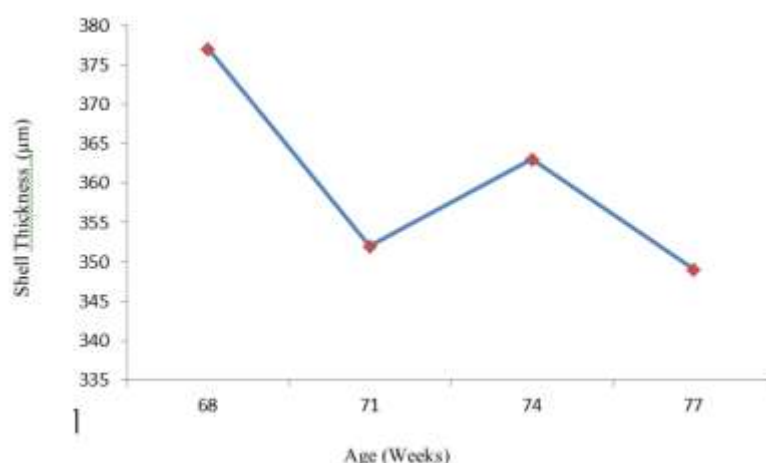


Fig 3. Effect of Chicken Age on Shell Thickness at Final Phase of Production

A previous study reported that eggshell thickness increased during the mid-laying period (40–55 weeks of age) and gradually decreased as the hens aged [17].

The results of evaluating the effect of hen age on eggshell breaking strength showed that the

highest value was recorded at 68 weeks of age, at 5.6 kg/cm^2 , whereas the lowest value was observed at 77 weeks of age, at 4.5 kg/cm^2 . These findings indicate that eggshell breaking strength decreased with increasing hen age (Figure 4).

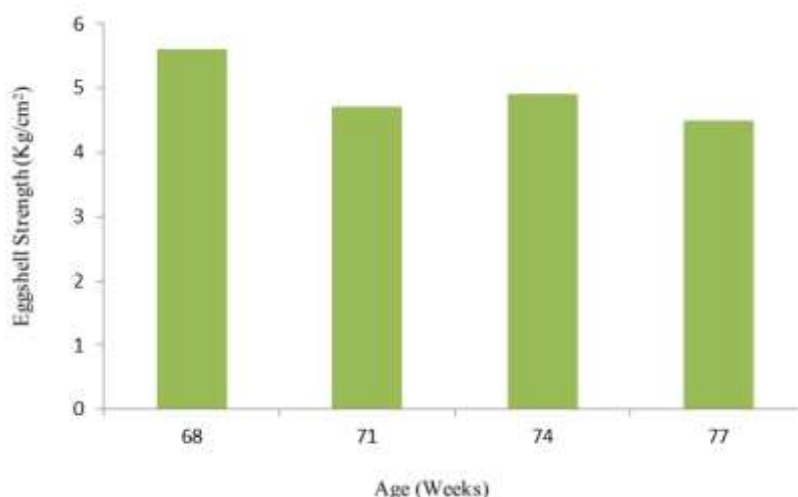


Fig 4. Effect of Chicken Age on Eggshell Strength at Final Phase of Production

The results concerning eggshell breaking strength in older laying hens showed that shell strength decreased with increasing hen age. Although the reduction in shell strength may become apparent from a particular point in the laying cycle, the available evidence indicates a consistent age-related decline in eggshell strength. In this regard, the findings reported in [18] demonstrated a significant reduction in eggshell breaking strength between 22 and 83 weeks of hen age, which is consistent with the results of the present study.

Research on eggshells has primarily focused on the premise that a better understanding of eggshell structure and formation could contribute to improvements in eggshell quality. Further insights into the biological and mechanical characteristics of the eggshell may facilitate advances in shell quality and integrity. With the objective of reducing production losses and associated economic costs, research aimed at improving egg quality has continued for several decades.

Although studies of eggshell characteristics have provided valuable insights, the evidence regarding effective approaches for directly improving eggshell quality remains inconclusive. Numerous studies have overlapping findings; however, they do not yet provide a comprehensive and integrated understanding of eggshell structure, formation, and quality. Given the biological nature of the

eggshell as a complex biomineralized structure, substantial natural variation is inevitable. Consequently, differences among research groups and experimental studies [19–23] are evident and warrant further investigation and critical discussion.

4- Conclusion

The present study specifically evaluated the physical properties of eggs under commercial poultry production conditions. Eggs are a staple food consumed worldwide, and their quality has a substantial impact on consumers and the food supply chain. The poultry industry is continuously evaluating strategies to reduce eggshell defects and breakage in order to minimize product losses and associated economic costs. Therefore, further research into these potential effects is recommended to address some of the unresolved questions concerning eggshell structure, quality, and mechanical integrity.

The overall findings of this study indicate that eggshell breaking strength decreases as egg weight increases, suggesting that larger eggs are more susceptible to breakage. Possible explanations for this relationship may include changes in eggshell pore size or alterations in crystal size and microstructure; however, these hypotheses have not yet been experimentally confirmed and should be investigated in future studies. In addition, the results indicated that

eggshell thickness remained relatively stable despite changes in egg weight and hen age.

Further studies are required to comprehensively identify and confirm the factors affecting eggshell mechanical integrity. A deeper understanding of the material properties, microstructure, and mechanical behavior of eggshells would benefit the poultry industry by facilitating the development of innovative approaches for modifying production and handling systems, thereby reducing eggshell breakage and associated waste. The present study demonstrates that substantial opportunities remain for future research on eggshell fracture behavior and on the intrinsic and extrinsic factors influencing eggshell mechanical performance.

Data Availability

The dataset was used for training, validation, and testing of deep learning models after preprocessing, quality control, and labeling. Due to considerations related to data ownership and research use of images, the raw data have not been made publicly available. Data related to this study will be made available to researchers for scientific and research purposes upon reasonable request and with the approval of the corresponding author.

Conflict of Interest

The authors declare that there are no financial, commercial, organizational, or personal conflicts of interest that could have influenced the research design, data collection and analysis, interpretation of results, or writing of the article.

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Authors Contributions

The first author participated in the study design, data collection and preparation, development and training of deep learning models, statistical and computational analyses, interpretation of

results, and preparation of the initial draft of the paper. The second and third authors participated in the design of the research methodology, supervision of the study process, scientific review, and final editing of the paper. All authors have read and approved the final draft of the paper and accept responsibility for its scientific content.

AI statement

In preparing this article, generative artificial intelligence tools were used in about 10% of the text preparation process. The use of artificial intelligence was done solely to improve writing and linguistic editing, translate some sections, correct sentence structure, and help organize the material. The authors carried out the design of experiments, data collection, data processing and analysis, training and evaluation of models, statistical calculations, interpretation of results, and scientific decision-making. The authors bear full responsibility for the accuracy, originality, and scientific content of the article.

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بررسی ویژگی‌های فیزیکی تخم مرغ و استحکام پوسته در فاز نهایی تولید صنعتی

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خواص فیزیکی،

تخم مرغ،

استحکام پوسته،

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فاز نهایی

تخم مرغ محصولی است که ارزش غذایی فراوانی دارد و منبع خوبی از پروتئین، ویتامین ها و املاح ضروری است که می تواند به عنوان یک ماده غذایی مهم در برنامه غذایی افراد قرار داشته باشد. این تحقیق در یک واحد مرغداری صنعتی ۱۰۰ هزار قطعه ای مجهز به حسگرهای هوشمند و خودکار در فاز نهایی تولید (۷۷-۶۸ هفتگی) انجام شد. در این بازه که مرحله مسن بودن طیور و انتهای تولید تخم مرغ است، دانستن روند خواص فیزیکی تخم مرغ ها برای مدیریت جیره غذایی و تحلیل هزینه به فایده برای تولیدکننده بسیار حائز اهمیت است. پارامترهای مورد مطالعه شامل خواص فیزیکی تخم مرغ شامل وزن، ضریب کرویت، شاخص شکل، سطح مقطع، ضخامت پوسته، وزن پوسته، درصد پوسته و استحکام پوسته بودند. نتایج نشان داد که وزن تخم مرغ در بازه نهایی تولید، روند افزایشی داشت ولی ضخامت پوسته و استحکام پوسته بعد از هفته ۷۴ به طور معنی داری کاهش یافتند. علیرغم معنی دار بودن طول و عرض تخم مرغ، شاخص شکل معنی دار نبود. ضریب کرویت نشان داد که تغییر شکل تخم مرغ ها از استوانه ای به دایره ای بودند. بیشترین مقدار استحکام پوسته تخم مرغ در هفته ۶۸، در حدود ۵/۶ کیلوگرم بر سانتیمتر مربع و کمترین آن در هفته ۷۷، با ۴/۵ کیلوگرم بر سانتیمتر مربع بود. با توجه به نتایج این تحقیق، لزوم مدیریت علمی در فاز نهایی تولید در صنایع مرغداری تخم گذار با لحاظ تغییرات خواص فیزیکی برای جلوگیری از بروز ترک و شکستگی تخم مرغ ها در راستای تضمین سودآوری ضروری است.

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