Kent Academic Repository

Narushin, Valeriy G., Kent, John P., Salamon, Attila, Romanov, Michael N. and Griffin, Darren K. (2023) *A simulation-based insight into the interrelationships between density and other physical parameters of the egg.* Journal of Food Engineering, 358 . ISSN 0260-8774.

Downloaded from

https://kar.kent.ac.uk/102310/ The University of Kent's Academic Repository KAR

The version of record is available from

https://doi.org/10.1016/j.jfoodeng.2023.111679

This document version

Author's Accepted Manuscript

DOI for this version

Licence for this version

CC BY-NC-ND (Attribution-NonCommercial-NoDerivatives)

Additional information

Versions of research works

Versions of Record

If this version is the version of record, it is the same as the published version available on the publisher's web site. Cite as the published version.

Author Accepted Manuscripts

If this document is identified as the Author Accepted Manuscript it is the version after peer review but before type setting, copy editing or publisher branding. Cite as Surname, Initial. (Year) 'Title of article'. To be published in ***Title of Journal*** , Volume and issue numbers [peer-reviewed accepted version]. Available at: DOI or URL (Accessed: date).

Enquiries

If you have questions about this document contact ResearchSupport@kent.ac.uk. Please include the URL of the record in KAR. If you believe that your, or a third party's rights have been compromised through this document please see our Take Down policy (available from https://www.kent.ac.uk/guides/kar-the-kent-academic-repository#policies).

A simulation-based insight into the interrelationships between density and other physical parameters of the egg

Valeriy G. Narushin[a,b], John P. Kent[c], Attila Salamon[d,e], Michael N. Romanov[f,g,]*, Darren K. Griffin[f,]*

[a] *Research Institute for Environment Treatment, Zaporizhya, Ukraine*
[b] *Vita-Market Ltd, Zaporizhya, Ukraine*
[c] *Ballyrichard House, Arklow, Co. Wicklow, Ireland*
[d] *Department of Ethology, ELTE Eötvös Loránd University, Budapest, Hungary*
[e] *ELTE NAP Canine Brain Research Group, Budapest, Hungary*
[f] *School of Biosciences, University of Kent, Canterbury, UK*
[g] *L.K. Ernst Federal Research Center for Animal Husbandry, Dubrovitsy, Podolsk, Moscow Oblast, Russia*

* Corresponding authors.
E-mail addresses: m.romanov@kent.ac.uk (M. N. Romanov); D.K.Griffin@kent.ac.uk (D. K. Griffin)

Valeriy G. Narushin:	https://orcid.org/0000-0001-6799-6605, e-mail: val@vitamarket.com.ua
John P. Kent:	https://orcid.org/0000-0002-4296-3249, e-mail: j.p.kent.82@cantab.net
Attila Salamon	https://orcid.org/0009-0009-1652-6991, e-mail: dr.attila.salamon@gmail.com
Michael N. Romanov:	https://orcid.org/0000-0003-3584-4644, e-mail: m.romanov@kent.ac.uk
Darren K. Griffin:	https://orcid.org/0000-0001-7595-3226, e-mail: D.K.Griffin@kent.ac.uk

Abstract

A bird's egg has a variety of distinct physical characteristics that assure its functionality as a naturally engineered ‘packaging’ for the growing embryo. It also contains essential nutrients for human food. Egg density (D) is one such crucial physical parameter frequently involved in studies pertaining to its interrelationship with the quality of both table and hatching eggs. In this investigation, we conducted more in-depth experiments based on theoretical research and simulation modelling methods. This specifically involved the possible use of D to predict the values of other egg parameters. The theoretically derived equation for D enabled us to reduce a number of parameters that affect the value of D. Herewith, we suggested that it would be more suitable for planning experiments and promising for studying eggs of various bird species to use parameter ratios rather than their original values. On the basis of simulation methods, we generated and analyzed an extensive database of ‘virtual’ chicken eggs that included all possible variations of the parameters from the proposed D equation. We established that the most influential factor on D is the density of egg interior (D_i) and the most predictable parameter by the D value is the shell thickness (T). Approximation of the obtained data on the dependence of T on D led to a prediction accuracy of $R = 0.68$. We also demonstrated that the ratio D_i/D was more dependent on the ratio of shell volume to whole egg volume and can be a very promising criterion for developing a new avenue of research on pre-incubational sorting of eggs. To refine the accuracy of prediction using this criterion, a further development of more efficient and precise methods for non-destructive measurement of T and D_s will be required.

Keywords: Simulation modelling; Egg quality; Egg parameters; Egg density; Egg specific gravity, Non-destructive testing

1. Introduction

A bird's egg is a unique object of animate nature possessing a complex of specific physical properties that ensure its functionality. It is a naturally engineered ‘packaging’ for both the developing embryo and contains a valuable nutrient content used in human consumption (Artemenko et al., 2014; Narushin et al., 2021e). One such important physical parameter is egg density (*D*), which is also often referred as ‘egg specific gravity’ to and is calculated as the ratio of the egg weight (*W*) to volume (*V*). This indicator is quite broadly used in studies on its interrelationship with the quality parameters of both table and hatching eggs (e.g., Bondarenko et al., 2007; Baydevlyatova et al., 2009; Shomina et al., 2009; Tkachenko et al., 2009; Khvostik and Bondarenko, 2020). Such acceptance of *D* is due to the fact that, firstly, it is an integral indicator. That is, it incorporates the characteristics of two egg properties at once, *W* and *V*. Secondly, *D* can be determined with a sufficient accuracy by (i) simple analytical weighing of the egg and immersing it in water, (ii) placing it in saline solutions of varying densities, or (iii) using calculation formulae to deduce *V*. Thirdly, *D* is extremely convenient for comparative analysis, since, being a relative value, it does not depend on the size of eggs when studying both their intraspecific and interspecific variability.

Mussehl and Halbersleben (1923) carried out possibly the first fundamental study of the effect of *D* on egg quality and hatching properties. The authors found little correlation between specific gravity and hatchability of hens' eggs. However, they pointed out that variation in the shell thickness (*T*) is more likely to influence the specific gravity of eggs. A decade later, Olsson (1934) reported the results of the relationship he found between the specific gravity of an egg and the percentage of shell. He also suggested that this parameter could be used as a non-invasive indicator of shell quality. Consequently, these results (Mussehl and Halbersleben, 1923; Olsson, 1934) and, especially the prospects for using a non-destructive and relatively simple index for evaluating eggshell strength. warranted further work to investigate and establish possible relationships between these egg characteristics. Foster and Weatherup (1979), examining the dependence of *D* on *T*, composed a table for correlation between the two parameters obtained as a result of both their own research and other studies. Hereby, the reported correlation data varied between 0.18 to 0.8, although the minimum value (0.18) found by Foster (1977) was classified as abnormal (Foster and Weatherup, 1979). Nevertheless, taking into account a rather wide spread of the data obtained, it can be assumed that the accuracy of the *T* prediction depending on *D* was clearly influenced by additional parameters. Sloan et al. (2000), using the data produced by Harms et al. (1990), demonstrated that the density of egg interior (D_i) contributed to a significant error in predicting *T* by the *D* value. As a consequence, one should be very careful when using *D* in making decisions relating to eggshell quality. Considering the theoretical equation for calculating *T* as proposed by Carter (1975), *T* was influenced by *W* and *V* values, as well as the density of the shell (D_s) and D_i. However, the author did not explain what effect each factor had separately. He also did not introduce *D* into the *T* dependence, using only its component values, *W* and *V*.

As regards the relationship between *D* and the ratio of shell weight (W_s) to *W*, the correlation between these values was slightly higher than between *D* and *T* (Holder and Bradford, 1979; Nordstrom and Ousterhout, 1982; Harms et al., 1990). A closer relationship can be explained by the following factors. Firstly, Romanoff and Romanoff (1949) pointed out that the ratio of W_s to *W* is practically an unchanged value regardless of *W*. Secondly, one of the components of the *W* value is *D*. Therefore, when determining correlations, *D* is included in both datasets studied and indirectly influences the increase in the strength of their relationship. It should also be taken into account the fact that most researchers studying the relationship of *D* with other parameters were limited in their studies to a relatively small experimental sample. Hamilton (2022), given both his own results and the outcomes of other authors, pointed out in his review that 'the prediction equations derived from one data set are generally not transferrable to another.' Therefore, to obtain an adequate dependence, a huge number of eggs should be used, covering all possible combinations of morphological egg parameters. To implement this in practice is not feasible. For this purpose, application of simulation methods can be attractive, encouraging, reliable and convincing, as has already been successfully shown in our previous simulation-based work on the mathematical (i.e., non-destructive) description of various physical parameters of the egg (Narushin et al., 2020a, 2020b, 2021a, 2021b, 2021c, 2021d, 2022b).

To ensure the success of the simulation procedure, it is advisable to have an idea of the possible relationship between the value of *D* and other parameters of the egg. In this respect, the goal of the present study was to evaluate *D* and its relationship with other physical properties of the egg using the simulation approach. To do this, we preliminarily carried out a theoretical justification, the purpose of which was to derive a theoretical dependence that reflects the functional interrelationship between *D* and a set of other physical egg parameters as outlined below. The methodology for conducting simulation studies implies the development of a mathematical model that was performed by us in the Theory section (see Eqns 6 and 7 below), as well as a set of all possible values of the parameters included in this model as independent values. It was the last aspect of the simulation study that was given the main attention since the adequacy of the results obtained depends on it.

2. Theory

Conventionally, a bird's egg with a weight *W* can be represented as the sum of two main structural components: the shell with a weight W_s and the interior (contents) with a weight W_i, respectively. Replacing the values of *W* by the products of physical values *V* and *D* and keeping the corresponding subscript indexation, we can write down:

$$VD = V_s D_s + V_i D_i \qquad (1)$$

Thence

$$D = \frac{V_s D_s + (V - V_s) D_i}{V} \tag{2}$$

or

$$D = \frac{V_s}{V} D_s + \left(1 - \frac{V_s}{V}\right) D_i \tag{3}$$

where D, D_s and D_i are respectively the densities of the egg, its shell and content (in g/cm^3), and V and V_s are respectively the volumes of the egg and its shell (in cm^3).

One of the components of Eqn3 is V_s/V, i.e., the ratio of shell volume (V_s) to V. With a small assumption, V_s can be represented as the product of its surface area (S) and T. Then, considering the ratio V_s/V, we can rewrite it in the following form:

$$\frac{V_s}{V} = \frac{ST}{V} \tag{4}$$

Previously, we already obtained fairly accurate formulae for calculating the parameters V and S (Narushin et al., 2022a), the use of which allowed us to rewrite Eqn4 as follows:

$$\frac{V_s}{V} = 30.529 \left(\frac{B}{L}\right)^{-1} \cdot \frac{\frac{B}{L} + 2.005}{\frac{B}{L} + 14.389} \cdot \left(\frac{L}{T}\right)^{-1} \tag{5}$$

where B is the maximum breadth of the egg, L is its length, and T is the shell thickness (all in cm).

Considering Eqn5, Eqn3 will be rewritten in the following form:

$$D = 30.529 \left(\frac{B}{L}\right)^{-1} \cdot \frac{\frac{B}{L} + 2.005}{\frac{B}{L} + 14.389} \cdot \left(\frac{L}{T}\right)^{-1} D_s + \left(1 - 30.529 \left(\frac{B}{L}\right)^{-1} \cdot \frac{\frac{B}{L} + 2.005}{\frac{B}{L} + 14.389} \cdot \left(\frac{L}{T}\right)^{-1}\right) D_i \tag{6}$$

The use of parameter ratios *B*/*L* and *L*/*T* in Eqn6 is more preferable than the single parameter values, since this significantly reduces the number of possible variants of their variability range. Moreover, the ratios facilitate an analogous analysis of eggs from various bird species.

One of the important criteria proposed by Narushin et al. (1998), which can be effectively used in the poultry industry for pre-incubational egg sorting, including sorting by sex of embryos (Narushin et al., 1994, 1996; Romanov et al., 1994; Trukhina et al., 2021), is the ratio of interior density (D_i) to D, i.e., D_i/D. In this regard, we also decided in the current study to undertake a correlation and regression analyses of this indicator. For these purposes, we transformed the theoretical expression (6) we derived into the following form:

$$\frac{D_i}{D}=\frac{1-30.529\left(\frac{B}{L}\right)^{-1}\cdot\frac{\frac{B}{L}+2.005}{\frac{B}{L}+14.389}\cdot\left(\frac{L}{T}\right)^{-1}\cdot\frac{D_s}{D}}{1-30.529\left(\frac{B}{L}\right)^{-1}\cdot\frac{\frac{B}{L}+2.005}{\frac{B}{L}+14.389}\cdot\left(\frac{L}{T}\right)^{-1}} \qquad (7)$$

3. Material and methods

We set ourselves the goal of removing all discrepancies between the obtained, sometimes conflicting data from the results of various studies on the possible influence of egg parameters on their density. This can only be done with the help of simulation modeling (see section Introduction). Therefore, we have paid great attention to the methodological aspects of planning such an experiment.

In accordance with the parameters included in the key mathematical model (Eqns 6 and 7), and in order to apply the simulation approach and generate a database of virtual eggs with a set of parameters that can presumably exist in nature, we need to determine the range of possible parameters for the following values *B*/*L*, *L*/*T*, D_i and D_s. As for the possible values of the shape index (*B*/*L*) and the ratio *L*/*T*, which characterizes how much *L* exceeds *T*, we previously considered their variations for chicken eggs in detail in Narushin et al. (2022b).

Based on the experimental data of our previous studies on the morphology of chicken eggs (Narushin, 1997, 1998, 2001a, 2001b, 2005; Narushin et al., 2004, 2020a), as well as published results of similar studies (Romanoff and Romanoff, 1949; Carter, 1968; Sloan et al., 2000; Lichovnikova, 2007; Liao et al., 2013; Ketta and Tůmová, 2018), the following ranges have been adopted for the present analyses:

B/L = [0.65…0.85],
L/T = [120…230],
D_i = [1.020…1.045] g/cm^3,
D_s = [2.0…2.5] g/cm^3.

With a set of component values in Eqn6, we were able to perform the simulation modelling by substituting all possible values from the specified ranges. For this purpose, each of the above parameter ranges was divided into the following sub-ranges:

B/L = [0.65, 0.7, 0.75, 0.8, 0.85],

L/T = [120, 130, 140, 150, 160, 170, 180, 190, 200, 210, 220, 230],

D_i = [1.020, 1.025, 1.030, 1.035, 1.040, 1.045] (g/cm^3),

D_s = [2.0, 2.1, 2.2, 2.3, 2.4, 2.5] (g/cm^3).

As a result, we generated 2160 different combinations of the above parameter values, each of which, after substitution into Eqn6, made it possible to calculate the D value for a specific virtual egg.

The resulting database of values was examined using the correlation and regression analyses. For these purposes, we used the STATISTICA 5.5 program (StatSoft, Inc./TIBCO, Palo Alto, CA, USA), as well as computational applications in Microsoft Excel.

4. Results

4.1. Contribution of component parameters to egg density

Having a database of independent variables (B/L, L/T, D_i, and D_s) and one dependent variable (D), we carried out a deeper analysis of their relationships and the magnitude of their effects.

It is well established (e.g., Petchko, 2018) that 'the size of regression coefficients shows how much each predictor variable contributes on its own to the variance in the dependent variable.' In this regard, the quantitative measurement of the effect of each factor in Eqn6, i.e., B/L, L/T, D_i and D_s, was carried out by regression analysis. The resulting regression equation had the following form:

$$D = 0.0981 - 0.0564\frac{B}{L} - 0.0003\frac{L}{T} + 0.9556D_i + 0.0444D_s\,, \tag{8}$$

with $R^2 = 0.972$.

The produced Eqn8 was fundamental for the analysis of the degree of influence of each of the independent parameters on the value of D. As follows from Eqn8, the greatest coefficient value in the regression equation corresponded to D_i, i.e., the density of egg interior. The value of this coefficient (0.9556) exceeded all the others.

For a greater explicitness and clarity, we presented the product of each coefficient by the mean value of the respective parameter in the form of a diagram (Fig. 1).

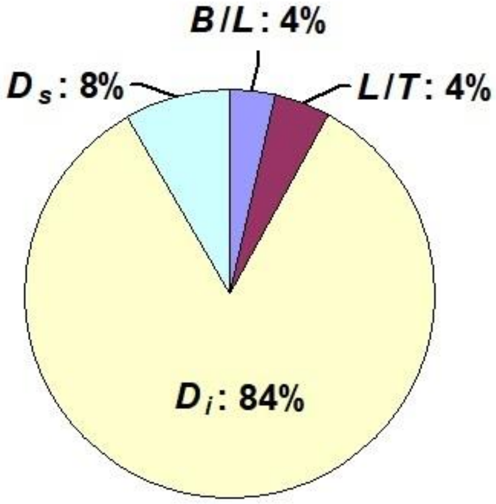
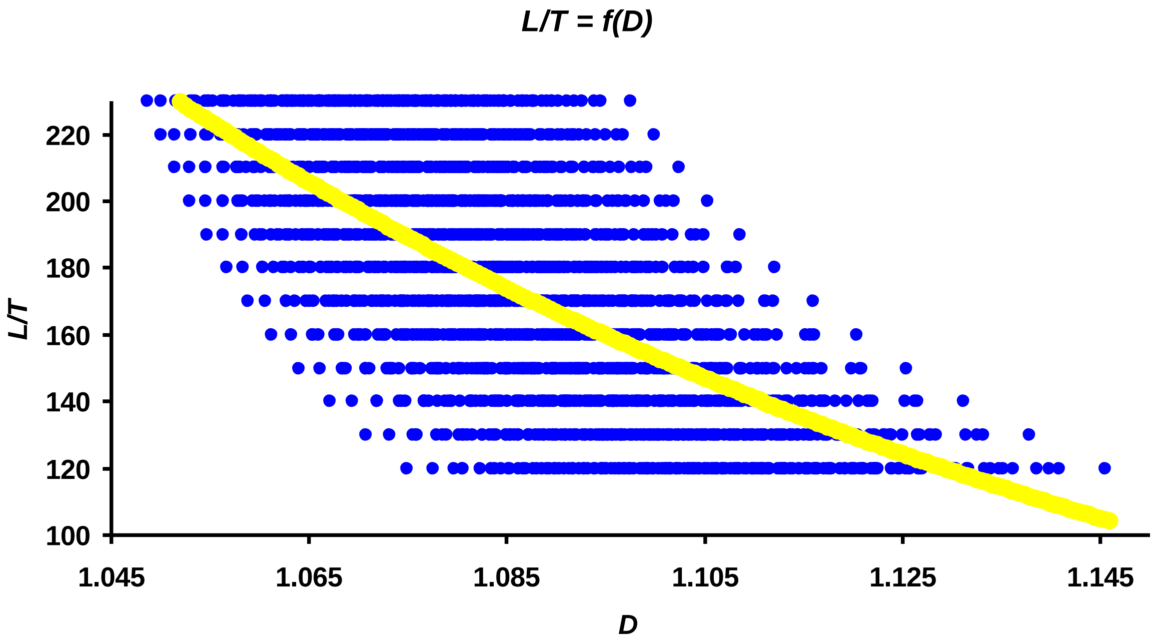


Fig. 1. Percentage contribution of each parameter included in the regression equation (Eqn8).

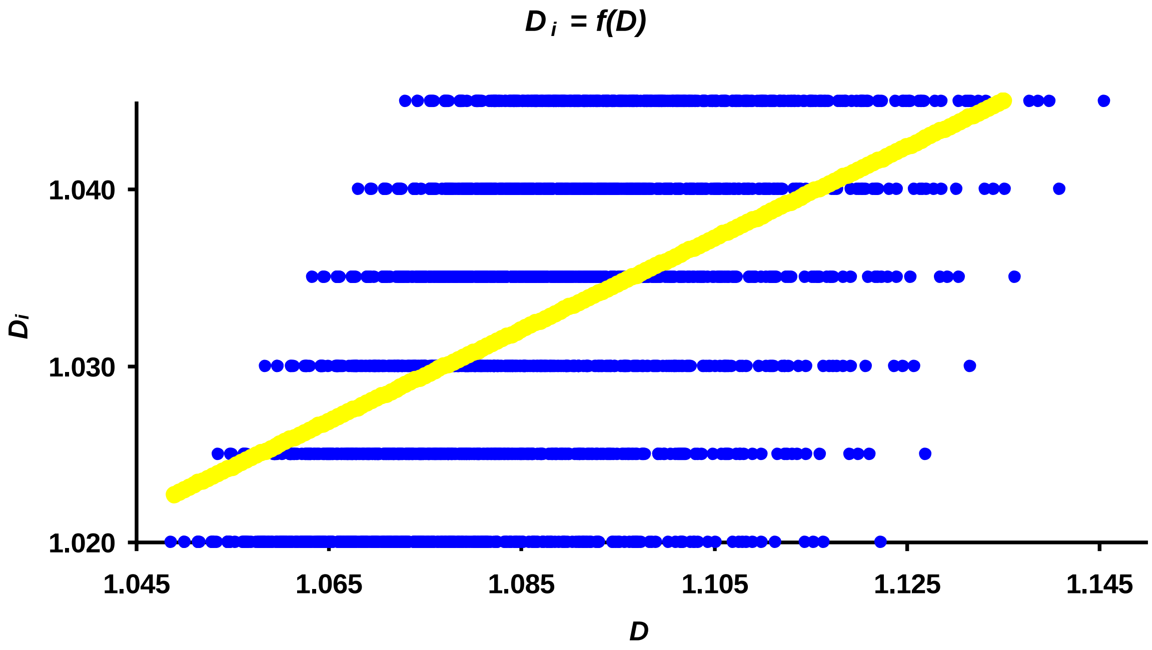
We estimated the variation coefficient (in percent) for each parameter included in the regression equation (Eqn8) as a ratio of the standard deviation and the mean value multiplying to 100%. The following results were obtained with respect to the appropriate mean values: 1.087 g/cm^3 ± 1.5% for D, 0.75 ± 9.4% for B/L, 175 ± 19.7% for L/T, 1.0325 g/cm^3 ± 0.8% for D_i, and 2.25 g/cm^3 ± 7.6% for D_s.

4.2. Correlation analysis of the dependence of D on other egg parameters

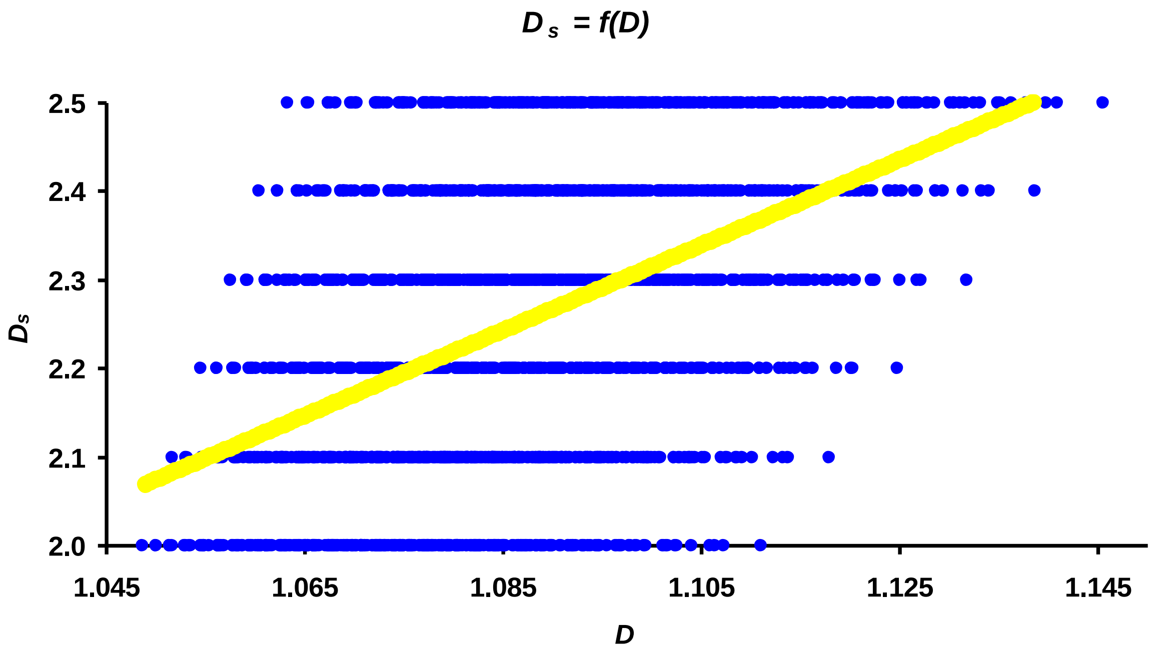
The correlation analysis made it possible to identify the interrelationships of individual parameters included in Eqn8 and the probability of predicting them using the D value (Fig. 2). Since the B and L values are quite trivial and accurate using conventional measurement methods, we did not implement their ratio in the analysis.



(a)



(b)



©

Fig. 2. Correlation dependences of parameters *L*/*T* (a), D_i (b), and D_s (c) on egg density, D. Trend lines are marked in yellow.

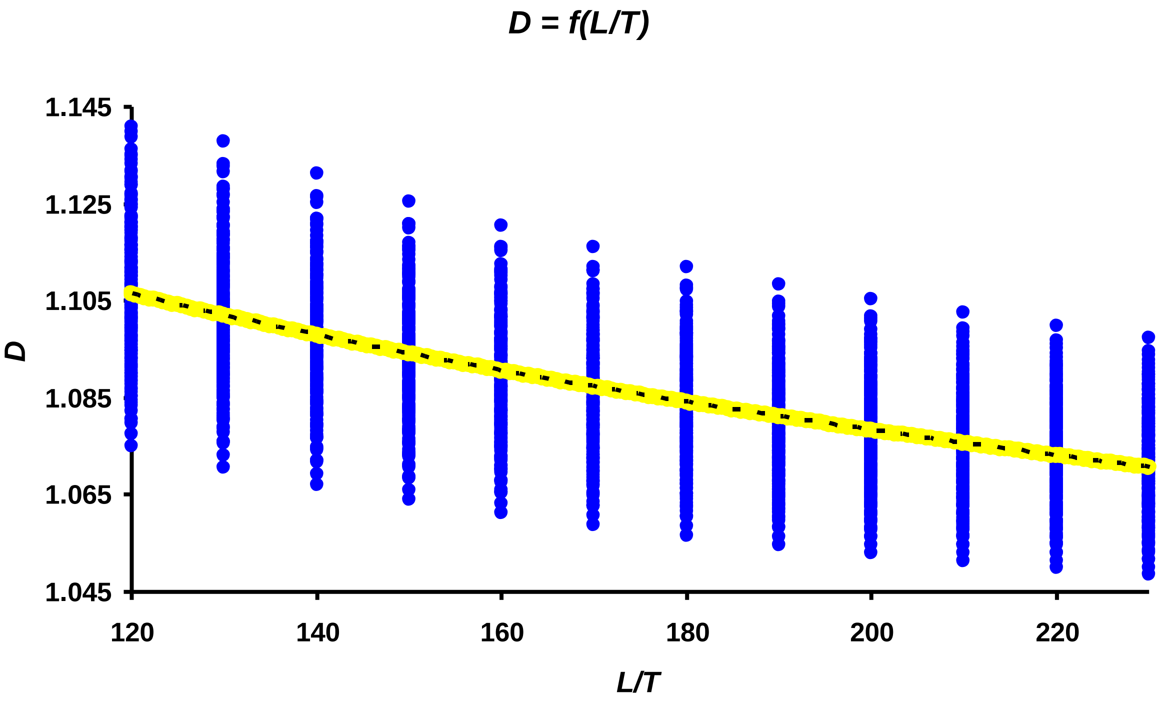
Trend lines (shown in yellow in Fig. 2) on the graphical dependences were approximated by the corresponding mathematical equations that are presented in Table 1 along with their coefficients of determination (R^2).

Table 1. The mathematical equations for predicting the *D* values with the individual egg parameters

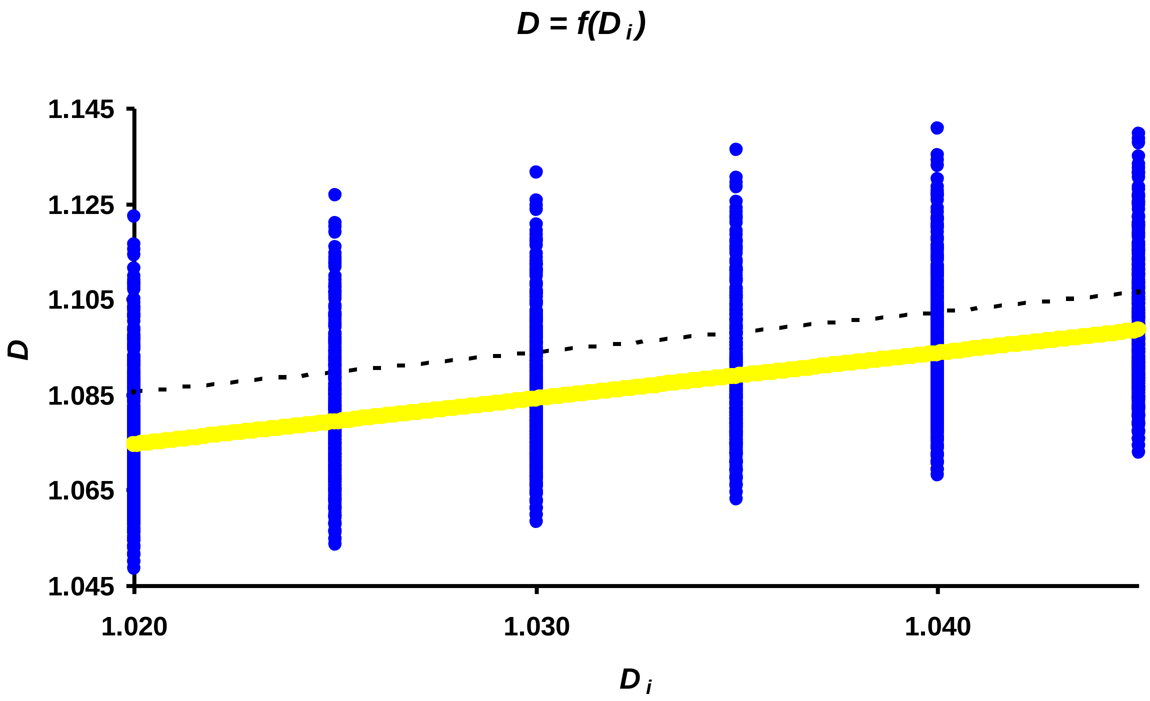
Independent variables	Approximated equations		Coefficient of determination (R^2)
L/*T*	$\frac{L}{T} = 1594414e^{-8.41D}$	(9)	0.462[a]
T	$T = \frac{Le^{8.41D}}{1594414}$	(10)	0.462[a]
D_i	$D_i = 0.26D + 0.75$	(11)	0.248[a]
D_s	$D_s = 4.82D - 2.98$	(12)	0.214[a]

[a] $p < 0.05$; the values without any index are insignificant

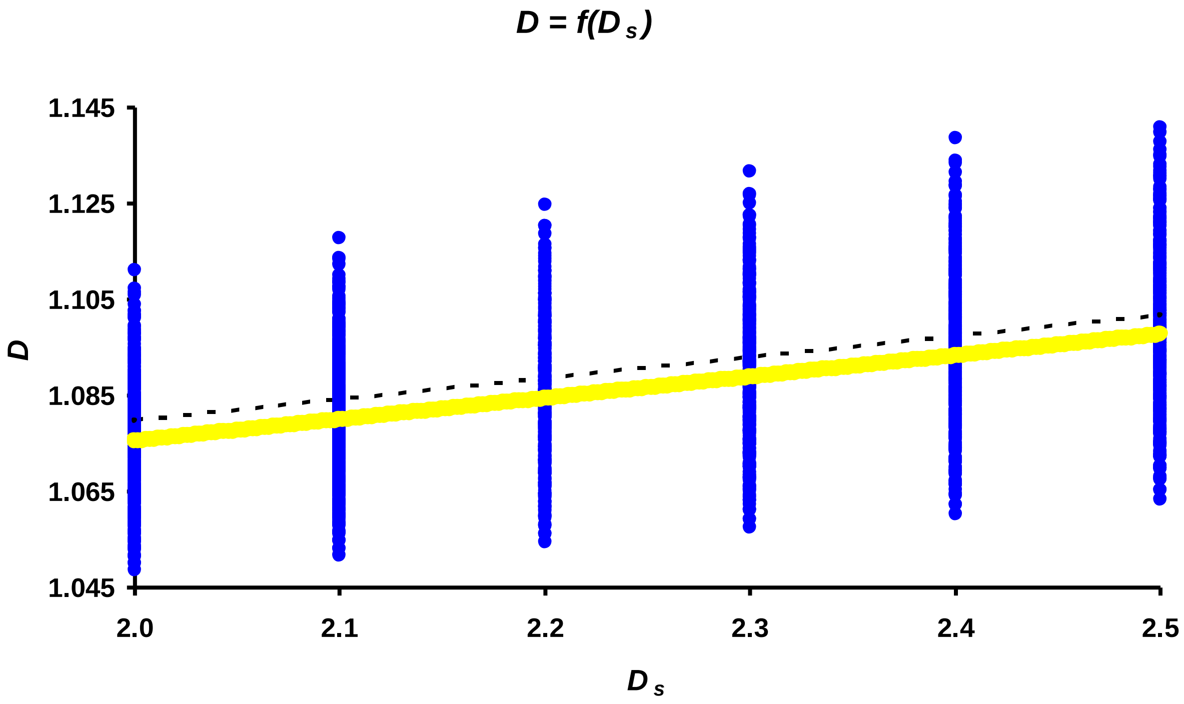
The analysis of the obtained mathematical expressions and, in particular, the correlation coefficients reflecting their adequacy showed that, despite the prevailing influence of D_i (Fig. 1), the highest prediction accuracy was identified for T (or its derivative, dimensionless coefficient, L/T) (Eqns9 and 10). However, the prediction for D_i (Eqn11), as well as D_s (Eqn12), was almost half as much. To understand what caused this discrepancy, we carried out the correlation analysis of the dependence of D on other parameters: L/T, D_i, D_s and B/L, visualization of which is given in Fig. 3.



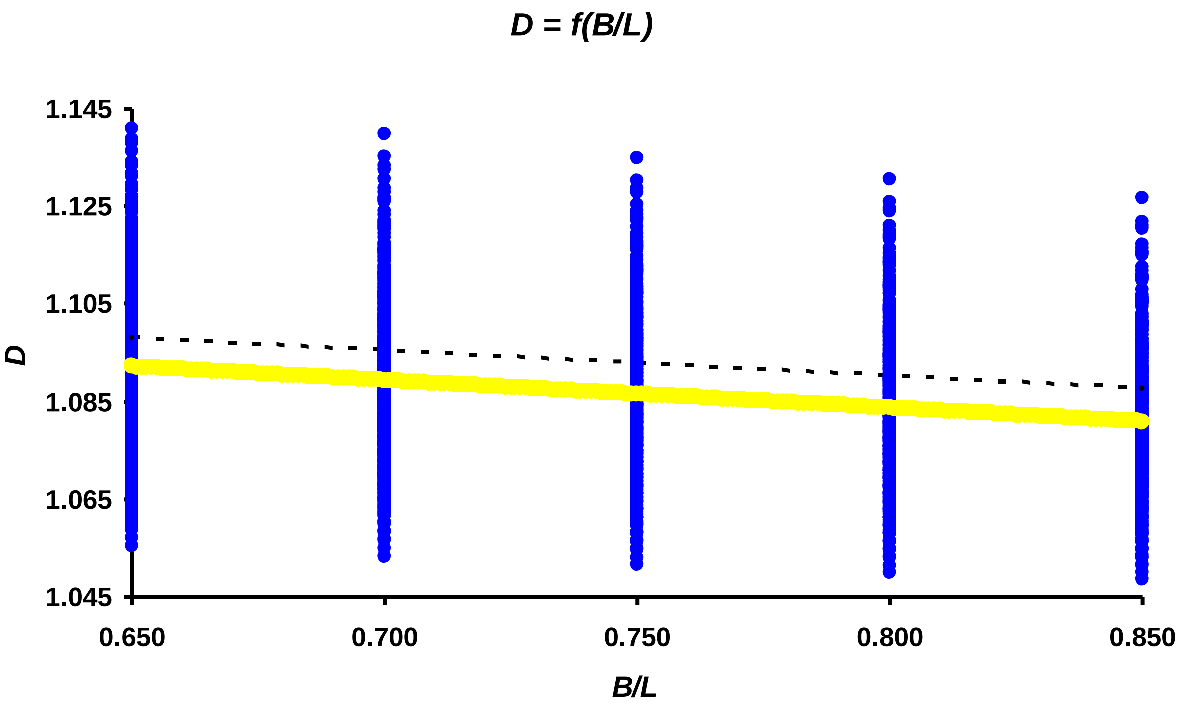
(a)


D = f(D i)
1.145
1.125
1.105
1.085
1.065
1.045
D
1.020
1.030
1.040
D i

(b)


D = f(D s)
1.145
1.125
1.105
1.085
1.065
1.045
D
2.0
2.1
2.2
2.3
2.4
2.5
D s

(c)



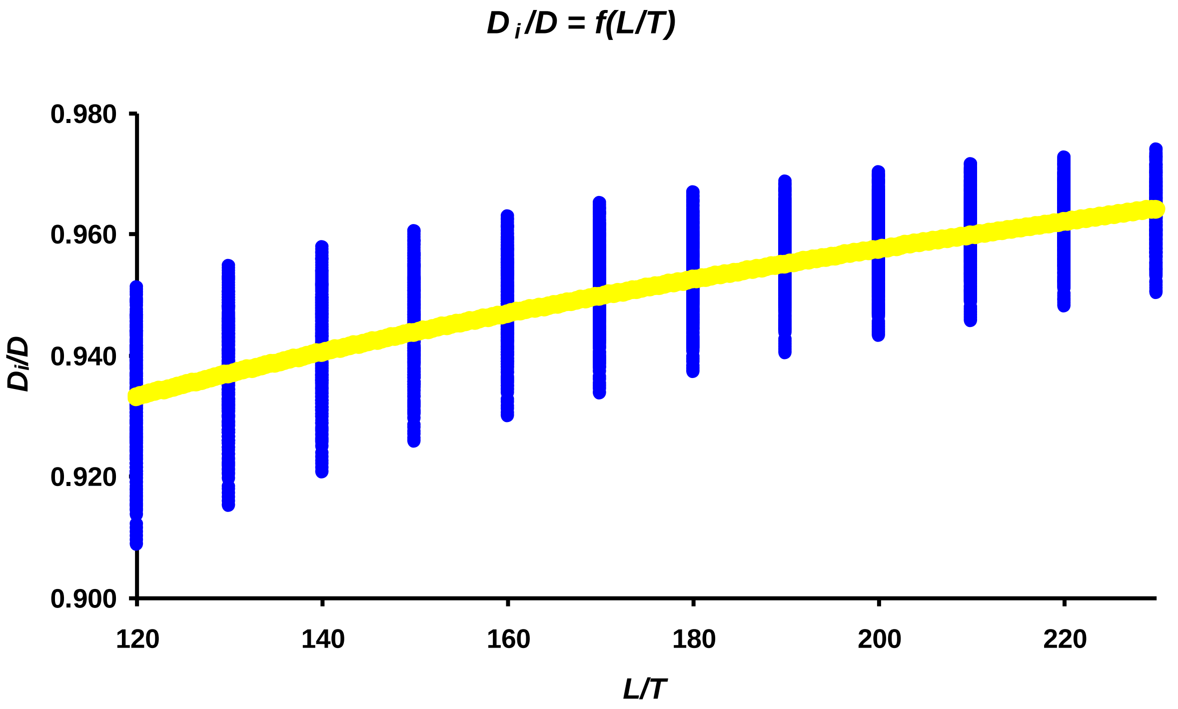
(d)

Fig. 3. Correlation dependences of egg density, *D*, on other related parameters: *L*/*T* (a), D_i (b), D_s (c), and *B*/*L* (d). Trend lines are marked in yellow; black dotted lines conform to the middle of the *D* values.

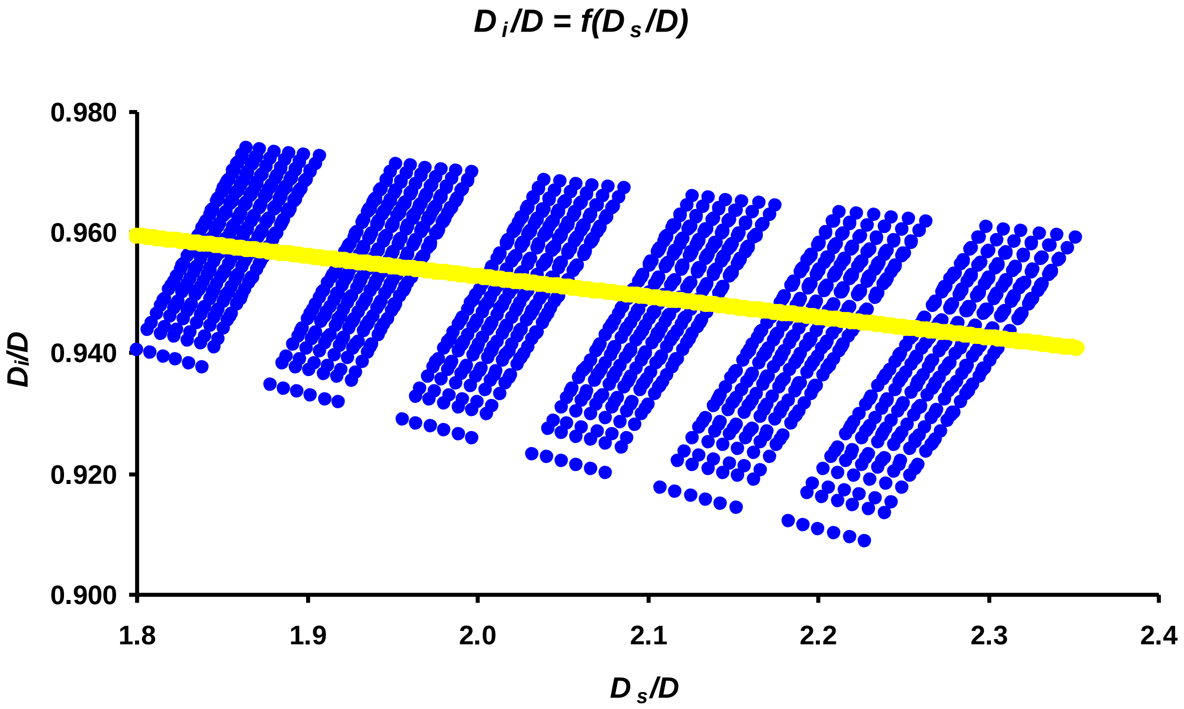
The analysis of trend lines (marked in yellow in Fig. 3) on graphical dependences demonstrated that the initial values D_i (Fig. 3B), D_s (Fig. 3C) and *B*/*L* (Fig. 3D) were located slightly below the line that conformed to the middle of the *D* values (black dotted line). That is, a larger amount of initial data of these parameters provided lower values of *D*. At the same time, the trend line for the parameter *L*/*T* (Fig. 3A) was located exactly in the middle of the generated sample, which was indicative of a uniform influence of this parameter on the entire range of *D* variants. Obviously, this explains a rather high correlational interrelationship between the *L*/*T* and *D*.

4.3. Correlation analysis of the influence of egg parameters on the ratio of densities D_i/D

Similarly, we analyzed the criterion of the ratio D_i/D (Eqn7). Particular attention was paid to the correlation dependences of D_i/D on the ratios *L*/*T* and D_s/D (Fig. 4).



(a)



(b)

Fig. 4. Correlation dependences of the ratio of interior density to egg density, D_i/D, on other dependent parameters: L/T (a), and D_s/D (b). Trend lines are marked in yellow.

The obtained data were approximated by the mathematical equations that were visualized as yellow lines in Fig. 4 and are presented in Table 2 along with their coefficients of determination (R^2).

Table 2. The mathematical equations for predicting the D_i/D values with the individual egg parameters

Independent variables	Approximated equations		Coefficient of determination (R^2)
L/T	$\frac{D_i}{D} = 0.048 ln\left(\frac{L}{T}\right) + 0.705$	(13)	0.614[a]
D_s/D	$\frac{D_i}{D} = -0.034\frac{D_s}{D} + 1.02$	(14)	0.157[a]
B/L and L/T	$\frac{D_i}{D} = 0.865 + 0.0491\frac{B}{L} + 0.0003\frac{L}{T}$	(15)	0.679[a]
	$\frac{D_i}{D} = 0.7423\left(\frac{B}{L}\right)^{0.0386} \cdot \left(\frac{L}{T}\right)^{0.0502}$	(16)	0.692[a]
V_s/V	$\frac{D_i}{D} = 0.997 - 1.057\frac{V_s}{V}$	(17)	0.700[a]

[a] $p < 0.05$; the values without any index are insignificant

Since the main geometric dimensions of the egg, *B* and *L*, can be, contrary to D_s, measured quite accurately without violating the integrity of the egg, we decided to include this ratio in the calculation of D_i/D. The resulting regression equation, indeed, made it possible to improve the accuracy of calculations (Table 2).

A somewhat different representation of dependence (15) allowed us to improve slightly the accuracy of the calculation (see Eqn16 in Table 2).

Based on Eqn5, the ratio V_s/V includes both parameters from Eqn16, i.e., B/L and L/T. In this respect, we decided to test the dependence $D_i/D = f(V_s/V)$ as a simpler alternative to Eqn5. The correlation dependence between these parameters is shown in Fig. 5.

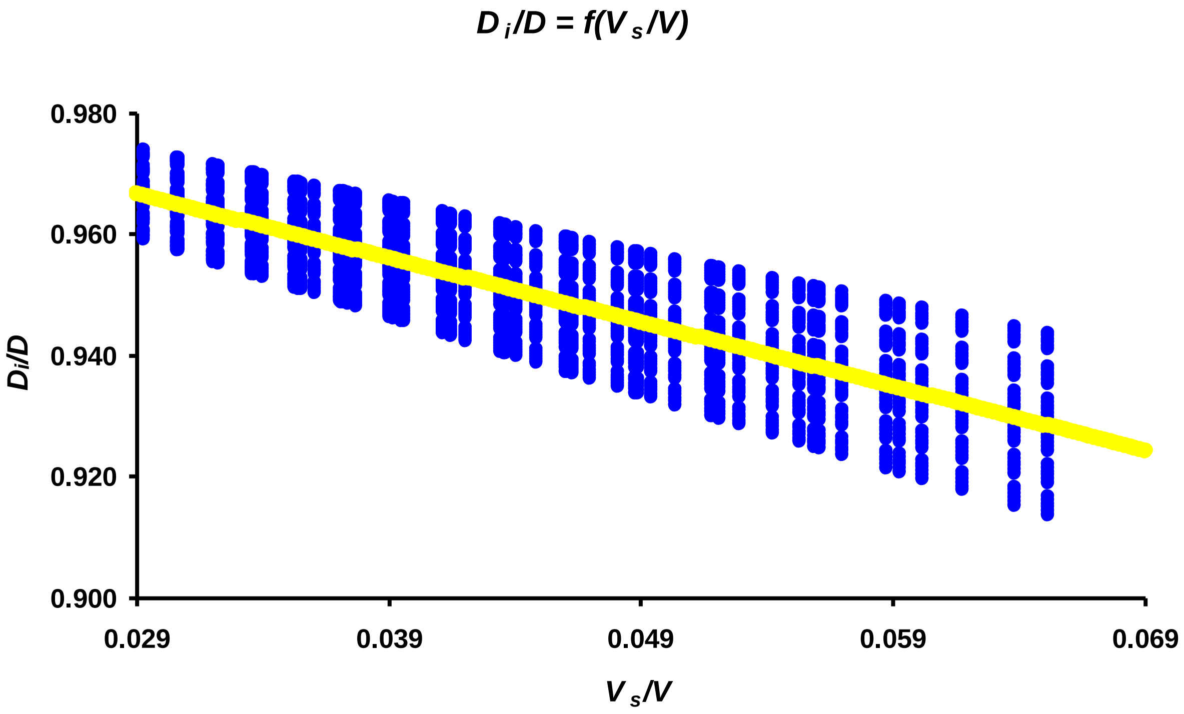


Fig. 5. Correlation dependence of the ratio of the interior density to the egg density, D_i/D, on the parameter V_s/V. Trend line is marked in yellow.

The obtained data were approximated by the mathematical equation that was visualized as a yellow line in Fig. 5 and is presented in Table 2.

Due to the fact that the resulting Eqn17 is simpler and more accurate, we recommend for use in practical calculations.

5. Discussion

On the basis of simulation studies, we generated a set of results that can be conditionally divided into two categories: (i) influencing parameters; and (ii) predicting parameters. Whereas the former enabled us to understand which variable values affect the value of *D*, the latter had a more applied function, since these allow us to estimate the value of the parameter of interest with a certain degree of accuracy.

As follows from Fig. 1 plotted using the regression analysis (Eqn8), it is clear that the greatest influence on *D* was exerted by D_i. This fact is quite obvious, since the egg contents make up about 90% of the whole egg (e.g., Romanoff and Romanoff, 1949). However, if the deviations of D_i with respect to their mean value were only ±0.8%, those for *D* already grew to ±1.5%. In other words, the process of a more pronounced variability of *D* involved shell parameters, for which we used the ratio *L*/*T* and D_s, as well as the geometric dimensions of the egg presented in this study by the shape index *B*/*L*.

Nonetheless, despite the strong influence of the parameter D_i on D, it turned out to be problematic to predict the value of D_i from D. The prediction accuracy of the obtained correlation dependence (Eqn11) was at the level of $R^2 = 0.248$. However, if we consider T, which had a very modest effect (at the level of 4%, Fig. 1) on the value of D, this can be recalculated from the value of D (Eqn10) already with an accuracy of almost twice as much ($R^2 = 0.462$) than for D_i. In our opinion, the reason for this discrepancy lies in the more uniform influence of the L/T indicator on D than other component values (Fig. 3). The use of simulation methods enabled not only to analyze virtual eggs of the most common ratios of geometric and physical parameters, but also to create unique combinations that may be quite rare, but, nevertheless, are possible in nature. As our findings showed, the influence of the parameter L/T was unchanged for any, even the most 'exotic' combinations of egg parameters. At the same time, the other indicators had a greater effect on eggs with a smaller D (Fig. 3).

The explored parameter of the density ratio D_i/D may turn out to be very promising for a whole avenue of new research and even for the pioneer direction of pre-incubational sorting of eggs (Narushin et al., 1994, 1996, 1998; Romanov et al., 1994; Trukhina et al., 2021). In this regard, we paid specific attention to the approximation of the correlational dependence for recalculating D_i/D depending on other egg parameters (Figs. 4 and 5).

The effect of D_s, which was more convenient to use as the ratio D_s/D, seemed to be rather weak (Eqn14). In this respect, the geometric parameters of the egg and T were more preferable for the prediction of D_s/D (Eqn16). Based on the theoretical dependence (5), these indicators, B/L and L/T, are instrumental in calculating the ratio V_s/V. The use of this parameter V_s/V to predict the ratio D_i/D (Eqn17) was the most significant in terms of calculation accuracy ($R^2 = 0.700$). In our previous work (Narushin et al., 2021d), we considered a theoretical approach to calculating V_s. However, a limiting factor for such predictive calculations is the lack of a non-destructive method for determining T. Narushin et al. (2021d) also noted that, in this regard, an integrated approach using technical means, e.g., commercially available apparatuses for testing shell thickness, like the ultrasonic device by ORKA (2023) or the non-destructive deformation device by Stable Micro Systems (2023), and a combination of basic egg measurements including W, V and S (e.g., Narushin et al., 2004) can give the desired result.

In this regard, it may be very promising to use other engineering solutions aimed at non-destructive determination of the T value that, however, have so far been worked out only for use in laboratory studies. First of all, these are various designs of devices for measuring the elastic deformation of the shell (e.g., Schoorl and Boersma, 1962; Nedomová, et al., 2014; Narushin et al., 2021e).

Equally promising are devices for measuring near infra-red (NIR) spectra and their corresponding correlation with the shell thickness (e.g., Narushin et al., 2004; Xiong et al., 2013; Dong, et al., 2017).

Undoubtedly, the value of D_s can also help improve the prediction accuracy of D_i/D. However, this will require the development of non-destructive instrumental methods for determining this parameter D_s.

6. Conclusions

In the present investigation, we implemented a simulation-based study to describe the interrelationship between density and other physical parameters of the egg. Based on theoretical research and analysis of the simulation modelling data, we showed that the use of ratios B/L, L/T, V_s/V and D_s/D seems to be more useful and promising than the original parameter values for planning the relevant experiments and for examining eggs of various bird species. Analysis of the database that we developed for the simulation modelling enabled to establish that D_i was the most influencing factor on D, while T was the most predictive egg parameter in terms of D. We also found that a promising criterion, the ratio D_i/D, which can be used to develop a new line of research on pre-incubational sorting of eggs, was more dependent on the ratio V_s/V. A further refinement of the prediction degree of this criterion D_i/D can be done by developing more efficient and accurate methods for non-destructive measurement of T and D_s.

Credit author statement

VGN: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Visualization, Writing – original draft, Writing – review & editing. JPK: Validation, Writing – review & editing. AS: Validation, Writing – review & editing. MNR: Project administration, Validation, Writing – original draft, Writing – review & editing. DKG: Supervision, Writing – review & editing.

Data availability

Data will be made available upon request.

Acknowledgments

Not applicable.

Declarations of interest

The authors have no conflict of interest to declare.

References

Artemenko, O.B., Tagirov, M.T., Baydevlyatova, O.M., Shomina, N.V., Tereshchenko, A.V., 2014. [Study of the dynamics of changes in fatty acid composition of egg yolks during embryonic development of hens of different productivity types]. Ptakhivnytstvo [Poultry Farming] 71, 7–17.

Baydevlyatova, O.N., Ogurtsova, N.S., Shomina, N.V., Tereshchenko, A.V., 2009. [Morphological indicators of egg quality in a new chicken subpopulation of the meat-egg type of productivity]. Ptakhivnytstvo [Poultry Farming] 64, 109–115.

Bondarenko, Yu.V., Tkachik, T.E., Zakharchenko, O.P., Ruda, S.V., Katerinich, O.O., Shekhovtsov, S.S., Kutnyuk, P.I., 2007. [Morphological quality traits of eggs of subpopulations of Birky meat-egg type chickens]. Ptakhivnytstvo [Poultry Farming] 59, 29–36.

Carter, T.C., 1968. The hen's egg: density of egg shell and egg contents. Br. Poult. Sci. 9, 265–271. https://doi.org/10.1080/00071666808415718.

Carter, T.C., 1975. The hen's egg: A rapid method for routine estimation of flock mean shell thickness. Br. Poult. Sci. 16, 131–143. https://doi.org/10.1080/00071667508416171.

Dong, X., Tang, X., Peng, Y., Dong, J., 2017. Nondestructive assessment of eggshell thickness by VIS/NIR spectroscopy. In: 2017 ASABE Annual International Meeting, 1700888 (American Society of Agricultural and Biological Engineers, St. Joseph, MI, USA). https://doi.org/10.13031/aim.201700888.

Foster, W.H., 1977. The identification of weak-shelled eggs at the packing station. Rec. Agric. Res. 25, 33–37.

Foster, W.H., Weatherup, S.T.C., 1979. The use of specific gravity of the egg to estimate shell thickness. Br. Poult. Sci. 20, 439–443. https://doi.org/10.1080/00071667908416605.

Hamilton, R.M.G., 2022. A comparison of the various equations published for the estimation of characteristics of hen’s eggs, the importance of reporting the compression rate for shell strength measurements, and distinction between egg specific gravity and density. Worlds Poult. Sci. J. 78, 447–466. https://doi.org/10.1080/00439339.2022.2026202.

Harms, R.H., Rossi, A.F., Sloan, D.R., Miles, R.D., Christmas, R.B., 1990. A method for estimating shell weight and correcting specific gravity for egg weight in eggshell quality studies. Poult. Sci. 69, 48–52. https://doi.org/10.3382/ps.0690048.

Holder, D.P., Bradford, M.V., 1979. Relationship of specific gravity of chicken eggs to number of cracked eggs observed and percent shell. Poult. Sci. 58, 250–251. https://doi.org/10.3382/ps.0580250.

Ketta, M., Tůmová, E., 2018. Relationship between eggshell thickness and other eggshell measurements in eggs from litter and cages. Ital. J. Anim. Sci. 17, 234–239. https://doi.org/10.1080/1828051X.2017.1344935

Khvostik, V.P., Bondarenko, Yu.V., 2020. [Qualitative indicators of eggs of meat and egg chickens of different genesis]. Visnyk Sums’koho Natsional’noho ahrarnoho universytetu, Seriya Tvarynnytstvo

[Bulletin of the Sumy National Agrarian University, Series Livestock], Issue 4 (43), 82–87. https://doi.org/10.32845/bsnau.lvst.2020.4.13.

Liao, B., Qiao, H.G., Zhao, X.Y., Bao, M., Liu, L., Zheng, C.W., Li, C.F., Ning, Z.H., 2013. Ning, Influence of eggshell ultrastructural organization on hatchability. Poult. Sci. 92, 2236–2239. https://doi.org/10.3382/ps.2012-02728.

Lichovnikova, M., 2007. The effect of dietary calcium source, concentration and particle size on calcium retention, eggshell quality and overall calcium requirement in laying hens. Br. Poult. Sci. 48, 71–75. https://doi.org/10.1080/00071660601148203.

Mussehl, F.E., Halbersleben, D.L., 1923. Influence of the specific gravity of hens' eggs on fertility, hatching power, and growth of chicks. J. Agric. Res. 23, 717–720.

Narushin, V.G., 1997. Mathematical model for non-destructive calculation of the morphological parameters of avian eggs. IFAC Proc. Volumes 30 (5), 283–287. https://doi.org/10.1016/S1474-6670(17)44446-6.

Narushin, V.G., 1998. Mathematical algorithm for quality control in egg production. Acta Hortic. 476, 345–348. https://doi.org/10.17660/ActaHortic.1998.476.40.

Narushin, V.G., 2001a. What egg parameters predict best its shell strength? In: Mulder, R.W.A.W., Bilgili, S.F. (Eds.), Proceedings of the 9th European Symposium on the Quality of Eggs and Egg Products, pp. 349–355 (WPSA Turkish Branch, Kusadasi, Turkey).

Narushin, V.G., 2001b. AP—Animal Production Technology: Shape geometry of the avian egg. J. Agric. Eng. Res. 79, 441–448. https://doi.org/10.1006/jaer.2001.0721.

Narushin, V.G., 2005. Egg geometry calculation using the measurements of length and breadth. Poult. Sci. 84, 482–484. https://doi.org/10.1093/ps/84.3.482.

Narushin, V.G., Romanov, M.N., Bondarenko, Yu.V., 1994. Studies on chick embryo sex determination and manipulation in the countries of the former USSR — a review. 1. Sex differences in eggs. In: Proceedings of the 9th European Poultry Conference: Plenary Papers and Contributed Papers, Vol. 1, pp. 320–321 (World's Poultry Science Association, UK Branch, Glasgow, Scotland, UK).

Narushin, V.G., Romanov, M.N., Bogatyr, V.P., 1996. On relationship between chicken egg morphological parameters and chick sex. In: Abstracts of the 2nd Ukrainian Poultry Conference, pp. 92–93 (World’s Poultry Science Association, Ukrainian Branch, Poultry Research Institute, UAAS, Borky, Ukraine).

Narushin, V.G., Romanov, M.N. Bogatyr, V.P., 1998. Method for preincubational prediction of embryo sex in chicken eggs. In: Proceedings of the 8th World Conference on Animal Production, Vol. 1, pp. 832–833 (Seoul, Korea).

Narushin, V.G., Van Kempen, T.A., Wineland, M.J., Christensen, V.L., 2004. Comparing infrared spectroscopy and egg size measurements for predicting eggshell quality. Biosyst. Eng. 87, 101–107. https://doi.org/10.1016/j.biosystemseng.2003.12.006.

Narushin, V.G., Lu, G., Cugley, J., Romanov, M.N., Griffin, D.K., 2020a. A 2-D imaging-assisted geometrical transformation method for non-destructive evaluation of the volume and surface area of avian eggs. Food Control 112, 107112. https://doi.org/10.1016/j.foodcont.2020.107112.

Narushin, V.G., Romanov, M.N., Lu, G., Cugley, J., Griffin, D.K., 2020b. Digital imaging assisted geometry of chicken eggs using Hügelschäffer's model, Biosyst. Eng. 197, 45–55. https://doi.org/10.1016/j.biosystemseng.2020.06.008.

Narushin, V.G., Romanov, M.N., Griffin, D.K., 2021a. A novel Egg Quality Index as an alternative to Haugh unit score. J. Food Eng. 289, 110176. https://doi.org/10.1016/j.jfoodeng.2020.110176.

Narushin, V.G., Romanov, M.N., Lu, G., Cugley, J., Griffin, D.K., 2021b. How oviform is the chicken egg? New mathematical insight into the old oomorphological problem. Food Control, 119, 107484. https://doi.org/10.1016/j.foodcont.2020.107484.

Narushin, V.G., Romanov, M.N., Griffin, D.K., 2021c. Non-destructive measurement of chicken egg characteristics: Improved formulae for calculating egg volume and surface area. Biosyst. Eng. 201, 42–49. https://doi.org/10.1016/j.biosystemseng.2020.11.006.

Narushin, V.G., Romanov, M.N., Griffin, D.K., 2021d. Non-destructive evaluation of the volumes of egg shell and interior: Theoretical approach. J. Food Eng. 300, 110536. https://doi.org/10.1016/j.jfoodeng.2021.110536.

Narushin, V.G., Chausov, M.G., Shevchenko, L.V., Pylypenko, A.P., Davydovych, V.A., Romanov, M.N., Griffin, D.K., 2021e. Shell, a naturally engineered egg packaging: Estimated for strength by non-destructive testing for elastic deformation. Biosyst. Eng. 210, 235–246. https://doi.org/10.1016/j.biosystemseng.2021.08.023.

Narushin, V.G., Romanov, M.N., Griffin, D.K., 2022a. Delineating an ovoidal egg shape by length and breadth: A novel two-parametric mathematical model. Biosyst. Eng. 224, 336–345. https://doi.org/10.1016/j.biosystemseng.2022.11.003.

Narushin, V.G., Griffin, A.W., Romanov, M.N., Griffin, D.K., 2022b. Measurement of the neutral axis in avian eggs reveals which species conform to the golden ratio. Ann. N. Y. Acad. Sci. 1517, 143–153. https://doi.org/10.1111/nyas.14895.

Nedomová, Š., Buchar, J., Strnková, J., 2014. Goose’s eggshell strength at compressive loading. Potravinárstvo – Slovak J. Food Sci. 8 (1), 54–61. https://doi.org/10.5219/346.

Nordstrom, J.O., Ousterhout, L.E., 1982. Estimation of shell weight and shell thickness from egg specific gravity and egg weight. Poult. Sci. 61, 1991–1995. https://doi.org/10.3382/ps.0611991.

Olsson, N., 1934. Studies on Specific Gravity of Hen’s Eggs. A New Method for Determining the Percentage of Shell on Hens’ Eggs. Otto Harrassowitz, Leipzig, Germany.

ORKA, 2023. Egg shell thickness gauge. ORKA Food Technology Ltd. Available at: https://eggtester.com/eggshell-thickness-gauge. (Accessed 7 July 2023).

Petchko, K., 2018. Chapter 14 - Results, discussion, and conclusion. In: How to Write About Economics and Public Policy. Academic Press, Elsevier Inc., The Netherlands, pp. 271–300. https://doi.org/10.1016/B978-0-12-813010-0.00014-4.

Romanoff, A.L., Romanoff, A.J., 1949. The Avian Egg. John Wiley & Sons Inc, New York, NY, USA.

Romanov, M.N., Narushin, V.G., Sakhatsky, N.I., 1994. Studies on chick embryo sex determination and manipulation in the countries of the former USSR — a review. 2. Shifting of sex ratio. In: Proceedings of the 9th European Poultry Conference: Plenary Papers and Contributed Papers, Vol. 1, pp. 324–326 (World's Poultry Science Association, UK Branch, Glasgow, Scotland, UK).

Schoorl, P., Boersma, H.Y., 1962. Research on the quality of the egg shell. In: Proceedings of the 12th World Poultry Congress, pp. 432–435 (Sydney, Australia).

Shomina, N.V., Tkachenko, S.M., Tagirov, M.T., Tereshchenko, O.V., 2009. [Monitoring the quality of hatching eggs during storage]. Efektyvne ptakhivnytstvo [Effective Poultry Farming], Issue 11, 29–33.

Sloan, D.R., Harms, R.H., Abdullah, A.G., Kuchinski, K.K., 2000. Variation in egg content density makes egg specific gravity a poor indicator of shell weight. J. Appl. Anim. Res. 18, 121–128. https://doi.org/10.1080/09712119.2000.9706333.

Stable Micro Systems, 2023. Egg quality testing. Available at: https://www.stablemicrosystems.com/EggQualityTesting.html. (Accessed 7 July 2023).

Tkachenko, S.M., Shomina, N.V., Tagirov, M.T., Tereshchenko, O.V., 2009. The influence of long-term egg storage on the quality of day-old young]. Ptakhivnytstvo [Poultry Farming] 64, 176–182.

Trukhina, A.V., Romanov, M.N., Smirnov, A.F., Narushin, V.G., 2021. [Prospects for producing individuals of predominantly a certain sex in birds]. In: [Materials of the 3rd International Scientific and Practical Conference on Molecular Genetic Technologies for Analysis of Gene Expression Related to Animal Productivity and Disease Resistance], pp. 80–94 (Sel'skokhozyaistvennye tekhnologii, Moscow, Russia). https://doi.org/10.18720/SPBPU/2/z21-43.

Xiong, H., Xu, H., Zhou, W., Yao, Y., Chen, H., 2013. Detection of intact egg eggshell quality based on NIR spectra. Nongye Gongcheng Xuebao/Trans. Chin. Soc. Agric. Eng. 29 (Supp. 1), 264–269. https://doi.org/10.3969/j.issn.1002-6819.2013.z1.041.