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Mathematical Modeling of Egg Production Curve in Khazak Indigenous Hens

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Abstract

The number of eggs produced in a given period (egg production rate) is an important trait in layers that change over time and can be presented as a curve. This study aimed to fit the weekly egg production data of Khazak indigenous hens using non-linear regression models and to select an appropriate model for describing the egg production curve for this bird. Biweekly egg production of 144 laying hens over 52 weeks of egg production was used to evaluate the egg production curve. Seven non-linear models (Gamma, McNally, Compartmental II, Nelder, Yang, Lokhorst, and Narushin-Takma) were fitted to egg production data. The four goodness fit criteria (Akaike’ s information criterion, Mean square error, Log Likelihood, and Bayesian information criterion) were used to compare the models. The results of the goodness of fit criteria showed that the Narushin-Takma and Yang models were the best and worst models, respectively, for describing the egg production curve of Khazak hens. The time and egg production at the peak with the Narushin-Takma model was similar to the actual values, and this model was significantly better than other studied models. The correlation between actual and predicted egg production indicated that the Narushin-Takma model could accurately predict the egg production of this breed. As a result, the Narushin-Takma model can be used to predict the egg production curve of Khazak hens in breeding programs and nutritional management.

Introduction

The rural economy could improve by rearing indigenous poultry, which is usual in many developing and underdeveloped countries (Vali, 2008). Resistance to suboptimal environmental conditions and diseases is the main characteristic and reason to breed indigenous birds.. In addition, raising indigenous hens plays a role in creating job opportunities, extra income for civilians, and reducing migration from rural areas (Deljoisaraian *et al*., 2011; Gheisari *et al*., 2016). Meeting the demands of rural families for poultry production in developing countries is achieved through the breeding of high-potential birds, especially indigenous chickens. However, the low productivity of indigenous poultry has reduced their contribution to rural development in some countries. Some factors, including inadequate health care, unsuitable nests, and insufficient knowledge of people in rural areas, have limited the achievement of optimal performance in chickens raised in rural areas. Moreover, no genetic improvement has been performed for the production traits of these birds (Khalafalla *et al.*, 2001; Gheisari *et al*., 2016).

The egg production rate in layers indicates the number of eggs produced during a given period and is an important trait in laying hens. Other characteristics of produced eggs, including their weight, the impeccability of the shell, and egg quality have a significant impact on the market and economic value (Safari-Aliqiarloo *et al*., 2018). The best definition of egg production rate, as a selective trait, is one of the main concerns for poultry producers. However, the changes in the egg production rate can be shown as a production curve, because it changes over time (Grossman and Koops, 2001; Gerber, 2006).

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Evaluation of the egg production process using mathematical models and estimation of egg production curves in laying hens are necessary to make economic decisions and evaluate productivity (Savegnago *et al.*, 2011; Mehri, 2013). Modeling the egg production process using non-linear regression models can be effective in the determination of the nutrition and breeding effects on egg production and it also investigates the egg production curve over time (Akilli and Gorgulu, 2020). Predictions of egg production in a specific period (annual or any other chosen period) and early selection of the breeder hens were facilitated using modeling egg production (Bindya *et al*., 2010). Non-linear regression models are used to show time-dependent changes in egg production. Some of these models include Wood, McNally, Adams-Bell, McMillan, Compartmental, Nelder, Lokhorst, and Narushin-Takma have three to seven estimated parameters (Grossman *et al*., 2000; Akilli and Gorgulu, 2020; Narinc *et al*., 2014). In literature, the models that are used to fit egg production have curve parameters with biological interpretation, which mainly summarize egg production curves with three or four parameters (Savegnago *et al*., 2012). The gamma model is often applied for modeling laying curves because its interpretation is straightforward, and usually best fitted to the data (Otwinowska-Mindur *et al*., 2016).

The laying pattern in the two selected and non-selected lines of White Leghorn hens was investigated using non-linear models, and it was reported that the McNally model had the best fit in comparison with other models in two lines (Savegnago *et al*., 2012). The Compartmental model was reported as an alternative model for predicting the egg production of broiler breeders (Safari-Aliqiarloo *et al*., 2018). Using mathematical models to describe egg production patterns in flocks of layer hens was reported in other studies (Savegnago *et al*., 2011; Narinc *et al*., 2014). In a study of the egg production pattern of Fayoumi layers, the modified compartmental model showed correspondence with actual egg production and was introduced as the best model for describing the egg production patterns of these layers (Mahmoud *et al*., 2021). The egg production of Spanish endangered Utrerana hen varieties (black, Franciscan, white, and partridge) were evaluated by mathematical models, and the Naroshin-Takma model was reported as the best model for white, Franciscan and black varieties, while the quadratic logarithmic model was the best model for partridge variety (Gonzalez Ariza *et al*., 2022). The Khazak breed is a small size native breed with short legs in the Sistan (Sistan region, IRAN) which is reared for egg production (Faraji-Arough *et al*., 2019). This breed has been adapted to the harsh environment, and low nutritional conditions, and are resistant to some local diseases. To our knowledge, there is no study regarding the modeling of the egg production curve of Iranian native hens. Therefore, this study aimed to evaluate non-linear regression models to describe egg production patterns in Khazak native hens and to select the best model for this breed.

Material and Methods

Bird management and data set

This research was performed at the Research Center of Special Domestic Animals (RCSD), University of Zabol, Zabol, Iran. The experimental procedures and animal handling of the present research were approved by the general ethical guidelines of the Animal Care and Use Committee of the RCSD and the Iranian Council of Animal Care (1995). The pullets were obtained from RCSD flocks and identified by leg-banded numbers. All pullets were raised as one rooster and six hens in a floor cage (3×3 m), and had access to food and water *ad-libitum*. A laying diet containing 2,800 kcal of ME/kg and 16% CP was used. A lighting program was 16L : 8D during the laying period. The produced eggs were individually recorded with the onset of sexual puberty over a 52 weeks egg- laying period using trap nests. The biweekly number of produced eggs was calculated by using the number of daily eggs produced. The biweekly egg production records from 144 Khazak hens were used to evaluate the egg production curve by mathematical models.

Mathematical models

To fit the egg production curve of the Khazak indigenous hens, the biweekly egg production rate for each hen was used. In the present research, the models that were frequently used in literature to evaluate the egg production curves in layer hens were considered. The non-linear models fitted to describe the egg production curve were as follows:

1. Gamma (Wood, 1967)

$$y_t = at^b e^{(-ct)},$$

where, y_t =egg production rate at t weeks of laying; and a, b, and c are the initial production; the rate of increase to the peak, and the rate of decrease after the peak, respectively.

2. McNally (McNally, 1971)

$$y_t = at^b e^{[-ct+dt^{(0.5)}]},$$

where, y_t, a, b, and c are similar to the Gamma model and d is proportional to the square root of time.

3. Compartmental II (McMillan, 1981)

$$y_t = a[1 - e^{-c(t-d)}]e^{-ct},$$

where, y_t =egg production rate at t weeks of laying and a, b, c, and d are the maximum potential of egg production, the rate of increase to the peak, the rate of decrease after the peak, and the mean an initial week of egg-laying, respectively.

4. Yang model (Yang *et al*., 1989)

$$y_t = \frac{ae^{-ct}}{1+e^{-b(t-d)}},$$

where, y_t represents the egg production rate at t weeks of laying and a, b, c, and d are the asymptotic value of egg production at the peak of egg-laying, a reciprocal indicator of the variation in the week of production of the first egg, the rate of decrease after the peak and mean a week of egg production at sexual maturity, respectively.

5. Logistic (Nelder, 1961)

$$y_t = a[1 + e^{(-bt)}]^{-d}e^{-ct},$$

where, y_t represents egg production rate at t weeks of laying; a is the asymptotic value of egg production at the peak of egg-laying, b is constant, d is the mean egg production week in which egg production reaches its peak, and c is the rate of decrease after the peak, respectively.

6. Narushin- Takma (Narushin and Takma, 2003)

$$y_t = \frac{at^3+bt^2+ct+d}{t^2+ft+g},$$

where, y_t =egg production rate at t weeks of laying; a, b, c, d, f, and g are parameters not biologically interpretable.

7. Lokhorst (Lokhorst, 1996)

$$y_t = \frac{100}{1+ab^t} - (c + dt + ft^2),$$

where, y_t =egg production rate at t weeks of laying; a and c = correction factor for start of the laying period; b= time between the start of the laying period and peak; d= the rate of decrease after the peak; f= the slope of final decrease.

Comparison of fitted models

The fitted non-linear models were evaluated by the goodness of fit criteria, including Akaike's information criterion (AIC), mean square error (MSE), Bayesian information criterion (BIC), and logarithm Likelihood (logLik).

The Akaike's Information Criterion (AIC): This criterion was used to correct the error of fitted models based on their number of parameters. In other words, this statistic is used to compare models with a different number of parameters (Leonard and Hsh, 2001). A lower value of this criteria indicates that the model is the best, and is calculated as follows (Akaike, 1974):

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

Where n= number of observations; SSE= sum of the squared error; p= number of parameters in the model.

Bayesian information criterion (BIC): The model with the lowest BIC is considered the best model, and calculated as follows (Wit *et al*., 2012):

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

Where n= number of observations; SSE= sum of the squared error; p= number of parameters in the model.

Mean square error (MSE): This criterion includes the variability of factors not considered by the investigator, and the lowest value for this criterion indicates that the model is the best (Gonzalez Ariza *et al*., 2022):

$$MSE = \frac{SSE}{n-p},$$

Where n= number of observations; SSE= sum of the squared error; p= number of parameters in the model.

All models were fitted to the weekly egg production rate of hens by the *nlme* package, and port algorithm of the R software (Pinheiro *et al*., 2014). F-test was conducted to determine which model is statistically better. F ratio was calculated as:

$$F = \frac{(SS_1 - SS_2)/df_1 - df_2}{SS_2/df_2}$$

Where SS and df are the sum of squares and degrees of freedom, respectively. The subscripts 1 and 2 refer to the models (van der Klein *et al*., 2020). Also, the graphical evaluation of actual and fitted data was performed to evaluate the model's flexibility. Furthermore, the correlation between the actual and predicted value of weekly egg production was calculated to determine the accuracy of the models and the significance of the correlation coefficient was performed by t-test.

Results

Descriptive statistics of egg production data for the studied population are shown in Table 1. The mean of egg production for Khazak hens over 52 weeks was 4.754 eggs for every biweekly internal. The mean maturity age was 195.6 days (27.9 weeks), and the mean egg production at the beginning of laying was 5.479 eggs for the first two weeks of laying. The peak production of this breed was in the third and fourth week of laying, with a mean of 6.157 eggs. Also, the mean egg production at the end of the laying period (51-52 weeks) was estimated at 4.667 eggs. This result shows that fitting linear regression models were not appropriate to describe an egg production curve of this breed, because production arrived at its peak in a short time and then decreased slowly.

Table 1. Descriptive statistics of egg production data for Khazak hens

Number of hens	Mean	Maturity age (d)	Average production in			Time of production in (wk)		
			Start	Peak	end	Start	Peak	end
144	4.754	195.6	5.479	6.157	4.667	1-2	3-4	51-52
Standard deviation	2.694	28.9	2.766	2.877	2.568	-	-	-
Minimum	1	137.2	1	1	1	-	-	-
Maximum	13	345.0	12	13	10	-	-	-

In the present study, seven non-linear models were fitted to describe an egg production curve of Khazak hens. Table 2 shows the goodness of fit criteria for the fitted models. The highest value for log-likelihood and lowest value for BIC, AIC, and MSE indicates that the model had the best fitting. Based on the AIC criterion, the Narushin- Takma was superior compared to other models. Moreover, the Yang model had the highest AIC value than other models, and other models, including McNally, Nelder, Lokhorst, Gamma, and Compartmental II were in the second to sixth ranks, respectively. The rank of models based on MSE, and log-likelihood criteria were similar to AIC criteria, so the Narushin-Takma and Yang models were the best and worst models, respectively, for describing egg production. Although, the Yang model had the highest BIC value, and was the worst model to describe an egg production curve. However, the Gamma model was the best model to describe an egg production curve. Overall, based on the four goodness of fit criteria, the Naroshin Takma model can be used as a suitable model for fitting the egg production curve in Khazak hens. The difference between the goodness of fit criteria values was small, which indicates models had the same quality for curve fitting.

Table 2. The goodness of fit criteria for fitted models

Model	MSE	LogLik	AIC	BIC
Gamma	7.031	-6534.41	13076.81	13100.46
McNally	7.015	-6530.74	13071.47	13101.03
Yang	7.057	-6539.01	13088.02	13117.58
Nelder	7.021	-6532.03	13074.07	13103.63
Lokhorst	7.023	-6531.85	13075.71	13111.18
Compartmental II	7.055	-6539.01	13086.02	13109.67
Narushin – Takma	6.997	-6526.30	13066.6	13107.99

MSE: Mean square error, LogLik: Log Likelihood, AIC: Akaike information criterion, BIC: Bayesian information criterion

The result of the Fisher test for the comparison of differences between fitted models is presented in Table 3. The Narushin Takma model (the best model) was significantly different from other models (P<0.05). Although, the difference between McNally and Lekhorst's model was not significant, however, their differences with other models were significant (P<0.001). A significant difference was not observed between the Nelder model with Lokhorst, and the Gamma model with Lokhosrt and Yang models, but the difference between other models was significant ($P < 0.05$).

Table 3. The Fisher test results (P-value) for comparison of differences between fitted models

	Narushin-Takma	McNally	Nelder	Gamma	Lekhorst	Compartmental II	Yang
McNally	0.012						
Nelder	0.003	<0.001					
Gamma	0.001	0.007	0.029				
Lekhorst	<0.001	1	0.550	0.078			
Compartmental II	<0.001	<0.001	<0.001	<0.001	<0.001		
Yang	<0.001	<0.001	<0.001	1	<0.001	1	

Table 4 shows the estimated model parameters for fitted models. The time of peak for Narushin-Takma and McNally was similar to the actual value (third and fourth weeks), but it was different from the actual time for other models. The number of egg production at the peak for the dataset of the present study was 6.16 eggs, which is close to the peak production value for Narushin Takma. Although, the time of peak for the McNally model was similar to the actual value, however, the peak production for this model was lower than the actual value in comparison with Gamma and Lekhorst models.

Actual and predicted values of egg production in various weeks by different models are shown in Fig 1. The amount of egg production predicted by the Gamma, Mc Nally (Fig 1a) Nelder, Yang (Fig 1b), Compartmental II, and Lokhorst (Fig 1c) models was different from actual values in many weeks. However, the predicted values of egg production by the Narushin Takma model (Fig 1d) were closer to the actual value in many weeks (especially in the early weeks of production). The graphical results show that the Narushin Takma model predicted the egg production of Khazak hens more correctly than the other studied models.

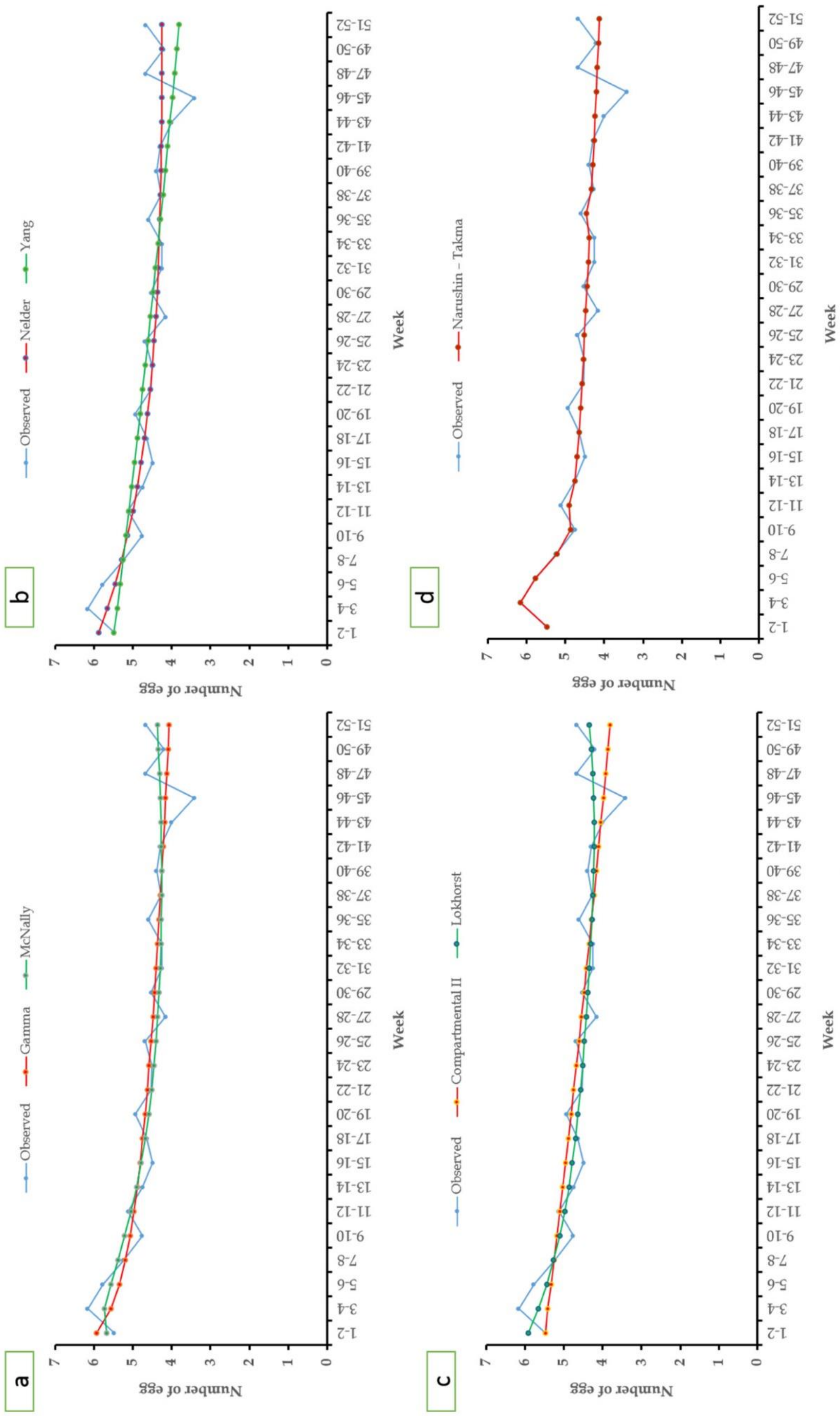

Figure 1. Observed and predicted values of egg production by different models in various weeks

Table 4. Curve parameter estimates and their standard errors for the fitted models

Parameter	Gamma	McNally	Yang	Nelder	Lokhorst	Compartmental II	Narushin-Takma
a	5.962±0.173	12.239±3.233	10.113±2.517	3.933±0.954	0.857±0.218	5.568±0.120	-0.028±0.016
b	-0.089±0.029	0.408±0.186	0.014±0.010	0.143±0.042	0.924±0.033	0.015±0.002	4.950±0.460
c	0.004±0.0003	-0.075±0.028	-3.13e-6±8.5e-7	-0.002±0.001	47.638±6.588	6.686±3.533	-20.616±9.588
d	-	-0.842±310	29.710±3.132	-0.641±0.083	2.283±1.072	-	30.730±15.499
f	-	-	-	-	-0.031±0.024	-	-4.273±1.463
g	-	-	-	-	-	-	6.020±2.629
*P_p	5.92	5.72	5.48	5.88	5.92	5.48	6.16
T_p	1-2	3-4	1-2	1-2	1-2	1-2	3-4

* P_p= number of egg production at peak; T_p= Time of peak (week).

The correlation between actual and predicted egg production in studied models is shown in Table 5. The range of the correlation value of all models was 0.768 to 0.883, and all correlations were significant (*P* < 0.01). The highest correlation was related to Narushin-Takma model and followed by the McNally model, which indicates that these models had a good prediction of the present study data. The Compartmental II and Yang model with a correlation of 0.768 with a higher standard error than other models show that the predicted egg production of these models has low accuracy.

Table 5. Correlation coefficient and standard error between actual and predicted egg production in fitted models

Models	Correlation coefficient	Standard error
Gamma	0.822**	0.086
McNally	0.858**	0.077
Yang	0.768**	0.098
Nelder	0.847**	0.080
Lokhorst	0.853**	0.078
Compartmental II	0.768**	0.098
Narushin – Takma	0.883**	0.070

**Significance level of correlations (*P*-value < 0.001).

Discussion

The productivity of laying hens was generally evaluated using egg production phenotype, which can be effective in maintaining the optimal level of gain by evaluating the efficiency of optimum managerial practices (Aboul-Seoud, 2008). Different methods for expressing egg production and its components have been reported (Dogan *et al*., 2010). The egg production curve is one of the valuable methods to show changes in egg production over time, which is of particular importance in terms of breeding and management (Ahmadu *et al*., 2017). The mean age at sexual maturity for the studied population was 195.6 days, that were higher than reported values for A (158 days) and B (154 days) strains of Shikabrown parents (Ahmadu *et al*., 2017), and New-Kampong crossbreed chickens (20-22 weeks, Adli and Sjofjan, 2022). Factors including genetic variation, body weight at maturity, and strain type (light and heavy) could be reasons for the difference in age at maturity. (Sowunmi *et al*., 1998; Agaviezor *et al*., 2011). The mean of sexual maturity for Castellana Negara hens was reported at 23 weeks of age (Miguel *et al*., 2007), which was lower than the present results. The mean sexual maturity and egg production rate for parent stocks of Korean Native chickens were reported to be 160.7 days, and 75.2 %, respectively (Kim *et al*., 2019), which were higher than our findings.

The mean egg production for Khazak hens has been estimated at 4.754 eggs each biweekly. A lower value for the mean of egg production (4.33 eggs each month) was reported in New-Kampong crossbreed chickens (Adli and Sjofjan, 2022). The egg production percentage of indigenous hens of Isfahan province ranged from 25.9 to 37.5% (Gheisari *et al*., 2016), which was similar to the present results (33.18% for the laying cycle). Ramlah (1996) reported 17% and 48% of the average egg production of Malaysian indigenous hens in the semi-intensive and intensive systems, respectively. Poor quality of diet, disease, and inappropriate husbandry management have been reported for low egg production in native hens (Kingori *et al*., 2010). However, the egg production rate for Egyptian (Osman, 2020), Castellana Negra hens (Miguel *et al*., 2007), and Fayoumi hens (Mahmoud *et al*., 2021) were reported to be higher than the present study.

Based on the four criteria, the Narushin-Takma, followed by McNally models were the best models to describe an egg production curve of Khazak hens (Table 2). The MSE value for the Narushin-Takma model was lower than other models. MSE is affected by the number of parameters. The lower MSE value for the Narushin Takma model is related to the greater number of its parameters compared to other models (Rahimzadeh *et al*., 2017). Because the total sum of squares in non-linear models is not equal to the regression sum of squares, and the residual sum of squares, therefore, adjusted coefficient of determination is inappropriate for evaluating the non-linear models (Spiess and Neumeyer, 2010). In the study of four models, including linear, exponential, algebraic, and Compartmental I for laying hens, no significant differences were observed between these functions (Fairfull and Gowe, 1990). Although, the Compartmental I model has been reported as the best model to describe an egg production curve of laying hens rather than other studied models (Anang and Indrijani, 2000), this model was the worst in the present study. In the evaluation of the egg production curve of the broiler dam line, the Yang model was reported as the best model (Bindya *et al*., 2010).

It has been reported that the McNally model was not flexible enough to fit egg production of selected and non-selected white Leghorn hens (Savegnago *et al.,* 2012), however, this model was the best model after the Narushin-Takma model to describe egg production of Khazak hens. The Compartmental I model was introduced as the best model to describe an egg production curve of Fayouni hens (Mahmoud *et al.,* 2021), which was opposite to our results. Similarly, the Narushin- Takma model showed the most accurate egg production curve of the Utrerana hens' varieties (Gonzalez Ariza *et al*., 2022), and Broiler breeder flocks (Faridi *et al*., 2011). The Nelder and Compartmental II models were reported as the best and worst models to describe the egg production rate of selected and non-selected lines of white Leghorn hens (Savegnago *et al*., 2012).

In a study on broiler breeder hens, the Yang model was reported as the best model for describing the egg production curve (Otwinowska-Mindur *et al.*, 2016), while this model was the worst model than other models for describing the egg production curve of Khazak hens. It has been reported that Gamma and modified compartmental models have been developed for modeling based on flock averages (Narinc *et al*., 2014). The reason for introducing different models to describe the egg production curve in various research can be due to the difference in bird species, the time interval of collected records, and fitting and comparing other models for the desired records.

In the present study, Khazak hens reached a peak egg production at the third and fourth weeks of laying (30-31 weeks of age) for the McNally model and first and second weeks of age (28-29 weeks of age) for the Gamma model, which was lower than 36.5 and 36.25 weeks of age for Gamma and McNally models for Fayoumi hens, respectively (Mahmoud *et al.*, 2021). Moreover, the egg production peak for meat-type broilers was estimated at 40 weeks of age using Gamma wood (Otwinowska-Mindur *et al*., 2016). Also, the peak egg production for Castellana Negra hens was reported at 28 weeks of age by Miguel *et al*. (2007). The models in this study offered parameters with biological interpretations, including peak egg yield, decrease and increase in the rate of egg production, and time of peak. The knowledge of these curve parameters for each breed could help improve egg production efficiency (Savegnago *et al*., 2012; Gonzalez Ariza *et al*., 2022).

Conclusion

The egg production rate of Khazak hens was low. However, this breed showed similar egg production rates in the hottest months of the year. This ability indicates an improved tolerance to high temperatures places. Therefore, this breed could be raised in areas where its climatic variations are excessive across seasons. The present results showed that all the models used to model egg production were at a similar level of accuracy. However, the Narushin-Takma model followed McNally model was identified as the best model to describe the egg production curve of Khazak hens based on goodness of fit criteria. Description of the laying performance of Khazak hens can help in making decisions about nutritional requirements, and is used as an important tool in the breeding program.

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