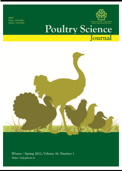

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Validation of Prediction Equations of the Egg Characteristics in Laying Hens

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Abstract

Poultry researchers have used mathematical models to explain some laying bird responses. There are many equations of the egg characteristics, but their validity has not yet been confirmed. Therefore, the aim of the current study was to assess the accuracy of the equations proposed to predict egg characteristics in laying hens. A total of one hundred forty-eight prediction equations of egg characteristics were collected from different studies. A total of 781 eggs from 75-week-old Hy-Line laying hens were gathered to measure egg quality characteristics, and other egg characteristics were calculated using these measurements. The residuals of the difference of observed and predicted values were used to calculate accuracy measurements like mean absolute deviation (MAD), mean squared error of prediction (MSEP), mean absolute percentage error (MAPE) and root mean squared error of prediction (RMSEP). RMSEP was used to estimate the error of the model (EM) with a 12% as the maximum level of validation of the egg characteristics prediction equation and 1.2% only for specific gravity. Nine egg characteristic prediction equations were validated with great accuracy because validated equations showed a value of MAD, MSEP, MAPE and RMSEP very low and EM less than 12%. Equations validated for external egg characteristic used easy-to-measure traits (i.e., egg weight, egg length, and egg width) as predictor variables. Fifteen egg characteristic prediction equations were validated with considerable accuracy. These equations might shorten the process of egg quality determination, reduce the waste of eggs, and thereby saving time and money.

Introduction

Egg production is regarded as one of the most profitable farm activities around the world because of the improvement of genetic and nutrition in laying hen. The majority of produced eggs are provided by conventional egg production systems (Matthews and Summer, 2015; USDA, 2018), and increasing the expenses related to the production process is of great concern to egg producers. Consumer acceptability and preferences are affected by characteristics so-called egg quality (Hisasaga *et al*., 2020). In order to evaluate egg quality, thousands of eggs are wasted, lots of money is expensed (to buy materials and equipment), and so much time is lost (USDA, 2020). In addition, the assessment of egg quality is a complicated task since it requires, trained personal, specific materials and equipment, and an exclusive place to efficiently conduct the complete process (Roberts *et al*., 2013). Because egg quality determination is a complex process, making mistakes is more common. Hence, innovative alternatives are necessary to avoid measurement mistakes and to diminish egg production expenses (Inca, 2016).

Researchers are using mathematical models in a logical way to describe complex concepts, natural phenomenon, hypotheses and ideas. Models solve current issues using numerical solutions (Tedeschi and Menendez, 2020). Mathematical models are representations of the reality, and allow us to anticipate future behaviors outcomes (Tedeschi, 2006) or biological phenomena in animal science. In poultry science, many models have been developed to predict egg quality characteristics; but so far, the accuracy of those models has not been assessed.

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Despite the fact that prediction models cannot entirely describe the reality under diverse conditions, they may contribute to observe some outcomes in a real system (Tedeschi, 2006). In a real system, a model will only have relevance if it represents the system with good accuracy (Hillston, 2003). Validation is a great form to verify if mathematical models are useful and accurate. Validation of models allows examining whether the intended model structure is appropriate -or the equation approximates the real system.

Many studies on laying birds have proposed mathematical models to estimate different egg quality characteristics. However, it has not been completely clarified if these models can predict egg quality characteristics with enough accuracy or they are useful enough to reduce the long procedure of egg quality characteristic determination. Therefore, the objective of the current study was to validate mathematical models to reduce mistakes and expenses in the egg quality determination process.

Materials and Methods

Biological materials and data collection

The experimental procedure was conducted at the Poultry Experimental Unit at the Universidad Nacional Agraria La Molina. Laying hens were raised in similar conditions according to Hy-line brown management recommendations. A total of 781 eggs from 75-week-age Hy-Line brown laying hens were collected during six weeks. At the end of the third week (77 weeks), egg quality characteristics were measured on every egg using a digital caliper (78-440, Stanley). Egg weight (EW, g), egg length (EL, mm), and egg width (EA, mm) were recorded. After cracking the eggs, shell weight (SW, g), shell thickness (ST, mm), albumen length (AL, mm; longest length), albumen width (AG, mm; perpendicular to AL), albumen height (AH, mm), yolk width (YG, mm; any direction), and yolk length (YL, mm; perpendicular to YG) were measured. The yolk was manually separated from the albumen and its weight (YW, g) and height (YH, mm) were determined. The albumen weight (AW, g) was determined with the following formula: AW = EW – SW – YW. Before cracking the eggs, the specific gravity (SG, g/cm^3) was determined using the saline solution technique as detailed by Inca *et al*. (2020). Furthermore, other external and internal characteristics (egg surface area, ESA; unit surface shell weight, U; shell ratio, SR; egg shape index, ESI; Haugh unit, HU; albumen index, AI; albumen ratio, AR; and yolk diameter, YD) were calculated by the calculations provided by Inca *et al*. (2020), as follows:

External egg characteristics:

Egg surface area (ESA, cm^2) = $3.9782 \times EW^{0.75056}$

Where, EW = egg weight (g).

Unit surface shell weight (U, mg/cm^2) = $\frac{SW}{ESA}$

Where, SW = shell weight (mg), ESA = egg surface area (cm^2).

Shell ratio (SR, %) = $\frac{SW}{EW} \times 100$

Where, SW= shell weight (mg), EW = egg weight(g).

Egg shape index (ESI, %) = $\frac{EG}{EL} \times 100$

Where, EG and EL are the egg width and length, respectively.

Internal egg characteristics:

Haugh unit (HU) = $100 \times \log (AH - 1.7\ EW^{0.37} + 7.6)$

Where, AH = albumen height (mm), EW = egg weight (g).

Albumen index (AI, %) = $\frac{AH}{[AL+AG]/2} \times 100$

Where, AH = albumen height (mm), AL = albumen length (mm), AG = albumen width (mm).

Albumen ratio (AR, %) = $\frac{AW}{EW} \times 100$

Where, AW=albumen weight (g), EW=egg weight(g).

Yolk diameter (YD, mm) = $\frac{YG+YL}{2}$

Where, YG = yolk width (mm), YL = yolk length (mm).

Equations for validation

A total of 148 equations were compiled from various studies using the Cochrane method (Chandler and Hopewell, 2013). All equations pretended to predict different egg characteristics using simple or polynomial linear regression. Each corresponding determination coefficient (R^2) was collected. All prediction equations collected are shown in Table 1.

Validation procedure

First, predicted values were estimated using prediction equations of the egg characteristics. These values were compared with observed ones (measurements obtained in the current study) to obtain residuals of every egg characteristic, according to Tedeschi (2006). Second, residuals were used to calculate the error of every equation. In order to measure the prediction accuracy of the models, mean absolute deviation (MAD), mean squared error of prediction (MSEP), mean absolute percentage error (MAPE) and root mean squared error of prediction (RMSEP) were used. Formulas to determine the prediction accuracy of the models were based on Inca (2016) and Vaneput (2020) studies, as follows:

Mean absolute deviation (MAD) = $\frac{\sum_{i=1}^{n}|Y_i - \hat{Y}_i|}{n} = \frac{\sum_{i=1}^{n}|E_i|}{n}$

Mean square error of prediction (MSEP) = $\frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{n} = \frac{\sum_{i=1}^{n}E_i^2}{n}$

Mean absolute percentage error (MAPE) = $\frac{\sum_{i=1}^{n}\left|\frac{Y_i-\hat{Y}_i}{Y_i}\right|}{n} = \frac{\sum_{i=1}^{n}\left|\frac{E_i}{Y_i}\right|}{n}$

Root mean squared error of prediction (RMSEP) = $\sqrt{\frac{\sum_{i=1}^{n}(Y_i-\hat{Y}_i)^2}{n}} = \sqrt{\frac{\sum_{i=1}^{n}E_i^2}{n}}$

Where, Y_i = observed values of egg quality characteristic, $\hat{Y}_i$ = predicted values of egg quality characteristic, E_i = sum of residuals, E_i^2 = sum of squared residuals, n = number of observations.

MAD outcomes were analyzed by one-way ANOVA, using GLM procedure. A comparison was made between MAD outcomes for each egg characteristic. Differences between mean MAD values were determined using Tukey test at 0.05 significance level. All data were analyzed with RStudio software version 1.4.1106 (RStudio Team, 2016). Finally, the error of the model was estimated using RMSEPP (Salvador and Guevara, 2013) and with the following formula:

$$\text{Error of model (EM, \%)} = \frac{RMSEP}{\hat{Y}} \times 100$$

Where, RMSEP = root mean squared error of prediction, $\hat{Y}$ = average value of the egg characteristics. For validation process, the maximum value established by the model of error was 12% for egg characteristics, and 1.2% only for specific gravity.

Table 1. Egg characteristics equations collected to be validated

N°	Reference	Year	Species	N*
R01	Nordstrom and Ousterhout	1982	Hen	14
R02	Harms *et al.*	1990	Hen	2
R03	Iposu *et al*.	1993	Hen	4
R04	Khurshid *et al.*	2003	Quail	16
R05	Seker	2004	Quail	6
R06	Narushin	2005	Hen	2
R07	Abanikannda and Leihgh	2007	Hen	6
R08	Yakubu *et al.*	2008	Chicken	17
R09	Alkan *et al.*	2008	Quail	10
R10	Fajemilehin	2008	Guinea Hen	18
R11	Alkan *et al.*	2009	Quail	28
R12	Callejo Ramos *et al.*	2010	Hen	5
R13	Çiçek *et al*.	2013	Quail	10
R14	Onunkwo and Okoro	2015	Guinea Hen	10

*N: Number of equations that each investigation provided.

Results

MAD, MSEP, MAPE and RMSEP and EM values from external egg characteristics are shown in Table 2. Egg weight equations were not accurate enough to be validated since all models had an EM greater than 12% (maximum value to validate equations). MAD, MSEP, MAPE, RMSEP and EM values indicated that egg length and egg width prediction models are not validated. These results showed no adequate accuracy, even when every collected equation had egg weight as a predictor variable. Moreover, all equations for egg length and egg width overestimated the values for prediction accuracy and EM, thus, none of the equations was validated (Table 2).

Both E31 and E40 indicated significant differences (P < 0.05) between shell weight equations for MAD. For these equations, MAD, MSEP and MAPE showed the lowest values and EM had a value of 10.52% and 10.82%, respectively, which are reasons to validate E31 and E40. Moreover, E31 and E40 have the egg length and egg width as predictor variables; therefore, E31 and E40 are useful models because egg weight and egg width are easy characteristics to measure (Table 3). Twelve equations were collected to predict shell thickness, but none of them was validated, because they had an EM greater than 12%. On the other hand, E60 and E63 were validated for specific gravity since these models pointed a lowest MAD and were significantly different (P < 0.05) from the other models of specific gravity. In addition, MAD, MSEP and MAPE had the lowest values. Thus, these results showed n incredible accuracy of E60 and E63 (Table 3). E60 and E63 had EM of 1.03 and 0.70%, respectively, lower than 1.2% (established only for this egg characteristic).

Table 2. MAD, MSEP, MAPE and EM values of equations of the external egg characteristic

N	Equation	Reference	MAD[1]	MSEP[2]	MAPE[3] (%)	EM[4] (%)
			Egg Weight			
E01	$Y = -21.658 + 0.828\ X_A + 0.373\ X_L\ (R^2 = 0.8260)$	R09	28.54[c]	833.72	43.37	44.12
E02	$Y = 41.595 - 0.599\ X_L\ (R^2 = 0.2110)$	R10	27.41[c]	793.68	41.32	43.04
E03	$Y = 39.318 - 0.205\ X_A\ (R^2 = 0.1682)$	R10	27.03[c]	771.15	40.75	42.43
E04	$Y = -3.3133600 + 1.835144\ X_L + 2.655127\ X_A\ (R^2 = 0.3186)$	R04	46.18[e]	2163.38	70.40	71.07
E05	$Y = 1.970096 + 2.252730\ X_L\ (R^2 = 0.2313)$	R04	41.97[d]	1791.18	63.92	64.66
E06	$Y = -1.0109318 + 3.616882\ X_A\ (R^2 = 0.1781)$	R04	50.57[f]	2591.51	77.12	77.78
E07	$Y = 14.89 + 5.40\ X_L\ (R^2 = 0.2970)$	R08	18.44[b]	366.06	27.70	29.23
E08	$Y = 22.21 + 5.34\ X_A\ (R^2 = 0.3010)$	R08	19.77[b]	423.16	29.66	31.43
E09	$Y = 14.71 + 3.10\ X_L + 3.17\ X_A\ (R^2 = 0.3444)$	R08	18.37[b]	364.42	27.57	29.17
E10	$Y = 15.30\ X_L^{0.63}\ (R^2 = 0.2958)$	R08	18.42[b]	366.08	27.65	29.23
E11	$Y = 23.60\ X_A^{0.44}\ (R^2 = 0.2863)$	R08	20.19[b]	440.85	30.28	32.08
E12	$Y = 2.3887 + 1.3179\ X_P\ (R^2 = 0.8850)$	R05	10.88[a]	125.07	16.79	17.09
E13	$Y = 7.5927 - (0.2424\ X_P) + 0.1160\ X_P^2\ (R^2 = 0.8890)$	R05	117.56[h]	15623.36	175.76	190.98
E14	$Y = 3.1954 + 2.1929\ X_Y\ (R^2 = 0.5930)$	R05	25.91[c]	700.69	39.35	40.44
E15	$Y = 12.6076 - (2.9558\ X_Y) + 0.6995\ X_Y^2\ (R^2 = 0.6060)$	R05	93.08[g]	10168.05	141.44	154.07
E16	$Y = 5.9338 + 6.3427\ X_S\ (R^2 = 0.3680)$	R05	20.49[b]	453.00	31.01	32.52
E17	$Y = 11.5143 - (6.8720\ X_S) + 7.7518\ X_S^2\ (R^2 = 0.3760)$	R05	201.36[i]	44346.74	306.73	321.75
			Egg length			
E18	$Y = 0.292 + 1.271\ X_W\ (R^2 = 0.5320)$	R11	24.00[d]	610.47	40.17	41.55
E19	$Y = 0.436 + 1.055\ X_W\ (R^2 = 0.3620)$	R11	10.02[b]	121.20	16.69	18.51
E20	$Y = 0.323 + 1.165\ X_W\ (R^2 = 0.3880)$	R11	17.09[c]	319.61	28.57	30.06
E21	$Y = 0.014 + 1.148\ X_W\ (R^2 = 0.1990)$	R11	8.82[a]	77.93	14.82	14.84
			Egg Width			
E22	$Y = 0.239 + 1.056\ X_W\ (R^2 = 0.7710)$	R11	25.41[a]	675.57	57.56	59.15
E23	$Y = 0.244 + 1.136\ X_W\ (R^2 = 0.5010)$	R11	30.65[c]	975.16	69.47	71.07
E24	$Y = 0.204 + 1.188\ X_W\ (R^2 = 0.2750)$	R11	34.02[d]	1196.67	77.11	78.73
E25	$Y = 0.016 + 1.104\ X_W\ (R^2 = 0.1550)$	R11	28.33[b]	835.81	64.19	65.80

[a-j] Means within the same column with different superscript letters are significantly different ($P < 0.05$).
[1] MAD = Mean absolute deviation. [2] MSEP = Mean squared error of prediction. [3] MAPE = Mean absolute percentage error. [4] EM = Error of model. X_W = Egg weight, X_L = Egg length, X_A = Egg width, X_P = Albumen Weight, X_Y = Yolk Weight, X_S = Shell Weight.

In the current study, results of equations of the external egg characteristics are presented in Table 4. There were significant differences ($P < 0.05$) in MAD between equations to estimate egg surface area so that E64 and E65 showed lower values of MSEP and MAPE. Also, EM was lower than 12% in E64 and E65 equations (10.11 and 6.29, respectively). Equations for unit surface shell weight (also called SWUSA; Zhang *et al.*, 2020) and shell ratio were not validated because prediction errors had higher values and EM were greater than 12%. There were significant differences in MAD for egg shape index prediction equations. E76 showed a lower value for MSEP and MAPE, and had a 7.08 for EM value; therefore, E76 was validated. Equations validated for external egg characteristic used easy-to-measure traits (i.e., egg weight, egg length, and egg width) as predictor variables.

Table 3. MAD, MSEP, MAPE and EM values of equations of the egg shell characteristics

N	Equation	Reference	MAD[1]	MSEP[2]	MAPE[3] (%)	EM[4] (%)
	Shell Weight					
E26	$Y = 3.716 + 0.04561\ X_L^5 + 0.170\ X_A^6 - 0.00831\ X_W^7$ ($R^2 = 0.0880$)	R10	0.96[f]	1.25	14.99	18.21
E27	$Y = 3.789 + 0.07572\ X_L$ ($R^2 = 0.0740$)	R10	1.92[i]	4.19	30.20	33.28
E28	$Y = 3.587 + 0.179\ X_A$ ($R^2 = 0.0820$)	R10	1.79[h]	3.69	28.05	31.24
E29	$Y = 4.549 - 0.0101\ X_W$ ($R^2 = 0.0840$)	R10	1.02[f]	1.39	15.88	19.15
E30	$Y = 2.77 + 0.49\ X_A$ ($R^2 = 0.0286$)	R08	1.27[g]	2.02	19.77	23.09
E31	$Y = 2.15 + 0.06\ X_W$ ($R^2 = 0.0390$)	R08	0.50[a]	0.42	8.41	10.52
E32	$Y = 2.13 + 0.05\ X_W + 0.007\ X_L$ ($R^2 = 0.0290$)	R08	0.81[e]	0.92	12.79	15.56
E33	$Y = 1.82 + 0.04\ X_W + 0.26\ X_A$ ($R^2 = 0.0372$)	R08	0.72[cd]	0.75	11.36	14.05
E34	$Y = 2.79\ X_A^{0.37}$ ($R^2 = 0.0338$)	R08	1.36[g]	2.27	21.18	24.53
E35	$Y = 0.74\ X_W^{0.48}$ ($R^2 = 0.0391$)	R08	0.78[de]	0.85	12.19	14.97
E36	$Y = 0.573 + 0.01532\ X_L + 0.0238\ X_W$ ($R^2 = 0.5070$)	R09	3.11[j]	10.12	49.96	51.73
E37	$Y = (2.0341 \times X_W) - 2.1014 \times (X_W/ X_G^8)$ ($R^2 = 0.9230$)	R02	0.87[f]	0.91	13.69	15.48
E38	$Y = -0.521102 + 0.310761\ X_L + 0.4074\ X_A$ ($R^2 = 0.0701$)	R04	3.03[j]	9.69	48.65	50.61
E39	$Y = 0.138189 + 0.062933\ X_W + 0.233078\ X_L$ ($R^2 = 0.0785$)	R04	0.68[bc]	0.69	10.90	13.50
E40	$Y = -0.001150 + 0.071568\ X_W + 0.311496\ X_A$ ($R^2 = 0.0710$)	R04	0.52[a]	0.44	8.66	10.82
E41	$Y = 0.8626 + 0.06418\ X_G$ ($R^2 = 0.4636$)	R01	5.35[j]	29.13	84.94	87.76
E42	$Y = 4.8334 + 0.005217\ X_W$ ($R^2 = 0.0045$)	R01	1.47[g]	2.60	22.52	26.24
E43	$Y = 2.1205 + 0.0555\ X_W$ ($R^2 = 0.4667$)	R01	0.61[b]	0.57	9.84	12.29
E44	$Y = -5.9724 + 0.06586 X_G + 0.09906\ X_W$ ($R^2 = 0.8902$)	R01	5.27[j]	28.13	84.16	86.24
E45	$Y = 2.1205 + 0.05545\ X_W$ ($R^2 = 0.4667$)	R01	0.62[b]	0.57	9.87	12.32
	Shell Thickness					
E46	$Y = 0.135 + 0.0031\ X_L$ ($R^2 = 0.0540$)	R09	0.043[a]	0.003	11.81	14.94
E47	$Y = 0.459 + 0.00367\ X_L$ ($R^2 = 0.0310$)	R10	0.129[c]	0.018	38.63	38.43
E48	$Y = 0.431 + 0.01451\ X_A$ ($R^2 = 0.0410$)	R10	0.143[f]	0.022	42.64	42.24
E49	$Y = 0.337 + 0.003608\ X_W$ ($R^2 = 0.0350$)	R10	0.221[h]	0.051	65.20	64.23
E50	$Y = 0.267 + 0.00376\ X_L + 0.0146\ X_A + 0.00375\ X_W$ ($R^2 = 0.0380$)	R10	0.248[i]	0.064	72.76	71.65
E51	$Y = 0.154646 + 0.076448\ X_A$ ($R^2 = 0.0420$)	R04	0.139[ef]	0.021	41.43	41.19
E52	$Y= 0.154721 + 0.000694\ X_W + 0.073939\ X_A$ ($R^2 = 0.0384$)	R04	0.173[g]	0.032	51.36	50.72
E53	$Y = 11.9836 + 0.3057\ X_G$ ($R^2 = 0.6073$)	R01	0.042[a]	0.003	30.94	14.37
E54	$Y = 42.3934 - 0.0768\ X_W$ ($R^2 = 0.0355$)	R01	0.036[a]	0.002	11.22	13.11
E55	$Y = -11.0561 + 0.4349\ X_G + 0.2112\ X_W$ ($R^2 = 0.7667$)	R01	0.070[b]	0.002	27.90	13.09
E56	$Y = -0.17 + 0.01\ X_W$ ($R^2 = 0.4120$)	R08	0.134[de]	0.023	39.92	43.15
E57	$Y = 0.001\ X_W^{1.55}$ ($R^2 = 0.4416$)	R08	0.304[j]	0.103	88.74	91.27
	Specific Gravity					
E58	$Y = 1.047 + 0.0842\ X_T$ ($R^2 = 0.1220$)	R12	0.012[b]	0.0002	1.06	1.15
E59	$Y = 1.070 + 0.00049\ X_C$ ($R^2 = 0.1300$)	R12	0.015[c]	0.0003	1.37	1.49
E60	$Y = 1.060 + 0.0028\ X_H$ ($R^2 = 0.2550$)	R12	0.009[a]	0.0001	0.86	1.03
E61	$Y = 1.040 + 0.00044\ X_U$ ($R^2 = 0.3020$)	R12	0.013[b]	0.0002	1.21	1.37
E62	$Y = 1.023 + 0.0572\ X_T + 0.000456\ X_C + 0.00036\ X_U$ ($R^2 = 0.4530$)	R12	0.013[b]	0.0002	1.22	1.33
E63	$Y = (X_W/0.9680) \times (X_W - X_S) + (0.4921 \times X_S)$ ($R^2 = 0.9230$)	R02	0.007[a]	0.0001	0.64	0.70

[a-j] Means within the same column with different superscript letters are significantly different ($P < 0.05$).
[1] MAD = Mean absolute deviation. [2] MSEP = Mean squared error of prediction. [3] MAPE = Mean absolute percentage error. [4] EM = Error of model. X_W = Egg weight, X_L = Egg length, X_A = Egg width, X_T = Shell thickness, X_G = Specific gravity, X_S = Shell weight, X_U = Haugh unit, X_C = Yolk color, X_H = Albumen height.

Table 4. MAD, MSEP, MAPE and EM values of equations of the external egg characteristics

N	Equation	Reference	MAD[1]	MSEP[2]	MAPE[3] (%)	EM[4] (%)
	Egg Surface Area					
E64	$Y = 10.561 - 0.178\ X_A - 0.045\ X_L + 1.535\ X_W\ (R^2 = 0.9960)$	R09	8.85[b]	85.88	9.49	10.12
E65	$Y = 6.254 + 1.387\ X_W\ (R^2 = 0.9940)$	R09	5.36[a]	33.28	5.71	6.29
E66	$Y = (0.9658\ X_A/\ X_L + 2.1378)\ X_L{*}\ X_A\ (R^2 = 0.9610)$	R06	62.31[c]	3936.06	68.89	68.44
E67	$Y = (3.155 - 0.0136\ X_L + 0.0115\ X_A)\ X_L\ x\ X_A\ (R^2 = 0.9610)$	R06	62.25[c]	3936.51	68.87	68.44
	Unit Surface Shell Weight					
E68	$Y= 19.1936 + 0.6767\ X_G\ (R^2 = 0.6561)$	R01	45.31[a]	2092.99	69.13	68.11
E69	$Y = 8.6878 - 0.0176\ X_W\ (R^2 = 0.0412)$	R01	59.63[b]	3606.66	88.65	89.41
E70	$Y = -30.6697 + 0.9565\ X_G + 0.4571\ X_W\ (R^2 = 0.8207)$	R01	62.96[c]	4008.40	96.49	94.26
	Shell Ratio					
E71	$Y = 12.49 - 0.06\ X_W\ (R^2 = 0.2400)$	R03	1.10[b]	1.75	11.31	14.01
E72	$Y = -0.3773 + 0.1140\ X_G\ (R^2 = 0.8751)$	R01	9.26[c]	86.54	102.84	98.65
E73	$Y = 13.4811 - 0.0728\ X_W\ (R^2 = 0.3295)$	R01	1.01[a]	1.52	10.49	13.05
E74	$Y = -0.8794 + 0.1169\ X_G + 0.004604\ X_W\ (R^2 = 0.8758)$	R01	9.44[c]	89.87	104.83	100.53
	Egg Shape Index					
E75	$Y = 0.78 - 0.00048\ X_W + 0.0311\ X_A - 0.0241\ X_L\ (R^2 = 0.9880)$	R09	5.87[b]	44.23	8.12	8.99
E76	$Y = 0.79 + 0.0307\ X_A - 0.02423\ X_L\ (R^2 = 0.9880)$	R09	4.34[a]	27.46	6.04	7.08

[a-j] Means within the same column with different superscript letters are significantly different (*P* < 0.05).
[1] MAD = Mean absolute deviation. [2] MSEP = Mean squared error of prediction. [3] MAPE = Mean absolute percentage error. [4] EM = Error of model. X_W = Egg weight, X_L = Egg length, X_A = Egg width, X_G = Specific gravity.

Prediction errors and EM values of prediction equations of the albumen characteristics are shown in Table 5. Results showed that E91 predicted albumen weight with great accuracy, because MAD was significantly different (*P* < 0.05) rather than other equations, and the value of MSEP and MAPE were lower and EM had a value of 7.15% (lower than 12%). These outcomes validated E91 equation. Equations collected to predict albumen length and albumen height had not enough accuracy to be validated. However, two models of albumen width were validated, E100 and E102 presented smaller values for prediction errors. Moreover, MAD values had a significant different (*P* < 0.05) in comparison with other models and EM values were less than 12%.

Table 6 presents prediction errors and errors of model values of prediction equations of the yolk characteristics. Only E124 was validated for yolk weight because MAD value showed a significant difference (*P* < 0.05) compared to other models. Additionally, MSEP and MAPE values were lower and EM was under 12%. The E134 had great prediction accuracy of yolk height. Prediction errors presented lower values and EM value was below 12% for E134. Equations to predict yolk width were not validated.

None of the equations was validated to predict the Haugh unit, yolk index and yolk diameter (Table 7). E146 was validated to predict albumen ratio. E146 showed a MAD value significantly different than E145 (*P* < 0.05), MSEP and MAPE values were lower, and EM had a value of 8.8.

A total of 15 equations were validated with reasonable accuracy (Table 8). These equations describe shell weight (n=2), specific gravity (n=2), egg surface area (n=2), egg shape index (n=2), albumen weight (n=1), albumen width (n=2), yolk weight (n=1), yolk height (n=1) and albumen ratio (n=2).

Table 5. MAD, MSEP, MAPE and EM values of equations of the albumen characteristics

N	Equation	Reference	MAD[1]	MSEP[2]	MAPE[3] (%)	EM[4] (%)
			Albumen Weight			
E77	$Y = -1.214 + 1.185\ X_W\ (R^2 = 0.8210)$	R07	36.75[m]	1361.38	93.92	93.20
E78	$Y = -1.185 + 1.172\ X_W\ (R^2 = 0.6740)$	R07	35.93[l]	1301.22	91.83	91.12
E79	$Y = -0.456 + 0.989\ X_W\ (R^2 = 0.6110)$	R07	24.68[i]	614.91	63.28	62.64
E80	$Y = -1.428 + 1.223\ X_W\ (R^2 = 0.7440)$	R07	39.02[n]	1534.94	99.69	98.96
E81	$Y = 0.314 + 0.803\ X_W\ (R^2 = 0.3970)$	R07	13.28[g]	180.16	34.33	33.90
E82	$Y = -0.533 + 1.009\ X_W\ (R^2 = 0.6720)$	R07	25.91[j]	677.61	66.41	65.75
E83	$Y = -0.686 + 0.461\ X_W + 0.0798\ X_L + 0.412\ X_A\ (R^2 = 0.7271)$	R04	7.88[cd]	68.88	19.47	20.96
E84	$Y = -0.553150 + 0.468198\ X_W + 0.426649\ X_A\ (R^2 = 0.7275)$	R04	7.67[c]	65.41	18.93	20.43
E85	$Y = 0.279557 + 0.468198\ X_W\ (R^2 = 0.7224)$	R04	8.70[de]	82.59	21.54	22.96
E86	$Y = -2.128934 + 0.925133\ X_L + 1.63522\ X_A\ (R^2 = 0.2919)$	R04	29.03[k]	866.31	72.99	74.35
E87	$Y = -1.258 + 0.499\ X_W\ (R^2 = 0.5460)$	R14	8.22[e]	73.82	20.39	21.70
E88	$Y = 9.690 + 0.261\ X_W\ (R^2 = 0.2100)$	R14	12.56[f]	171.63	31.04	33.09
E89	$Y = 10.194 + 0.215\ X_W\ (R^2 = 0.4320)$	R14	15.33[h]	250.98	38.05	40.02
E90	$Y = -9.43 + 0.68\ X_W\ (R^2 = 0.4260)$	R08	4.60[b]	24.54	11.50	12.51
E91	$Y = 0.06\ X_W^{1.54}\ (R^2 = 0.4382)$	R08	2.37[a]	8.02	6.14	7.15
			Albumen Length			
E92	$Y = -53.843 + 2.712\ X_A + 1.376\ X_L\ (R^2 = 0.2530)$	R09	59.48[f]	3623.90	69.63	68.67
E93	$Y = 0.402 + 1.255\ X_W\ (R^2 = 0.1870)$	R11	8.00[a]	119.05	8.65	12.45
E94	$Y = 0.329 + 1.233\ X_W\ (R^2 = 0.1760)$	R11	8.67[b]	136.15	9.37	13.31
E95	$Y = 0.219 + 1.045\ X_W\ (R^2 = 0.3010)$	R11	19.08[c]	450.66	21.16	24.21
E96	$Y = 0.019 + 1.228\ X_W\ (R^2 = 0.1890)$	R11	9.02[b]	144.87	9.74	13.73
E97	$Y = -2.427 + 1.126\ X_L\ (R^2 = 0.6281)$	R13	23.13[d]	619.93	25.65	28.40
E98	$Y = 8.770 + 0.815\ X_A\ (R^2 = 0.6280)$	R13	43.09[e]	1963.29	48.52	50.54
			Albumen Width			
E99	$Y = 0.877 + 0.599\ X_W\ (R^2 = 0.4040)$	R11	35.88[d]	1353.69	46.76	48.44
E100	$Y = 0.354 + 1.156\ X_W\ (R^2 = 0.3880)$	R11	6.21[a]	69.95	8.15	11.01
E101	$Y = 0.354 + 1.211\ X_W\ (R^2 = 0.3560)$	R11	7.26[b]	84.99	9.82	12.14
E102	$Y = 0.013 + 1.160\ X_W\ (R^2 = 0.1620)$	R11	6.21[a]	70.07	8.14	11.02
E103	$Y = -101.895 + 4.092\ X_L\ (R^2 = 0.6825)$	R13	65.51[e]	4414.60	88.02	87.47
E104	$Y = 5.035 + 0.864\ X_A\ (R^2 = 0.6672)$	R13	32.97[c]	1168.55	42.64	45.00
			Albumen Height			
E105	$Y = -0.493 + 1.201\ X_W\ (R^2 = 0.2850)$	R11	70.82[i]	5076.66	1015.01	977.38
E106	$Y = 0.149 + 0.443\ X_W\ (R^2 = 0.2870)$	R11	21.85[d]	487.71	316.00	302.94
E107	$Y = -0.333 + 0.581\ X_W\ (R^2 = 0.2650)$	R11	30.40[e]	940.34	438.06	420.65
E108	$Y = -0.028 + 0.678\ X_W\ (R^2 = 0.2220)$	R11	37.06[f]	1394.20	533.03	512.20
E109	$Y = -16.774 + 1.003\ X_W\ (R^2 = 0.6538)$	R10	41.58[h]	1772.37	597.94	577.50
E110	$Y = -14.241 + 0.997\ X_W - 0.464\ X_A - 0.170\ X_L\ (R^2 = 0.6844)$	R10	40.67[g]	1695.78	584.94	564.88
E111	$Y = 24.236 - 0.690\ X_A\ (R^2 = 0.3110)$	R10	13.92[b]	195.35	202.30	191.73
E112	$Y = 29.097 - 0.836\ X_L\ (R^2 = 0.3180)$	R10	16.84[c]	285.02	243.72	231.59
E113	$Y = -0.326 + 0.196\ X_W\ (R^2 = 0.3958)$	R13	5.21[a]	30.66	78.47	75.96
E114	$Y = -0.484 + 0.196\ X_W\ (R^2 = 0.3958)$	R13	5.05[a]	29.04	76.21	73.92

[a-j] Means within the same column with different superscript letters are significantly different ($P < 0.05$).
[1] MAD = Mean absolute deviation. [2] MSEP = Mean squared error of prediction. [3] MAPE = Mean absolute percentage error. [4] EM = Error of model. X_W = Egg weight, X_L = Egg length, X_A = Egg width.

Table 6. MAD, MSEP, MAPE and EM values of equations of the yolk characteristics

N	Equation	Reference	MAD[1]	MSEP[2]	MAPE[3] (%)	EM[4] (%)
	Yolk Weight					
E115	$Y = 10.525 + 0.01093\ X_W + 0.295\ X_L + 0.124\ X_A\ (R^2 = 0.0200)$	R10	3.08[b]	12.67	17.71	21.47
E116	$Y = 12.224 + 0.007073\ X_W\ (R^2 = 0.6000)$	R10	3.91[c]	18.78	22.69	26.14
E117	$Y = 11.708 + 0.161\ X_A\ (R^2 = 0.0850)$	R10	4.18[c]	21.02	24.31	27.65
E118	$Y = 11.494 + 0.314\ X_L\ (R^2 = 0.1770)$	R10	3.25[b]	13.93	18.73	22.51
E119	$Y = -0.618041 + 0.339520\ X_W + 0.156591\ X_A\ (R^2 = 0.6080)$	R04	5.76[d]	36.69	35.63	36.53
E120	$Y = -0.303204 + 0.355813\ X_W\ (R^2 = 0.6054)$	R04	6.45[e]	45.29	39.81	40.59
E121	$Y = 0.003214 + 1.141682\ X_A\ (R^2 = 0.0830)$	R04	11.56[h]	137.06	69.38	70.61
E122	$Y = 0.050845 + 0.921437\ X_L\ (R^2 = 0.1848)$	R04	11.05[g]	125.40	66.28	67.54
E123	$Y = -3.663 + 0.405\ X_W\ (R^2 = 0.5830)$	R14	6.31[e]	44.38	38.86	40.18
E124	$Y = 3.358 + 0.214\ X_W\ (R^2 = 0.2050)$	R14	1.37[a]	3.44	8.62	11.19
E125	$Y = 1.876 + 0.273\ X_W\ (R^2 = 0.6860)$	R14	3.27[b]	13.24	20.46	21.95
E126	$Y = -1.37 + 0.43\ X_W\ (R^2 = 0.4773)$	R08	10.21[f]	109.57	62.68	63.13
E127	$Y = 0.23\ X_W^{1.14}\ (R^2 = 0.4989)$	R08	10.49[f]	116.28	64.28	65.04
	Yolk Width					
E128	$Y = 0.543 + 0.811\ X_W\ (R^2 = 0.6530)$	R11	13.54[b]	205.95	34.05	35.81
E129	$Y = 0.326 + 1.027\ X_W\ (R^2 = 0.2790)$	R11	27.46[c]	789.98	68.85	70.13
E130	$Y = 0.202 + 1.181\ X_W\ (R^2 = 0.1250)$	R11	37.41[d]	1447.58	93.73	94.93
E131	$Y = 0.015 + 1.266\ X_W\ (R^2 = 0.1820)$	R11	42.79[e]	1886.09	107.17	108.36
E132	$Y = 11.706 - 0.136\ X_L\ (R^2 = 0.3541)$	R13	36.46[d]	1336.40	90.91	91.21
E133	$Y = 2.152 + 0.458\ X_W\ (R^2 = 0.3537)$	R13	8.04[a]	72.17	19.96	21.20
	Yolk Height					
E134	$Y = 2.908 + 0.261\ X_A\ (R^2 = 0.4650)$	R09	0.96[a]	1.34	6.18	7.62
E135	$Y = 0.354 + 0.675\ X_W\ (R^2 = 0.3580)$	R11	29.36[f]	877.96	193.87	195.32
E136	$Y = 0.371 + 0.663\ X_W\ (R^2 = 0.1960)$	R11	28.59[e]	832.84	188.80	190.24
E137	$Y = 0.236 + 0.788\ X_W\ (R^2 = 0.1810)$	R11	36.63[g]	1364.35	241.89	243.49
E138	$Y = -0.021 + 1.094\ X_W\ (R^2 = 0.2440)$	R11	56.40[h]	3225.47	372.35	374.38
E139	$Y = 7.848 + 0.140\ X_W\ (R^2 = 0.1470)$	R14	1.86[b]	4.36	12.52	13.76
E140	$Y = 7.184 + 0.150\ X_W\ (R^2 = 0.1850)$	R14	1.86[b]	4.40	12.48	13.82
E141	$Y = -2.018 + 0.372\ X_W\ (R^2 = 0.2924)$	R13	7.15[c]	55.92	47.32	49.30
E142	$Y = 4.262 + 0.355\ X_W\ (R^2 = 0.2912)$	R13	12.32[d]	156.14	81.51	82.37

[a-j] Means within the same column with different superscript letters are significantly different ($P < 0.05$).
[1] MAD = Mean absolute deviation. [2] MSEP = Mean squared error of prediction. [3] MAPE = Mean absolute percentage error. [4] EM = Error of model. X_W = Egg weight, X_L = Egg length, X_A = Egg width.

Table 7. MAD, MSEP, MAPE and EM values of equations of the internal egg calculated characteristics

N	Equation	Reference	MAD[1]	MSEP[2]	MAPE[3] (%)	EM[4] (%)
	Haugh Unit					
E143	$Y = 117.74 - 0.85X_W$ ($R^2 = 0.2350$)	R03	21.36[b]	526.66	25.09	27.64
E144	$Y = 108.612 - 0.507X_W$ ($R^2 = 0.1840$)	R14	10.30[a]	139.55	12.38	14.23
	Albumen Ratio					
E145	$Y = 58.06 + 0.12X_W$ ($R^2 = 0.2500$)	R03	5.65[b]	40.74	9.69	10.58
E146	$Y = 49.03 + 0.24X_W$ ($R^2 = 0.3560$)	R03	4.53[a]	28.40	7.79	8.83
	Yolk Index					
E147	$Y = 0.164 + 0.006X_W$ ($R^2 = 0.2120$)	R14	18.72	371.56	51.37	52.18
	Yolk Diameter					
E148	$Y = -4.406 + 0.824X_A + 0.195X_L + 0.168X_W$ ($R^2 = 0.7940$)	R09	13.25	181.47	32.38	32.74

[a-j] Means within the same column with different superscript letters are significantly different ($P < 0.05$).
[1] MAD = Mean absolute deviation. [2] MSEP = Mean squared error of prediction. [3] MAPE = Mean absolute percentage error.
[4] EM = Error of model. X_W = Egg weight, X_L = Egg length, X_A = Egg width.

Table 8. Equations validated of egg characteristics.

N	Equation	Reference	MAD[1]	MSEP[2]	MAPE[3] (%)	EM[4] (%)
	Shell Weight					
E31	$Y = 2.15 + 0.06 X_W$ ($R^2 = 0.0390$)	R08	0.50[a]	0.42	8.41	10.52
E40	$Y = -0.001150 + 0.071568 X_W + 0.311496 X_A$ ($R^2 = 0.0710$)	R04	0.52[a]	0.44	8.66	10.82
	Specific Gravity					
E60	$Y = 1.060 + 0.0028 X_H$ ($R^2 = 0.2550$)	R12	0.009[a]	0.0001	0.86	1.03
E63	$Y = (X_W/0.9680) \times (X_W - X_S) + (0.4921 \times X_S)$ ($R^2 = 0.0007$)	R02	0.007[a]	0.0001	0.64	0.70
	Egg Surface Area					
E64	$Y = 10.561 - 0.178 X_A - 0.045 X_L + 1.535 X_W$ ($R^2 = 0.9960$)	R09	8.85[b]	85.88	9.49	10.11
E65	$Y = 6.254 + 1.387 X_W$ ($R^2 = 0.9940$)	R09	5.36[a]	33.28	5.71	6.29
	Egg Shape Index					
E75	$Y = 0.78 - 0.00048 X_W + 0.0311 X_A - 0.0241 X_L$ ($R^2 = 0.9880$)	R09	5.87[b]	44.23	8.12	8.99
E76	$Y = 0.79 + 0.0307 X_A - 0.02423 X_L$ ($R^2 = 0.9880$)	R09	4.34[a]	27.46	6.04	7.08
	Albumen Weight					
E91	$Y = 0.06 X_W^{1.54}$ ($R^2 = 0.4382$)	R08	2.37[a]	8.02	6.14	7.15
	Albumen Width					
E100	$Y = 0.354 + 1.156 X_W$ ($R^2 = 0.3880$)	R11	6.21[a]	69.95	8.15	11.01
E102	$Y = 0.013 + 1.160 X_W$ ($R^2 = 0.1620$)	R11	6.21[a]	70.07	8.14	11.02
	Yolk Weight					
E124	$Y = 3.358 + 0.214 X_W$ ($R^2 = 0.2050$)	R14	1.37[a]	3.44	8.62	11.19
	Yolk Height					
E134	$Y = 2.908 + 0.261 X_A$ ($R^2 = 0.4650$)	R09	0.96[a]	1.34	6.18	7.62
	Albumen Ratio					
E145	$Y = 58.06 + 0.12X_W$ ($R^2 = 0.2500$)	R03	5.65[b]	40.74	9.69	10.58
E146	$Y = 49.03 + 0.24X_W$ ($R^2 = 0.3560$)	R03	4.53[a]	28.40	7.79	8.83

[a-j] Means within the same column with different superscript letters are significantly different ($P < 0.05$).
[1] MAD = Mean absolute deviation. [2] MSEP = Mean squared error of prediction. [3] MAPE = Mean absolute percentage error. [4] EM = Error of model. X_W = Egg weight, X_L = Egg length, X_A = Egg width, X_H = Albumen height, X_S = Shell weight.

Discussion

Results of egg weight prediction models are inconsistent, according to the determination coefficient; for instance, E13 had a high value of the determination coefficient (R^2 = 0.8890) that was greater than E12 (R^2 = 0.8850). E13 was supposed to predict egg weight with reasonable accuracy, but in the current study E13 showed the lowest prediction capacity of egg weight. Moreover, E21 was close to be validated even when its determination coefficient showed a lowest value (R^2 = 0.1990) compared to the other models. Moreover, egg weight did not have the ability to predict egg length and egg width with enough accuracy, even though Olawumi and Ogunlade (2008), Dermanović and Mitrović (2013), Ojedapo (2013), and Mube *et al*. (2014) indicate egg weight had a strong correlation with egg length and egg width.

Two models were validated for shell weight, this egg characteristic is highly related to shell strength, and egg producers use shell weight as an indicator of egg quality. These models may be helpful for egg industry because both models have egg weight and egg width as predictors and are easy to measure (Inca *et al*., 2020). Shell thickness is an important indicator of egg break resistance and is highly correlated with the presence of cracks in shell. In the current investigation, it was not possible to validate any equation for shell thickness, but some models (i.e., E54 and E55) were close to being validated, E63 showed a result that agrees with its determination coefficient (R^2 = 0.9230) and is decent model to predict specific gravity, but E63 has shell weight as the predictor variable, and breaking egg is necessary to obtain this characteristic (Inca *et al*., 2020). The same issue was presented with E58 and E61.

Although all the equations for egg surface area had higher determination coefficients (> 0.9610), just two equations were validated (E54 and E65). E65 have some advantages; for instance, egg weight is the only necessary and easy to measure variable. Also, E65 presented good accuracy to predict egg surface area. Likewise, two models were validated with enough accuracy for egg shape index, both concur with their determination coefficients (R^2 = 0.9880). Martínez (2005) mentioned that regression equations with two or more predictor variables estimate the response variable with appropriate accuracy.

Albumen weight is a good indicator of egg quality because it represents the most significant portion of the egg weight, compared to shell weight and yolk weight. Egg protein is mainly located in albumen (Sotherland and Rahn, 1987) containing about 10.5% protein (Willems *et al*., 2013). In the current study, an equation was validated for albumen weight with great accuracy (E91). This equation has egg weight as a predictor variable, making E91 a valuable model for farm conditions. Also, the result is consistent with Olawumi and Ogunlade (2008) and Alipanah *et al*. (2013) reports in which high phenotypic correlation was found between egg weight and albumen weight.

Albumen length equations were not validated, but E93 was almost near to predict with reasonable accuracy. Even though two models (E100 and E102) were validated for albumen width, the determination coefficients of both E100 and E102 are inconsistent with the results of the present study because these models showed very low R^2 compared with the other prediction equations of albumen width. According to R^2 of E100 and E102, the independent variable could not explain the dependent variable well (albumen width). This result is consistent with Martínez (2005) because he mentioned that the objective of regression analysis is not to get a high determination coefficient value, but to obtain accurate estimators of the regression coefficients values. Furthermore, prediction models for albumen height evidenced that predictor variables (egg weight, egg length and egg width) had no relation with response variable (albumen height). Alkan *et al*. (2008) and Alipanah *et al*. (2013) found low correlations between albumen height and egg weight, egg length and egg width, supporting the results in the current study.

The determination coefficient of E124 (R^2= 0.2050) demonstrates a weak capacity to explain the total variation of the response variable (yolk weight). Previous studies have indicated that the exclusive use of the determination coefficient is not a reliable indicator to explain the total variation of the response variable (Achen, 1982; Goldberger, 1991; Hernández, 1993). In addition, E124 has egg weight as a predictor variable, making this equation useful to predict yolk weight. These results agree with Kul and Seker (2004) and Zhang *et al*. (2005), who reported the highest phenotypic correlation between egg weight and yolk weight. Equations for yolk width were far away to be validated. This result agrees with Fajemilehin *et al*. (2009), Onunkwo and Okoro (2015), and Inca *et al*. (2020), who reported low correlations between yolk width and egg weight. E134 was validated to predict yolk height with excellent accuracy; also, this model has egg width as a predictor variable, which is an easy measurement characteristic under farm conditions, making E134 a very appropriate model according to the aims of the current investigation.

E143 and E144 had not enough predictive accuracy in of Haught Unit, and both of them had egg weight as the predictor variable. Debnath and Ghosh (2015) indicated that egg weight has a low phenotypic correlation (r = 0.19) with Haught Unit in layers, meaning that egg weight is a poor predictor to estimate Haught Unit. E145 and E146 were validated to predict albumen ratio with good accuracy, even when both equations have a low determination coefficient (0.250 and 0.356, respectively). Once again, results evidence that using the determination coefficient as the only index of regression models may generate mistakes (Martínez, 2005). Prediction equations for yolk index and yolk diameter were not accurate enough to be validated.

Most of the validated equations include, as predictors, egg characteristics that are easy to measure (egg weight, egg length and egg width). These prediction equations are very useful, because it is not necessary to break the egg in order to estimate its characteristics. In addition, using the determination coefficient as an indicator of the relationship between the response and predictor variables is unreliable if it is used as the only indicator in regression equations. The equations validated in the present study may be used by egg producers, poultry researchers and animal nutritionists to investigate egg characteristics of different laying species because they can help to reduce the costs of egg quality characteristics determination.

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