

## EGG MORPHOMETRY AND EGGSHELL COLOR CHARACTERISTICS OF CHUKAR PARTRIDGE (*ALECTORIS CHUKAR*)

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### ABSTRACT

Eggshell color is an important external trait in birds, reflecting pigment deposition and species-specific characteristics. The aim of the present study was to characterize the eggshell color of chukar partridge (*Alectoris chukar*) eggs in different shell regions and across egg weight categories using instrumental colorimetric measurements in the CIE L\*a\*b\* system in a population reared in a game farm in Bulgaria. A total of 90 fresh eggs obtained from captive-bred birds maintained for restocking purposes in a game farm in Bulgaria were analyzed. The birds were 12 months old and in the mid-laying period. Eggs were classified into three weight categories (<21 g, 21–23 g, and >23 g). Egg morphometry was assessed through measurements of egg weight, major axis length, and minor axis length, from which the shape index and shell surface area were calculated. The mean color coordinates (L\* = 78.12, a\* = 7.71, b\* = 17.90) position the eggshell color in the light yellowish-reddish region of the CIE L\*a\*b\* color space, corresponding to the pale cream spotted coloration typical of chukar partridge eggs. Minor but statistically detectable regional variations in color parameters were observed across the eggshell surface, while no statistically significant differences in color characteristics were detected among the examined egg weight categories. These results indicate that eggshell color in chukar partridge eggs is relatively stable across different egg sizes, with slight regional variation reflecting differences in pigment deposition within the eggshell.

**Key words:** *Alectoris chukar*, eggshell color, CIE L\*a\*b\*, colorimetry, eggs, Chroma.

### Introduction

The chukar partridge (*Alectoris chukar* Gray, 1930) is a traditional game bird belonging to the family Phasianidae and is widely distributed across Southeastern Europe, the Middle East, parts of North Africa (Egypt), and large areas of South and East Asia (Bilal, 2022). The global population is estimated at 5–35 million individuals, and the species is currently classified as Least Concern on the International Union for Conservation of Nature Red List (BirdLife International, 2019).

Under natural conditions, chukar partridges typically lay between 8 and 16 eggs per clutch (Yilmaz & Tepeli, 2009). However, clutch size may increase considerably under captive rearing conditions, where birds are maintained under improved environmental and nutritional conditions (Kirikci *et al.*, 1999). The egg mass generally ranges from 16 to 25 g, with average dimensions of approximately 42 mm (major egg axis) and 31 mm (minor egg axis) (Caglayan *et al.*, 2014; Alkan *et al.*, 2015; Zahra *et al.*, 2015).

Egg coloration in birds is highly variable and has evolved in association with several biological functions, among which protection, particularly through camouflage, is considered one of the

most important (Castilla *et al.*, 2007; Gu *et al.*, 2025). Eggshell color is primarily determined by two pigments: protoporphyrin and biliverdin (Baird *et al.*, 1975). The relative presence and distribution of these pigments determine the final shell coloration. Biliverdin pigmentation, either alone or in combination with protoporphyrin, typically results in blue-green eggshell coloration, whereas protoporphyrin pigmentation produces cream to brown shells (Lu *et al.*, 2021). In contrast, the absence or very low concentration of these pigments results in white eggshells (Gu *et al.*, 2025). The spots or markings on eggshells may vary in intensity, size, and shape and are often characteristic of particular bird species. These markings are caused by localized deposition of protoporphyrin on or within the eggshell surface during shell formation (Kennedy & Vevers, 1976; Bulla *et al.*, 2012).

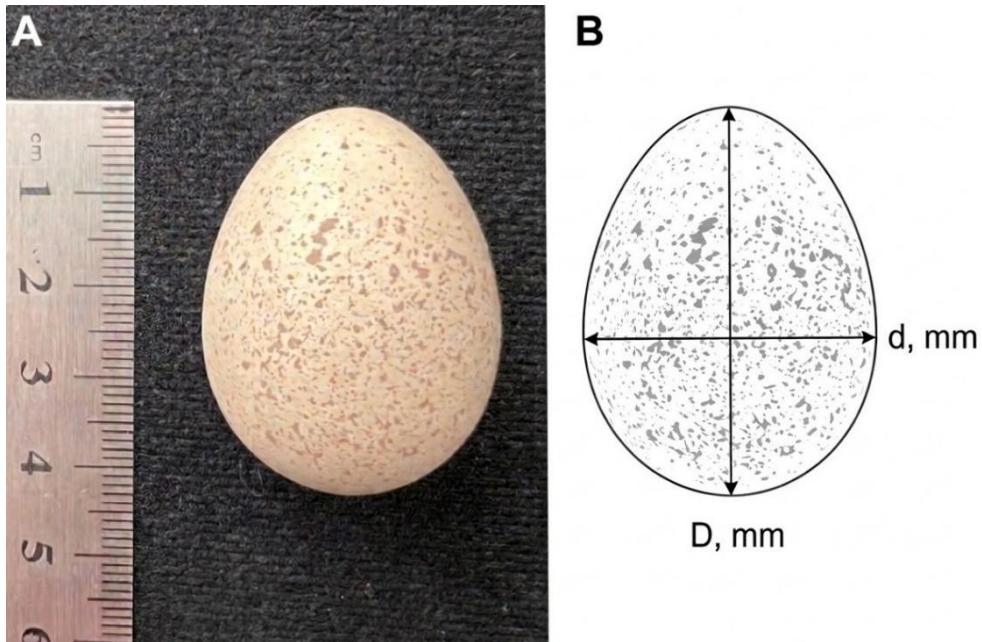
Chukar partridge eggs are typically described as yellowish to grey-brown in color, often with reddish-brown speckling (Harrison & Castell, 2004). Based on visual assessment, Zahra *et al.* (2015) classified chukar partridge eggs into five color groups ranging from white to dark cream, differing in the size and distribution of dark spots. In contrast, Caglayan *et al.* (2014) categorized the eggs into two groups - spotted and non-spotted, and further evaluated their color characteristics using colorimetric measurements in the CIE L\*a\*b\* system. Based on the available literature, this appears to be the only study applying instrumental colorimetry to chukar partridge eggshells, with measurements performed only at the blunt pole of the egg.

Information in the scientific literature regarding the colorimetric characteristics of chukar partridge eggs determined by instrumental methods therefore remains limited, and data on the relationship between eggshell color and egg size are lacking. Therefore, the aim of the present study was to characterize the eggshell color of chukar partridge (*Alectoris chukar*) eggs in different regions of the shell and across egg weight categories using instrumental colorimetric measurements in the CIE L\*a\*b\* system in a population reared in a game farm in Bulgaria.

## Materials and Methods

A total of 90 fresh eggs of the chukar partridge (*Alectoris chukar*) were used in the study. All eggs were collected within a single day in May 2025. The eggs were obtained from captive-bred birds kept at a specialized game farm for restocking purposes located near the city of Sliven, Southern Bulgaria. Only clean eggs with intact shells were selected for the study. The birds were 12 months old, corresponding to the mid-laying period. The eggs were classified into three groups according to their weight: <21 g, 21-23 g, and >23 g. Eggs without shell spotting were not observed; therefore, all analyzed eggs exhibited varying degrees of eggshell spotting typical of the species.

Egg morphometry was assessed through external measurements including egg weight (W, g), major axis length (D, mm), and minor axis length (d, mm) of each egg (Figure 1). Using these parameters, the shape index (SI, %) and shell surface area (cm<sup>2</sup>) were calculated. Egg weight was measured using an electronic scale (Kern EMB 200-3, KERN & SOHN GmbH) with an accuracy of ±0.01 g. Egg dimensions were measured with a Vernier caliper (ZIIU Standard model 150, 250 mm, ZIIU Standard Plc., accuracy ±0.05 mm).



**Figure 1: Morphometric measurements of a chukar partridge (*Alectoris chukar*) egg. A: Original photograph used for size, colour and pattern assessment; B: Schematic representation of the measurement positions for the major (D) and minor (d) egg axes.**

The shape index (SI, %) was computed according to the following equation:

$$SI = (d/D) \times 100 [1],$$

where  $d$  represents the minor egg axis (mm), and  $D$  the major egg axis (mm) (Romanoff & Romanoff, 1949).

Shell surface area (SSA,  $\text{cm}^2$ ) was estimated based on egg weight using the formula:

$$SSA = 4.835 \times W^{0.662} [2],$$

where  $W$  corresponds to egg weight expressed in grams (Paganelli *et al.*, 1974).

Eggshell color was evaluated by instrumental colorimetric analysis using a portable colorimeter (PCE-CSM 2, PCE Instruments SE) fitted with a silicon photodiode sensor, an LED illuminant D65, and an 8-mm measuring aperture. Measurements were obtained within the CIE  $L^*a^*b^*$  color space. For each egg, color measurements were taken at three standardized positions: the equatorial region, the pointed end, and the blunt end. The  $L^*$ ,  $a^*$ , and  $b^*$  values recorded at each location were averaged to obtain mean values.

To characterize overall eggshell coloration, the mean  $L^*$ ,  $a^*$ , and  $b^*$  values from the three measurement sites were used for subsequent calculations. Based on the CIE  $L^*a^*b^*$  data, chroma ( $C^*$ ) and the shell color index ( $SCI^{**}$ ) were derived. Chroma was calculated using the equation:

$$C^* = \sqrt{(a^2 + b^2)} [3],$$

where “ $a$ ” indicates the green-red axis and “ $b$ ” the blue-yellow axis of the CIE color space (CIE, 1976).

The shell color index, proposed by Lukanov *et al.* (2016; 2018) was calculated using the following equation:

$$SCI^{**} = (L^* - C^*) [4],$$

where  $C^*$  expresses color saturation and  $L^*$  denotes lightness on a scale from 0 (black) to 100 (white).

AI-assisted tools (ChatGPT, OpenAI, version 5.2) were used to support language editing and translation into English. Additionally, the 3D visualization of the CIE  $L^*a^*b^*$  color space (Figure 2) was generated using Python code (Matplotlib library) developed with the assistance of the Gemini AI (Google) and executed in the Google Colab environment. All scientific interpretation, data analysis, and final conclusions were performed exclusively by the authors.

Statistical analyses were performed using the software package SPSS, version 26.0 (IBM Corp., Armonk, NY, USA). Results are presented as mean  $\pm$  standard deviation (SD). For the evaluation of general morphometric traits, descriptive statistics were applied, including mean, standard deviation, minimum, and maximum values.

Prior to analysis of variance, data were tested for normality and homogeneity of variances. Differences among egg groups classified according to weight and among different eggshell regions (pointed end, equatorial region, and blunt end) were evaluated using one-way analysis of variance (ANOVA). When significant differences were detected, group means were compared using Tukey's post hoc test (adjusted for unequal sample sizes). Statistical significance was set at  $P < 0.05$ .

## Results and Discussion

The summarized values for the external morphometric traits of the examined chukar partridge eggs are presented in Table 1. The mean egg weight was  $21.89 \pm 1.35$  g, ranging from 17.52 to 24.64 g. The mean values of the major and minor egg diameters were  $41.01 \pm 1.24$  mm and  $31.35 \pm 0.79$  mm, respectively, with relative variations of 13.67% for the major axis and 13.03% for the minor axis. A more rounded egg shape results in higher values of the shape index (SI), whereas more elongated eggs are characterized by lower SI values (Genchev & Lukanov, 2018). In the present study, the mean shape index was  $76.49 \pm 2.34\%$ , ranging from 69.18% to 80.90%, indicating a relatively uniform egg shape within the studied sample. The obtained results for the main external morphometric characteristics of chukar partridge eggs are comparable with those reported by other authors (Caglayan *et al.*, 2014; Alkan *et al.*, 2015; Zahra *et al.*, 2015; Ameen *et al.*, 2023; Cam *et al.*, 2024). The mean eggshell surface area (SSA) was  $37.28 \text{ cm}^2$ , with individual values ranging from 32.18 to  $40.33 \text{ cm}^2$ . The observed variation in SSA is logically associated with differences in egg size and weight.

**Table 1: Basic morphometric traits of eggs from the chukar partridge (n = 90)**

| Parameter | W, g  | D, mm | d, mm | SI, % | SSA, $\text{cm}^2$ |
|-----------|-------|-------|-------|-------|--------------------|
| Mean      | 21.89 | 41.01 | 31.35 | 76.49 | 37.28              |
| SD        | 1.35  | 1.24  | 0.79  | 2.34  | 1.53               |
| Min       | 17.52 | 38.41 | 28.98 | 69.18 | 32.18              |
| Max       | 24.64 | 44.49 | 33.32 | 80.90 | 40.33              |

Note: W – egg weight; D – major egg axis; d – minor egg axis; SI – shape index; SSA – shell surface area; SD – standard deviation.

The main colorimetric characteristics related to the CIE  $L^*a^*b^*$  color space for all examined eggs are presented in Table 2, and Figure 2 illustrates a 3D representation of the color coordinates ( $L^*$ ,  $a^*$ ,  $b^*$ ) for the Chukar partridge egg. The eggs were characterized by a mean lightness value ( $L^*$ ) of  $78.12 \pm 2.82$ , with individual values ranging from 74.00 to 83.77. These values indicate that the eggshell color of the chukar partridge falls within the range typical of light-colored eggshells. This is expected due to the visibly light background color of the shell and the relatively small and weakly pigmented spots, which have only a limited influence on overall shell lightness.

Lower values of the lightness parameter ( $L^*$ ) are associated with higher concentrations of the brown pigment protoporphyrin, whereas higher values are characteristic of shells with little or no pigmentation (Li *et al.*, 2013; Lu *et al.*, 2021). When compared with the uniformly colored shells of chicken eggs, the obtained values are comparable to those typical of cream-colored chicken eggs, indicating a moderate level of overall protoporphyrin pigmentation. In brown eggshells,  $L^*$  values are typically below 65, whereas in non-pigmented shells they usually exceed 90 (Lukanov *et al.*, 2016). In the study of Caglayan *et al.* (2014), which investigated two types of eggshell coloration in the chukar partridge, slightly lower mean  $L^*$  values were reported for spotted eggs, whereas the lightness of non-spotted eggs was comparable to the values observed in the present study for spotted eggs. These minor differences may be attributed to genetic variation among the studied populations, the measurement location on the eggshell, the type of instrument used, the laying period, and other experimental conditions. When considering the specific region of eggshell color measurement, the present study showed slightly higher mean  $L^*$  values at the pointed end of the egg compared with the blunt end and the equatorial region, with differences of approximately 1.6% and 2.65% ( $P < 0.05$ ), respectively (Figure 3). This pattern suggests a slightly lower degree of pigment deposition in the pointed region of the eggshell. A similar relationship in the distribution of eggshell pigmentation across different egg regions has also been reported for chicken eggs (Lukanov *et al.*, 2016).

The other two main parameters of the CIE  $L^*a^*b^*$  system are the chromatic axes  $a^*$  and  $b^*$ , representing the red–green and yellow–blue color spectra, respectively. Positive values of  $a^*$  indicate a shift toward red, whereas negative values indicate a shift toward green. Along the  $b^*$  axis, positive values correspond to yellow coloration, while negative values indicate blue coloration (CIE, 1976).

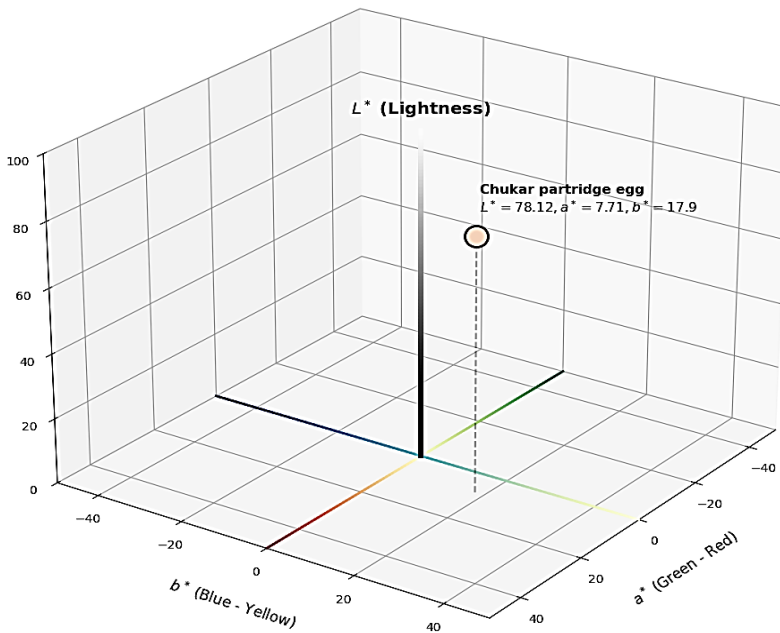
In the present study, low positive mean values of  $a^*$  were recorded for all examined eggs, with an average value of  $7.71 \pm 1.95$  (min-max: 2.74 - 10.07), which places the eggshell color of the chukar partridge in the lower range of the red spectrum. This can be explained by the presence of protoporphyrin deposition, whereas the presence of the other main pigment, biliverdin, would be associated with negative  $a^*$  values (Lukanov *et al.*, 2016; Drabik *et al.*, 2021; Beranova *et al.*, 2024). When comparing the  $a^*$  values obtained in the present study with those reported by Caglayan *et al.* (2014) for chukar partridge eggs, more pronounced differences are observed than for the  $L^*$  parameter. The authors reported nearly twofold lower mean values for the spotted eggs ( $a^* = 4.06 \pm 0.25$ ). This discrepancy may be related to the genetic characteristics of the studied population, in which a relatively large proportion of eggs without spotting was recorded. The lower degree of eggshell spotting and the weaker deposition of protoporphyrin may therefore influence the overall  $a^*$  values. Unlike the  $L^*$ , more pronounced differences in  $a^*$  values were observed among the three examined regions of the egg (Figure 3). The lowest mean value was recorded in the equatorial

region (7.48), whereas the highest value was found at the blunt end (7.97), representing a nonsignificant difference of 6.15% ( $P > 0.05$ ). A similar pattern of regional variation in  $a^*$  values associated with protoporphyrin deposition has also been reported in chicken eggs (Lukanov *et al.*, 2016).

The mean value of  $b^*$  was relatively high and positive, amounting to  $17.90 \pm 2.25$ , with minimum–maximum values ranging from 12.55 to 20.82. These results may also be associated with protoporphyrin deposition in the eggshell. In the scientific literature, lower positive or negative  $b^*$  values close to zero are typically reported for non-pigmented eggshells, whereas eggshells with biliverdin deposition usually show slightly higher values (approximately 6.5 - 10.0) (Lukanov *et al.*, 2016; Drabik *et al.*, 2021; Beranova *et al.*, 2024). Interestingly, the presence of protoporphyrin and the degree of eggshell deposition with this pigment do not appear to exert a strong influence on  $b^*$  values. This is evident from the study of Lukanov *et al.* (2016), where eggs with dark brown shells exhibited lower  $b^*$  values than those with brown shells. These findings suggest that, unlike the  $a^*$  parameter, the  $b^*$  values observed in the present study are comparable to those reported by Caglayan *et al.* (2014) for spotted eggs. This may indicate that the  $b^*$  parameter is influenced more strongly by the overall coloration of the eggshell rather than by the degree of spotting or the intensity of pigment deposition.

When the yellow component ( $b^*$ ) was analyzed across different regions of the egg, only minor nonsignificant differences of approximately 3.36% were observed ( $P > 0.05$ ). The lowest values were recorded in the equatorial region (17.53) compared with the two poles of the egg.

The observed regional variations in eggshell colorimetric parameters can be attributed to the position of each egg zone during shell formation, as well as the distribution of pigment-secreting glands in the uterine segment (shell gland) of the oviduct. As the equatorial region represents the widest part of the egg, its passage likely causes a relative stretching of the oviduct wall, resulting in a reduced density of pigment glands per unit area. Consequently, pigmentation in this region is less intense, as reflected by the lower  $a^*$  and  $b^*$  values. In contrast, at the pointed and blunt ends, where the oviduct maintains a more natural shape and higher gland density, the egg exhibits stronger pigmentation. The higher lightness ( $L^*$ ) observed at the pointed end further suggests a lower degree of maculation (spotting) in this specific region. Therefore, the final eggshell appearance in the chukar partridge reflects a combined effect of background pigment deposition and the spatial distribution of surface spotting.



**Figure 2:** 3D representation of the mean eggshell color coordinates ( $L^*$ ,  $a^*$ ,  $b^*$ ) of chukar partridge eggs in the CIE Lab\* color space ( $L^* = 78.12$ ;  $a^* = 7.71$ ;  $b^* = 17.90$ ).  $L^*$  represents lightness (0 = black, 100 = white),  $a^*$  indicates the green–red axis, and  $b^*$  indicates the blue–yellow axis of the CIE Lab\* color system. Different superscript letters indicate statistically significant differences among eggshell regions ( $P < 0.05$ ).

**Table 2:** Eggshell colorimetric traits of the chukar partridge (n = 90)

| Parameter | $L^*$ | $a^*$ | $b^*$ | $C^*$ | $SCI^{**}$ |
|-----------|-------|-------|-------|-------|------------|
| Mean      | 78.12 | 7.71  | 17.90 | 19.53 | 58.59      |
| SD        | 2.82  | 1.95  | 2.25  | 2.75  | 5.48       |
| Min       | 74.00 | 2.74  | 12.55 | 12.85 | 50.87      |
| Max       | 83.77 | 10.07 | 20.82 | 23.13 | 70.92      |

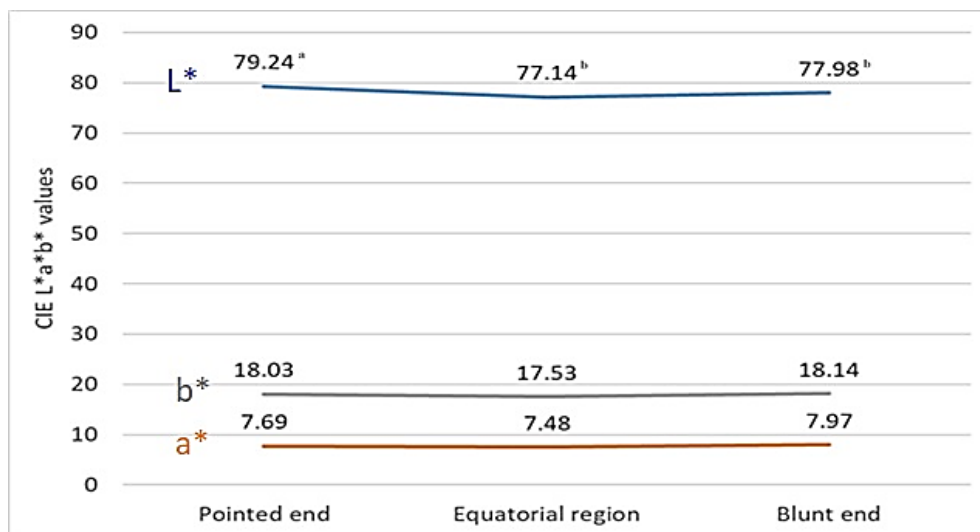
Note:  $L^*$  – lightness;  $a^*$  – green-red axis of the CIE  $L^*a^*b^*$  color space;  $b^*$  – blue-yellow axis of the CIE  $L^*a^*b^*$  color space;  $C^*$  – chroma;  $SCI^{**}$  – shell color index; SD – standard deviation.

The mean value of chroma ( $C^*$ ) for the examined chukar partridge eggs was  $19.53 \pm 2.75$ , ranging from 12.85 to 23.13. This parameter is derived from the chromatic coordinates  $a^*$  and  $b^*$  and reflects the saturation of eggshell color (Formula 3). Although Caglayan *et al.* (2014) did not calculate chroma ( $C^*$ ), recalculation based on their reported  $a^*$  and  $b^*$  values (4.06 and 18.25, respectively) gives an approximate value of  $C^* \approx 18.70$ , which is comparable to the mean value obtained in the present study.

The eggshell color index ( $SCI^{**}$ ), which integrates the three color coordinates ( $L^*$ ,  $a^*$  and  $b^*$ ) of the CIE  $L^*a^*b^*$  color space, showed a mean value of  $58.59 \pm 5.48$  for the examined chukar partridge eggs. The within-group variation ranged between the minimum and maximum values by approximately 28.3%. If the  $SCI^{**}$  value is recalculated for the spotted eggs reported by Caglayan

*et al.* (2014), a slightly lower but comparable value (57.23) is obtained. This similarity can be explained by the relatively weaker influence of the  $a^*$  coordinate, where the main differences between the studies occur.

The intermediate position of chukar partridge eggs according to this index is associated with their typical light cream background color, whereas considerably higher SCI values are characteristic of non-pigmented eggs, and lower values are typical of darkly pigmented eggshells as brown and dark brown (Lukanov *et al.*, 2016).



**Figure 3:** Basic color parameters ( $L^*$ ,  $a^*$ ,  $b^*$ ) of different eggshell regions in the chukar partridge ( $n = 90$ ).  $L^*$  – lightness;  $a^*$  – red–green axis;  $b^*$  – yellow–blue axis of the CIE  $L^*a^*b^*$  color space. Different superscript letters indicate statistically significant differences among eggshell regions ( $P < 0.05$ ).

The second objective of the present study, in addition to the instrumental colorimetric characterization of chukar partridge (*Alectoris chukar*) eggs, was to evaluate the effect of egg size on the color characteristics of the eggshell. Comparison among the different weight categories showed that medium-sized eggs (21–23 g) represented the largest proportion of the sample (56.7%), followed by small eggs (<21 g) and large eggs (>23 g), accounting for 26.7% and 16.6%, respectively. Statistically significant differences among the groups were confirmed with respect to mean egg weight ( $P < 0.001$ ) (Table 3). Although no statistically significant differences were detected among the egg weight categories for the five examined color parameters, several interesting tendencies were observed. In particular, larger eggs tended to exhibit slightly lower lightness ( $L^*$ ) values ( $77.4 \pm 3.0$ ) and higher values for redness ( $a^* = 8.2 \pm 2.01$ ) and yellowness ( $b^* = 18.4 \pm 2.31$ ) compared with medium-sized and small eggs ( $P > 0.05$ ). These tendencies also influenced the derived parameters  $C^*$  and  $SCI^{**}$ .

Overall, the results indicate that no statistically significant differences in eggshell color characteristics were associated with egg size in the examined sample. However, a limitation of the present study is the relatively small number of eggs in the large and small weight categories.

Studies on chicken eggs have shown that the total amount of pigment deposited in the eggshell does not increase with egg size. Consequently, with increasing age of the hens and the associated

increase in egg size, a lightening of the pigmented eggshell color is often observed, expressed mainly as an increase in  $L^*$  values and a decrease in  $a^*$  values (Odabaşı *et al.*, 2007; Bi *et al.*, 2018; Lu *et al.*, 2021). In contrast, such a tendency was not clearly observed in the present study. This discrepancy may be related to differences in the production conditions and laying intensity of the birds, as chukar partridges generally exhibit much lower laying intensity than commercial laying hens.

**Table 3: Eggshell colorimetric traits of the three weight categories (small, medium, and large) of chukar partridge eggs.**

| Egg weight                          | n  | AEW, g                 | $L^*$     | $a^*$    | $b^*$     | C*        | SCI**     |
|-------------------------------------|----|------------------------|-----------|----------|-----------|-----------|-----------|
| <21 g                               | 24 | 20.4±1.08 <sup>a</sup> | 78.1±2.96 | 7.7±2.03 | 18±2.34   | 19.6±2.87 | 58.5±5.72 |
| 21-23 g                             | 51 | 22.0±0.5 <sup>b</sup>  | 78.3±2.72 | 7.6±1.91 | 17.7±2.21 | 19.3±2.69 | 59.0±5.33 |
| >23 g                               | 15 | 23.9±0.39 <sup>c</sup> | 77.4±3.0  | 8.2±2.01 | 18.4±2.31 | 20.1±2.83 | 57.3±5.75 |
| ANOVA <i>P</i> -value               |    | < 0.001                | 0.538     | 0.536    | 0.618     | 0.579     | 0.551     |
| Tukey post-hoc test <i>P</i> -value |    | < 0.001                | NS        | NS       | NS        | NS        | NS        |

*Note: Values are expressed as mean ± SD. n – number of eggs; AEW – average egg weight;  $L^*$ ,  $a^*$ ,  $b^*$  – CIE  $L^*a^*b^*$  color parameters; C – chroma; SCI\*\* – shell color index; NS – not significant. Different superscript letters within the same column indicate statistically significant differences among groups ( $P < 0.05$ ).*

## Conclusion

The obtained results indicate that the eggshell color of chukar partridge (*Alectoris chukar*) eggs is characterized by relatively high lightness ( $L^*$ ) values and positive chromatic coordinates ( $a^*$  and  $b^*$ ), positioning the color within the light yellowish-reddish region of the CIE  $L^*a^*b^*$  color space, corresponding to the pale cream background color, typical of the species. Minor zonal differences in color parameters were observed across the eggshell surface, with slightly higher  $L^*$  values recorded at the pointed end and lower values in the equatorial region, indicating small variations in pigment deposition. No statistically significant differences in eggshell color characteristics were detected among the examined egg weight categories, suggesting that eggshell color in the studied population is largely independent of egg size.

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