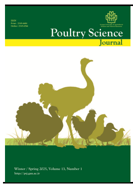

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Long-Term Egg Production Curve Fitting Using Nonlinear Models For Superior Local Chicken of Indonesia

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Abstract

The objective of this study was to analyze the unique tendencies reported along the egg-production curve for the Kampung Unggul Badan Litbang Pertanian (KUB) chicken. This research was superior to others due to its comprehensive analysis of multiple nonlinear models specifically tailored to the unique egg production patterns of the indigenous KUB chicken, providing highly accurate and practical predictive capabilities for local poultry farming. Egg production was monitored in 797 KUB chickens from 17 breeding flocks. The study evaluated Logistic, Compartmental, Gamma, and Yang to represent the egg production curve. The Yang function, which is suggested as the best-fitting model, accurately reflected the characteristics of the observed data on egg production for KUB chickens. The Yang function had the highest correlation coefficient, medium pseudo R^2, lowest MSE, AIC, and BIC. The rankings for the Logistic, Compartmental, and Gamma functions were second, third, and fourth, in that order. In order to predict future results in the weekly egg production of KUB chickens, it is advised that the Yang be used to monitor the beginning rate of production to peak, the peak time of production, and the gradual fall after the peak using prior experiences.

Introduction

Livestock production in general and domestic poultry production in particular plays a vital socio-economic role for people living in low-income countries of Africa and Asia (Mohammadifar *et al.*, 2014; Moazeni *et al.*, 2016a). Domestic poultry is widely distributed avian species around the world due to their short generation interval and adaptability in a wide range of agro-ecologies (Mohammadifar and Mohammadabadi, 2018; Moazeni *et al.*, 2016b; Khabiri *et al.*, 2022). The domestic poultry provides high-quality protein and income for poor rural households and is the most widely kept livestock species in the world (Mohammadabadi *et al.*, 2010; Mohammadifar and Mohammadabadi, 2018). This is due to the presence of the valuable traits of poultry like disease resistance, adaptation to harsh environments and ability to utilize poor-quality feeds (Shahdadnejad *et al.*, 2016; Khabiri *et al.*, 2023).

Egg production in the poultry industry has extensive effects on the economy, nutrition, agriculture, environment, and society as a whole. To ensure a sustainable and secure food supply, it is necessary to strike a balance between the benefits and challenges of egg production. In addition, mathematical modeling could be used to approach productivity and economic-level decisions (Ahmad, 2011). Furthermore, mathematical models have the potential to aid in the anticipation of egg production during yearly cycles and facilitate the identification of high-quality breeding avian specimens (Ariza *et al.*, 2022). For poultry breeding, estimates of egg production are essential, as are production schedules based on those estimates. The design of the feeding and nutrition applications that will vary over time, as well as the forward-looking management plans of poultry farmers, depend heavily on the precise modeling of the production pattern and the selection of the most reliable prediction methodologies.

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Nonlinear models such as the logistic function, compartmental function, gamma function, McNally, and Adams-Bell models were fitted for predicting the percentage of egg production (Savegnago *et al*., 2012; Narinc *et al*., 2013; Emamgholi Begli *et al*., 2021). In addition, all the models are suitable, yet the Adams-Bell model suited the percentage of hen-day egg production in Japanese quail somewhat better than the others (Narinc *et al*., 2013). Kampung Unggul Badan Litbang Pertanian (KUB) chicken is an improved native chicken of the Indonesia Agency for Agriculture Research and Development and has great potency in egg production (Bakrie *et al*., 2021). Therefore, the utilization of mathematical modeling can facilitate the identification and selection of chicken populations exhibiting optimal egg production rates across various time intervals. Moreover, strategies in poultry breeding programs aim to increase egg volumes, feed efficiency, growth rate, and body weight (BW); decrease abdominal fat; have low production costs and better regulate the biochemical and physiological parameters (Mohammadabadi *et al*., 2010; Mohammadifar and Mohammadabadi, 2017). The primary problem this study aims to solve is the need for accurate and reliable models to predict egg production in KUB chickens, which will help optimize breeding, management, and feeding strategies to enhance productivity and meet diverse consumer demands in low-income countries. This research was being conducted for the first time. The superiority to others is due to its comprehensive analysis of multiple nonlinear models specifically tailored to the unique egg production patterns of the indigenous KUB chicken, providing highly accurate and practical predictive capabilities.

Materials and Methods

Chickens

The study was conducted in a poultry breeding house in the Agriculture Instrument Standardization Agency of Central Java, Ministry of Agriculture, Republic of Indonesia. The KUB chickens had been placed in growing cages from day-old chicks until 12 weeks of age. The sexing was done at 12 weeks of age, and then KUB chickens were placed in breeding flocks. The number of chickens in each flock was 60, with a sex ratio of 1:5. A total of 797 KUB hens from 17 breeding flocks were observed for egg production. A diet was given that contained 3,000 kcal of ME/kg and 20% CP for 1 to 12 weeks of age, 2,750 kcal of ME/kg and 15% CP for 12 to 18 weeks of age, and 2,800 kcal of ME/kg and 16.5% CP for 18 to 76 weeks of age. The eggs were recorded every morning between 7:00 a.m. and 10:00 a.m. over the 56-week egg production period (from 21 to 76 weeks of age). Egg production was measured cumulatively and proportionately in accordance with the hen-housed notion and the hen-day concept.

Nonlinear Model

The study investigated four nonlinear models, namely Yang, Compartmental, Gamma, and Logistic, to ascertain which function would best depict the egg production curve of KUB chickens.

The logistic function is introduced by Nelder's (1961) generalized version of the logistic curve. The detail functions were as follows:

$$Y_t = a\left[1 + e^{(-ct)}\right]^{-d} e^{-bt} \quad (1)$$

In the logistic model, Y_t is taken into account as egg production at time t. a and b are parameters relating to the peak and declining slope of production, respectively, while c is the constant coefficient. d is a parameter connected to the incremental slope of production, while e is the base of natural logarithms.

Compartmental is a function introduced by McMillan *et al*. (1970). The detail function is as Equation 1:

$$Y_t = a\left[1 - e^{-c(t-d)}\right] e^{-bt} \quad (2)$$

where Y_t is egg production rate at t weeks of laying period; a is the asymptotic value of egg production at the peak of egg-laying; b is the rate of production decrease after the peak (egg production decrease per week); c is the weekly rate of increase in egg production; and d is the average of the initial week of egg-laying.

Gamma or the McNally function, is a function for egg production in poultry introduced by McNally (1971). The detail function is as Equation 2:

$$Y_t = at^b e^{(-ct+dt^{0.5})} \quad (3)$$

where Y_t is taken into account as egg production at time t weeks of laying, e is the natural logarithm; a, b, and c are the asymptotic value of egg production of the peak of laying, increasing phase slope, and decreasing phase slope of the production curve, respectively and d constants.

Yang Function is introduced by Yang *et al*. (1989). The detail function is expressed as equation 4:

$$Y_t = \frac{ae^{-bt}}{1 + e^{-c(t-d)}} \quad (4)$$

where Y_t is taken into account as egg production at time t; a is the asymptotic value of egg production at the peak of egg-laying; b is the mean week of egg production at sexual maturity; c is the reciprocal indicator of the variation in the week of production of the first egg; and d is the rate of production decrease after the peak (eggs/hen-day decrease per week).

The Goodness of Fit Criteria

The best function and model to describe the egg production curve of KUB chickens were chosen using the goodness of fit criteria listed below. Mean squared error (MSE) is a performance metric applied to assess model quality and choose the top model from a pool of candidate models. In order to get the

MSE for each function, the following equation divides the error sum of squares by the degree of freedom:

$$MSE = \frac{SSE}{n-p} \quad (5)$$

where n is the number of observations, p is the number of model parameters, and SSE is the error sum of the square.

The Akaike Information Criterion (AIC) was employed to evaluate how well the errors were compensated. This statistic's lower value suggests that the model is quite well-fitted (Narinc *et al*., 2014). Equation 6 defines these criteria.

$$AIC = n\ ln\left(\frac{SSE}{n}\right) + 2p \quad (6)$$

Where ln indicates the natural logarithm, n, p, and SSE are as described before.

Bayesian Information Criterion (BIC) is a valuable criterion for selecting the optimal model among a range of models. BIC may be able to stop overfitting that arises from adding more model parameters by adding a penalty term for the extra number of parameters. According to Lewis *et al*. (2010) and Wit *et al*. (2012), the best model is the one with the lowest BIC. BIC may be computed using the following equation.

$$BIC = n\ ln\left(\frac{SSE}{n}\right) + p\ ln\,(n) \quad (7)$$

where the SSE, n, ln, and p are as described before. Pseudo-R^2 is similar to the coefficient of determination used to evaluate the reliability of a model in linear regression analysis (Naric *et al*., 2013). Equation 8 defines this coefficient.

$$Pseudo - R^2 = 1 - \left(\frac{SSE}{SST}\right) \quad (8)$$

where SSTc is the corrected total sum of squared and SSE is as described before.

The correlation coefficient (r) between observed and predicted egg production is used for assessing the predicting ability of the models; the best model is the one with the highest **r** (Felipe *et al*., 2015). The r was calculated by using the Pearson correlation formula.

Estimated egg production parameters, predicted egg production, and fitted criteria were performed by SAS On Demand for Academic (SAS Institute Inc., 2021). The egg production parameters and prediction of each function were estimated using the NLIN Procedure. Then, the correlation coefficient was calculated using the CORR procedure.

Results and Discussion

The monthly egg production data of 17 flocks of KUB chickens are displayed in Table 1. The KUB hens began egg production at an average age of 21 weeks, with an initial mean production rate of 22.36%. This rate gradually increased, reaching an average of over 50% during the laying period of 9-20 weeks. The peak egg production period was noted in the 29–32 weeks of the laying period. From 33 to 56 weeks, a decrease in egg production of about 7% was observed. The mortality of hens was 12.17% at the age of first egg during the laying period, which is tracked for 21 weeks. Four nonlinear models predicted diverse production of eggs from the first week to the 56th week of laying. The logistic model predicting the egg production of KUB chickens in the first week laying period was 8.63%, and in the end was 45.84%. The peak of egg production predicted by Logistic model was 53.72% in the 18 weeks of the laying period.

Table 1. Descriptive statistics of monthly egg productions

Week	N	Mean (%)	SD	Minimum (%)	Maximum (%)
1-4	797	22.36	11.89	8.05	43.35
5-8	789	45.39	7.95	36.41	61.58
9-12	785	50.94	4.21	42.37	58.37
13-16	781	51.02	5.19	40.17	55.71
17-20	778	50.32	5.14	42.92	58.72
21-24	776	46.28	2.73	41.82	49.89
25-28	769	48.96	6.13	40.35	59.41
29-32	766	52.55	6.18	45.88	63.76
33-36	762	48.67	3.91	45.17	57.24
37-40	746	48.09	4.17	42.24	56.43
41-44	727	46.42	5.94	39.29	53.57
44-48	708	48.23	4.49	41.26	56.80
49-52	701	45.72	3.81	39.49	52.82
53-56	700	45.48	2.76	41.68	49.46

N = Number of chickens; SD = standard deviation.

The anomaly has predicted that egg production will increase and decrease unexpectedly in the 18 weeks and 42 weeks of laying periods, respectively (Figure 1). The number of predicted egg production both at the beginning and the end of the laying period by Compartmental model was 5.96%, and 45.55%, respectively. The peak of egg production (50.87%) was predicted in the 15 weeks of laying period (Figure 2). Figure. 3 presents the egg production curve estimated using the Gamma function. Gamma predicts higher egg production at the onset (20.20%) and lower at the end (42.38%). This model also estimated the highest production at the peak (51.91%) in the 24 weeks of laying. The predicted egg production estimated by the Yang model is presented in *Figure 4*. The predicted egg productions at the onset of production and the end of the laying period were 10.20% and 45.93%, respectively. The peak of egg production (50.79%) predicted in the 12 weeks of the laying period was earlier than the other models.

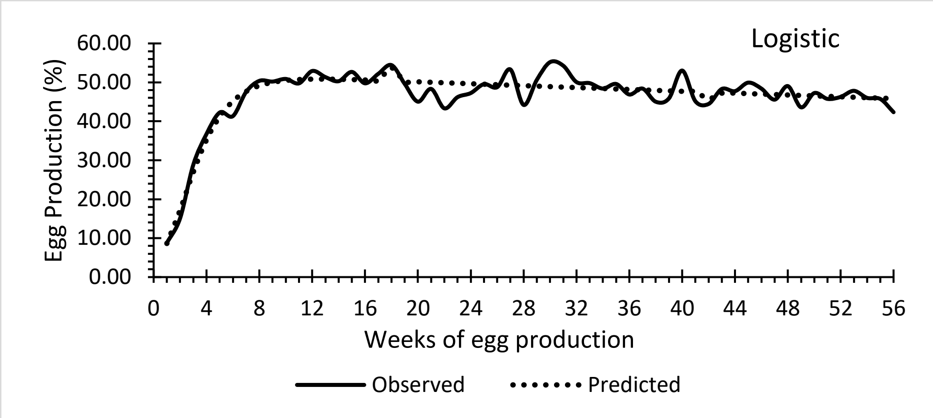

Figure 1. Prediction of egg production for KUB hens by Logistic model compared with observed data

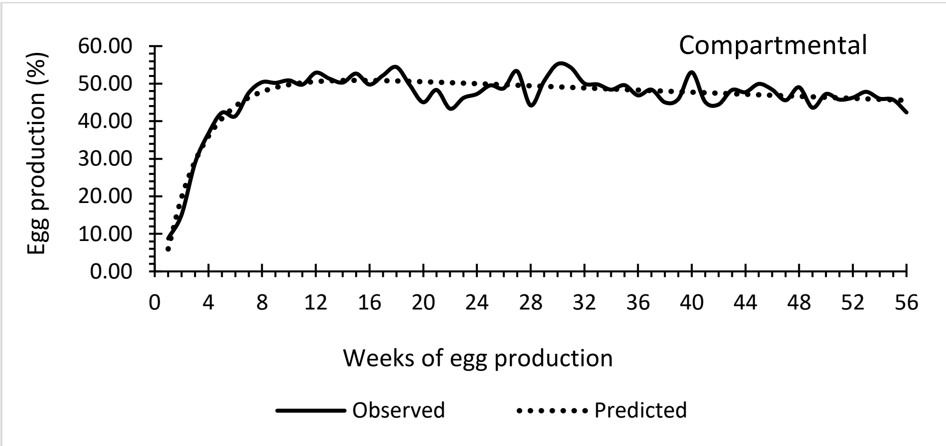

Figure 2. Prediction of egg production for KUB hens by Compartmental model compared with observed data

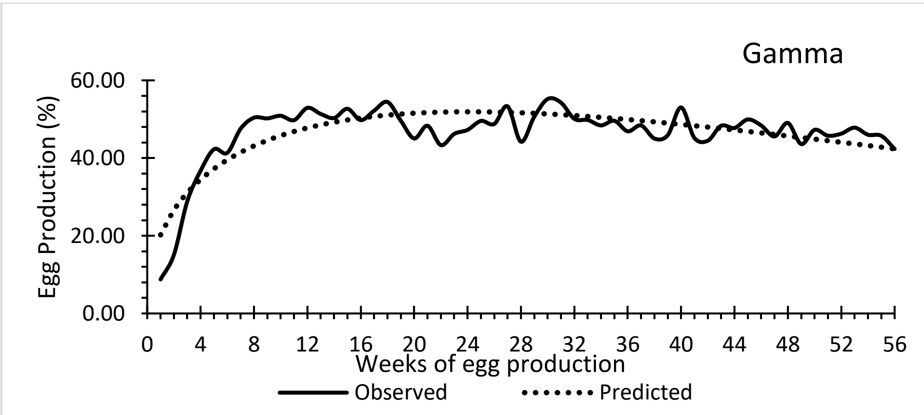

Figure 3. Prediction of egg production for KUB hens by Gamma model compared with observed data

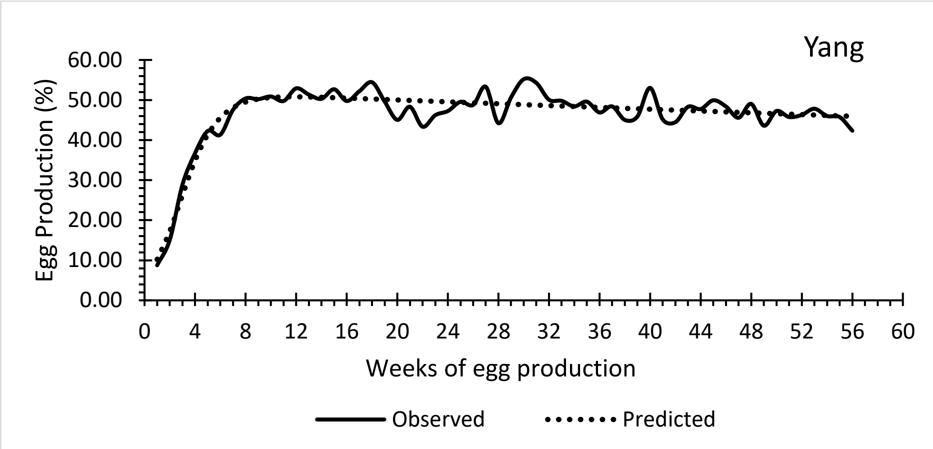

Figure 4. Prediction of egg production for KUB hens by Yang model compared with observed data

Description of Observed Egg Production

The performance of hens in this study was greater than the first study reported egg production of KUB chickens (Iskandar and Sartika, 2014). The chickens used in their study were the first generation of KUB. The first egg was reached at 23.4 weeks of age. The average egg production in the first week was 10.12%. The peak production at 51.8% was achieved between 28-30 weeks of the laying period. The mortality of hens monitored during the laying period was 14.11%. Recently, the breeding center of KUB chickens released a new strain, namely KUB2, with higher egg production. The average egg production of KUB2 was 61.1%, and the peak of production reached 90.6% (Sartika and Iskandar, 2019). The main goal of the breeding program for KUB chicken is to build and expand the chicken to increase egg production and to create associations of farmers. The prediction of egg production will be useful for the farmers to manage the feed, environment and market as long as the laying period. The results may, therefore, guarantee that efficient systems and management approaches are customized to satisfy the requirements of every variation while satisfying the widest range of customer requests.

The goodness of fit criterion

Table 2 presents the expected egg production characteristics for KUB hens as predicted by four models: Compartmental, Logistic, Yang, and Gamma. Each model identified the highest values for parameters a, b, c, and d, respectively. The analysis of egg production for KUB hens using the Logistic model revealed excellent parameter estimates. The estimated parameter that reflects the peak production, a, was 52.76. This result was lower than the average observed egg production for KUB hens from 17 flocks. A similar result has been reported by Savegnago *et al*. (2011). They reported that peak production for White Leghorn hens estimated by the Logistic model was slightly lower than the observed data. The c estimated (0.57) in the recent study was similar to their estimate (0.61). While they reported higher parameters connected to the incremental slope of production than that estimated in the recent study. The estimated parameter for the declining slope of production in KUB hens (b = 4.16) is significantly higher than that reported for commercial breeds 0.061-0136 (Kuhi and France, 2019). The result indicates genetic and environmental differences. These variations suggest that selective breeding and improved management practices can reduce the decline in egg production for KUB hens. Targeting the initial production rate, extending the peak production period, and mitigating the decline slope can enhance overall productivity.

Table 2. Estimated egg production parameters + their standard error for KUB chickens using four nonlinear models

Parameters	Logistic	Compartmental	Gamma	Yang
a	52.76 ± 1.94	53.73 ± 2.29	20.56 ± 2.66	52.48 ± 1.88
b	4.16 ± 1.19	0.63 ± 0.31	0.99 ± 0.37	3.03 ± 0.31
c	0.57 ± 0.11	0.34 ± 0.07	0.52 ± 0.01	0.72 ± 0.15
d	0,002 ± 0.001	0.003 ± 0.001	0.43 ± 0.001	0.002 ± 0.001

The asymptotic value of the peak production for KUB hen, estimated by Compartmental function, was 53.73, slightly lower than the observed data. This model predicted egg production would decrease by 0.3% per week. That rate was lower than the result estimated by the Compartmental model (0.71%)

reported in white Leghorn hens (Savegnago *et al*. 2012). They reported that the average of the first week of egg laying and the weekly rate of increase in egg output were 0.275 and 1.264, respectively. In comparison, the parameters estimated for KUB hens in this study were 0.34 and 0.63, respectively. The parameter a was positively correlated with the weekly rate at which egg production increases and the mean of the first week of egg-laying. In contrast, it was negatively correlated with the rate of production decrease after the peak production (Safari-Aliqiarloo *et al*., 2018).

The analysis of egg production for KUB hen analysis by using the Gamma model showed the lowest estimated asymptotic value, which was 20.56. The value was estimated at the beginning of egg production. As stated by Otwinowska-Mindur *et al*. (2016), peak production for the Gamma model was lower than the real value, even if the peak period was comparable to the value. The characteristic of the Gamma model was a sharp rise in output from the beginning to the peak followed by a sharp decline. The egg production curve's phase slope, which increases and decreases for KUB hens estimated by the function were 0.99 and 0.52, respectively. The estimated parameters were the highest compared with other models. In the previous study, Narinc *et al*. (2014) reported an asymptotic value for laying hen estimated by the Gamma model was 60.93. While they reported a lower rate of increasing and lowering, the egg production curve's phase slopes were 0.99 and 0.52, respectively.

The investigation of egg production for KUB hens using the Yang model revealed excellent estimated parameters due to its superior ability to accurately fit the entire production curve, reflected in lower MSE, AIC, and BIC values and a higher correlation coefficient. At the highest point of egg laying, the expected asymptotic value of egg production, a, was 52.48. The rate of declining production (eggs/hen-day decrease per week) after the peak was 0.002. Faraji-Arough *et al*. (2023), the reported rate of production decrease after the peak for Khazak indigenious hens was 0.014. The Yang model was utilized to estimate the mean week of egg production for KUB chickens at sexual maturity, as well as the reciprocal indicator of variance in the week of the first egg production. The values estimated were 0.72 and 3.03, respectively. To this purpose, the rate of growth and the rate of reduction in egg production may be the most crucial in the modeling of chicken egg production, according to Gavora *et al*. (1971), using a 4-parameter model.

Functions Performance

Table 3 displayed the function's goodness of fit. When the MSE criteria were used to compare the researched functions' goodness of fit, it was found that while all functions fitted almost equally, the Gamma function, which had the highest MSE of 27.53, performed less well than the other functions in explaining the egg production curve in KUB chickens. In particular, the Yang function, which has MSE values of 19.49, is the most appropriate function to describe the egg production curve. Then, with MSE values of 20.18 and 21.68, respectively, the Logistic and Compartmental functions described moderate to the available egg production. In contrast, Savegnago *et al*. (2012) reported that the Compartmental model was the worst for representing the egg production curve of White Leghorn chickens in both selected and non-selected lines in Brazil, while the Logistic model was the best.

Table 3. Goodness of fit statistics of the four models for describing the egg production curve in KUB chickens

Model	MSE	AIC	BIC	r	Pseudo R^2
Logistic	20.18	172.11	180.21	0.865	0.771
Compartmental	21.68	176.14	184.24	0.854	0.784
Gamma	27.53	189.51	197.61	0.807	0.776
Yang	19.49	170.17	178.28	0.867	0.779

MSE = Mean squared error; AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; r = correlation coefficient

Using the AIC fitting criterion to examine differential performance, the functions were arranged in order of accuracy (from lowest to highest AIC values) as follows: Yang, Logistic, Compartmental, and Gamma. The result of the recent study was similar to the study in Broiler breeder hens Otwinowska-Mindur *et al*. (2016) that reported high AIC for Compartmental and Gamma functions. The Gamma function was the most inappropriate function to track the trend in egg production in KUB chickens, with a BIC value of 197.61. In contrast, the Yang function, with a BIC value of 178.28, was the most appropriate function, according to the BIC fitting criterion. The examined functions' BIC values provided the same order as the AIC, indicating fitting appropriateness for characterizing the egg production curve in KUB Hens. Rather than only comparing two nested models at a time, AIC and BIC may be used to assess numerous models continuously, not just nested ones. They can also be used to the common quantity of interest in order to weight the estimates derived from various models. Because AIC and BIC are effectively viewed as separate Bayesian priors, these weighting procedures employ either one of them but not both. A sensitivity analysis might be carried out by contrasting the outcomes from both AIC and BIC, even though there is not yet a formal theoretical basis for explicitly merging both into a single weighing system (Kuha, 2004; Dziak *et al*., 2020).

The model with the highest coefficient correlation was Yang (0.867) followed by Logistic (0.865), Compartmental (0.854), and Gamma (0.807). Capacity is demonstrated by the coefficient correlation, which assesses the linear connection between the observed and expected values. Since the correlation coefficient gauges the degree of coincidence between observed and expected values, this coefficient may be understood as the prediction accuracy (Domínguez-Viveros *et al*., 2020). A comparison among the functions on the basis of Pseudo R^2 values for Logistic, Gamma and Yang were similar, whereas Pseudo R^2 for the Compartmental was slightly higher. The results implying that the Compartmental model has good fit to represent the egg production curve of KUB hens. The result was in contrast to the estimate in fitting the egg production cruve for Japanese quail (Narinc *et al*., 2013). They reported that the Compartmental has the lowest Pseudo R^2.

The criteria showed that the current dataset of egg production for KUB chickens is well-fitted to three of the four functions. The gamma function that fits the egg production curve of KUB chickens the least is the one with the highest MSE, AIC, and BIC and the lowest correlation value (0.807). It is distinguishable that the Gamma function could not be consistent with the observed and even other anticipated egg production curves in light of the simultaneous visualization of all the egg production curves in Fig. 3. Underfitting of the starting and end egg production, overfitting of the peak production, and unfitting of the rates of reduction and increase in egg production can all lead to this lack of congruency. All of this evidence serves to undermine the quality of fit and accuracy (Shibak *et al*., 2023).

Table 4. The rank of fitted models in describing the KUB chicken egg production curve

Model	MSE	AIC	BIC	Pearson Correlation	Pseudo R^2	Final rank
Logistic	2	2	2	2	4	2
Compartmental	3	3	3	3	1	3
Gamma	4	4	4	4	3	4
Yang	1	1	1	1	2	1

MSE = Mean squared error; AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; r =Correlation coefficient

The final ranks of the fitted models according to various model selection criteria are displayed in Table 4. The Yang function, which is suggested as the best-fitting model, accurately reflected the characteristics of the observed data on egg production for KUB chickens. Additionally, the Compartmental and Logistic models were determined to be the second and third best-fitted, respectively. The Gamma function, on the other hand, was found to be the least well-fitting function as it was unable to befit and showed a significant departure from the observed egg production curve. The results of the current investigation agreed with the Gamma functions' established performance in the examination of chicken egg production. According to earlier research, Gamma models were too rigid to adequately represent rates of egg production near the curve's peak (Oni *et al*., 2007; Savegnago *et al*., 2012; Mahmoud *et al*., 2021). An acceptable mathematical function must accurately explain all phases of egg production from the beginning to the finish, as the Yang function did in the present study. Additionally, the findings of a genome-wide association study on the characteristics of egg production show that during the whole laying period, there are genetic variations in the composition and heritability of the different stages of egg production (Liu *et al*., 2019). Selection techniques based on egg production curve characteristics performed more consistently and satisfactorily. The findings of this study can be utilized to develop a selection strategy for KUB chickens based on particular curve characteristics.

Conclusion

In conclusion, using historical performance to predict future outcomes in weekly egg production of KUB chickens, the Yang may be suggested as a suitable function for tracking the beginning rate of production to peak, the peak time of production, and the slow fall after the peak.

Conflict of Interest

The authors declare that they have no conflict of interest

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