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EVALUATION OF FOUR NONLINEAR MODELS DESCRIBING EGG PRODUCTION CURVE OF FAYOUMI LAYERS

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ABSTRACT: Egg production data used in this work were obtained from records of Fayoumi chickens flock belongs to El-Takamoly poultry project at Al-Azab, Fayoum Governorate. Egg production records over a 52-wk egg laying period related to 1900 hens. All data was summarized on a weekly basis as eggs per hen per week on hen-day (survivor) basis. Regarding Wood and McNally models, (a) stands for initial egg production, (a) parameter value was very low (0.001) for both models. The increasing rate to the egg production peak (parameter b) was 2.90 for the Wood model and 2.19 for the McNally model. Similarly, parameter c, the decreasing rate of egg production from the peak, was estimated to be 0.08 for the Wood model and 0.06 for the McNally model. Depending on compartmental function m, n, p and q represent scale parameter, measure of persistency of egg production, sexual maturity rate, and age at first egg, respectively and estimated values for these parameters were 86.47, 0.01, 0.23 and 21.61 wks of age, respectively, Concerning the modified compartmental model the parameters A, B, C and D represent a scale parameter, the rate of decrease in laying ability, the reciprocal indicator of the variation in sexual maturity and the mean age of sexual maturity of the hens, respectively. In this work the estimated values of the abovementioned parameters were 75.26, 0.006, 1.14 wks and 24.96 wks of age for A, B, C and D respectively. According to goodness of fit criteria, modified compartmental model was the best model for describing the egg-laying pattern of Fayoumi layers which had the lowest Akaike information criterion and Bayesian information criterion values and the highest coefficient of determination. Moreover, the modified compartmental model showed correspondence with the actual hen day of egg production (age and percentage at peak were 29.44 weeks of age and 64.16%, respectively).

Key words: Egg production curves, Wood, McNally, Compartmental, Modified compartmental, Fayoumi layers.

INTRODUCTION

Egg production is one of the most important parts of the commercial poultry industry. Fayoumi breed which is a native breed that known to have many advantages such as easy adaption to harsh environment, relatively low nutritional requirements, resistance to some diseases, and high fertility and hatchability (Hosny, 2006). Moreover Fayoumi breed particularly plays a very vital role in synthetic breeds development by intercrossing with exotic breeds (Shalaby, 2016). One of the main concerns for poultry breeders in this regard - how to best define egg production rate as a selection trait - is “production curve” which is a term that can represent the changes of egg production rate over time. Mathematical modeling of egg production can help the breeders to predict whole record production from part record; the predictions play important roles in early selection, production planning, and making economical decisions (Yang *et al*., 1989). The curve shape can be described by the following phases: sexual maturity, followed by increasing to maximum production, a peak production, stable decrease of egg production and persistency of production (Fialho and Ledur, 1997, Grossman and Koops, 2001). It is well known that there are some aspects affect egg production including: environmental rearing conditions (i.e., temperature and humidity, Elijah and Adedapo, 2006), body weight (Álvarez and Hocking, 2007 and Selvaggi *et al.,* 2015) ,diseases either bacterial or viral (Spedding, 1988) and nutritional balance (Rozenboim *et al*., 2007). In poultry studies, mathematical models were found to be very useful tools to fit egg production, egg weight, growth rate, and feed intake curves (Faridi *et al*., 2011). The most often used model for the laying curve was Wood function, because it is relatively simple to apply, also compartmental models and their modifications have been used (Narinc *et al*. 2014). Models which have parameters with biological interpretation such as compartmental model and its modification made it possible to the egg production pattern to be summarized in three or four parameters (Savegnago *et al*., 2012). Although there are numerous studies on modeling growth, the studies of modeling egg production are sparse that could be due to the longer time required (Narinc *et al*., 2014). Therefore, the current study aimed to compare the potential of four non-linear models (Wood, MacNally, compartmental and modified compartmental), to study their biologically meaningful parameters which could be used in the selection programs in the future and to detect which model best fits the egg production data of Fayoumi strain.

MATERIAL AND METHODS

Flock management and egg production

Weekly egg production records over a 52-wk egg laying period (from 21 to 72 wk of age) related to 1900 Fayoumi hens - belongs to El-Takamoly Poultry Project at Al-Azab, Fayoum Governorate, Egypt - were used in this study during the period from January to December 2019. Weekly production data expressed as eggs per hen per week on hen-day (survivor) basis. Feed was provided based on body requirements so different standard diets formulated as follows: a starter diet (1 to 6 wk of age) containing a minimum of 20 % crude protein (CP%), 2900 Kcal ME, grower diets divided into two phases (7 to 12 wk of age) containing 16 % CP%, 2800 K cal/ME, (13 until 18 wks of age) a minimum of 14 % CP%, 2700 K cal/ME, respectively. Laying period is divided into two stages: the first stage from 19 wks until 42 wks of age and the pullets were fed laying diet contained 18% CP% and 2800 Kcal/kg of diet and the second stage from 42 weeks of age until season finale where the pullets fed laying diet contained 16% CP% and 2800 Kcal/kg of diet. Hens fed 120g per day according to Egyptian Ministerial Decree No.1498 during these lay periods.

At certain period of egg production, hen-day egg production (HDEP) was calculated according to the following equation: HDEP=

$$\frac{\text{Total number of eggs produced during a week}}{\text{Total number of hens alive in the same week}} \times 100$$

Statistical analyses

Hen day egg production was analyzed by a fixed model (SAS, 2011) to calculate the month of egg production specific means by the following model:

$$Y_{ij} = \mu + M_i + e_{ij}$$

where: Y_{ij} = the observations for a trait; μ is the overall mean; M_i = the fixed effect of i^{th} month of egg production and e_{ij} = the random error term. Means were compared for month of egg production as main effect by Duncan's new multiple range test (Duncan, 1955). A probability of $P<0.05$ was required for significance.

Mathematical models

The weekly hen day rate was used to fit the mean population curve by means of the iterative Gauss-Newton least squares method, as described by Hartley (1961), with a nonlinear regression procedure (NLIN) within the SAS 9.3 software (SAS Institute Inc., 2011). The nonlinear models applied to fit the egg production data and the equations of peak related traits were presented in Tables 1and 2.

Statistical criteria to evaluate the fitted curves

The goodness of fit of each nonlinear mode was evaluated by means of Akaike’s information criterion (AIC), Bayesian information criterion (BIC) and Coefficient of Determination (R^2).

AIC: is calculated as follows: $AIC = n \,.\ln (SSE/n) + 2k$

BIC: is calculated as follows: $BIC = n \,.\ln (SSE/n) + k \,.\, \ln(n)$

Coefficient of determination: is calculated as follows: $R^2 = 1 - (SSE/SST)$

Where, SST the total sum of squares, SSE is the sum of square errors, n is the number of observations and k the number of parameters.

RESULTS AND DISCUSSIONS

Means ± standard errors for observed hen day egg production% of Fayoumi hens are existed in Table 3. Significant differences due to month of egg production effect were found for hen day egg production, the third month of egg production (29-32 wks of age) had the highest hen day egg production. An average hen day egg production ranged from 6.42 to 63.50%. In this study, the averages of hen day egg production are in line with many reports (Miah *et al*., 2002, Zaman *et al*., 2004, Khan *et al*., 2006, Bekele *et al*., 2010, Shafik *et al*., 2013 and Osman, 2020).

Estimated parameters of egg production models and production peak related traits are shown in Table 4. Regarding Wood and McNally models, (a) value stands for the initial egg production. In this study, (a) parameter value was very low (0.001) for both models. The increasing rate of the peak of egg production (parameter b) was over estimated as 2.90 for the Wood model and 2.19 for the McNally model (Table 4).

Similarly, parameter c, which stands for the decreasing rate of the peak, was estimated to be 0.08 for the Wood model and 0.06 for the McNally model. This is due to the fact that the McNally model is a slight modification of the Wood model and the parameters that symbolized with the same letter also have the same biological meaning as shown in Table 4. There was a wide range of Wood function parameters as ranged from 5.59×10^{-8} to 72.79 , from 0.04 to 7.85 and from 0.0006 to 0.19 for a, b and c, respectively (Yang *et al*., 1989, Miyoshi *et al.*, 1996 , Narinc *et al*., 2014 and Otwinowska-Mindur *et al*., 2016). Similar trends were found for McNally model parameters a, b and c as they ranged from 0.55 to 60.93, 0.55 to 2.59 and from -0.089 to 0.02, respectively (Savegnago *et al.*, 2012 and Narinc *et al*. 2014).

In the current study, Fayoumi hens reached peak of egg production at 36.50 and 36.25 weeks of age while presistency of peak lasted for 9.85 and 8.79 weeks for Wood and McNally models, respectively (Table 4). Also, Congleton *et al*. (1981), Yang *et al*. (1989) indicated that the Wood model delayed estimated peak, in addition Otwinowska-Mindur *et al*. (2016) reported that the meat type broiler reached egg production peak at 40 weeks of age using Wood function.

The graphical analysis showed that Wood and McNally models were not flexible enough at the inflection point to fit the egg production rate at the peak accurately as shown in Figure 1. This is may be the reason why the estimates for parameter b of models Wood and McNally exceeded the maximum egg production, which was 1(100%) and parameter a values were very low. Similar trend was found by Congleton *et al.* (1981) who reported that using Wood curve was highly biased during the most of the process, also Savegnago *et al*. (2012) reported that McNally model was not flexible enough to fit egg production data.

Depending on compartmental function each of m, n, p and q represented scale parameter, measure of persistency of egg production, sexual maturity rate, and age at first egg, respectively and the estimated values for these parameters were 86.47, 0.01, 0.23 and 21.61 wks of age, respectively, as shown in Table 4. Using the compartmental function, both Yang *et al*. (1989) and Savegnago *et al*. (2012) estimated values ranged from 103.32 to 129.75, 0.007 to 0.01122 and 0.2753 to 0.4225 for m, n and p respectively, while lower (better) value ranged from 18.26 to 21.29 for q parameter indicating that flocks of previous studies reached sexual maturity slightly earlier than that obtained in this study.

Concerning the modified compartmental model, the parameters represent A ,B ,C and D the scale parameters: the rate of decrease in laying ability, the reciprocal indicator of the variation in sexual maturity and the mean age of sexual maturity of the hens, respectively. In this work the estimated values of the abovementioned parameters were 75.26, 0.006, 1.14 wks and 24.96 wks ofage for A, B, C and D, respectively, as presented in Table 4.

Using the modified compartmental function, Yang *et al*. (1989), Savegnago *et al*. (2012) and Narinc *et al*. (2014) obtained estimated values ranged from 95.86 to 122.13, 0.005 to 0.01 and 1.14 to 1.55 for A, B and C, respectively, while lower (better) values ranged from (20.94 to 23.82) for D parameter indicating that flocks of previous studies reached sexual maturity earlier than the one of this study, which may be due to the differences in strain, breeding method and environmental conditions. There is difference between the estimates for parameters C and D in the modified compartmental model implying that the age at sexual maturity (parameter D) occurred on average 1.14 week after the age at first egg (parameter C).

In the current work, according to compartmental model, age and percentage of egg production at peak were 35.43 weeks of age and 58.14%, respectively. While, the corresponding parameters were 29.44 weeks of age and 64.16%, respectively by modified compartmental model (Table 4). These values were close to observed week and percentage of egg production in which the Fayoumi hens reached their peak (Table 3). Moreover, the modified compartmental model showed correspondence with the actual hen day of egg production.

By compartmental model on a flock of (Ross 308 –Iran), Safari-Aliqiarloo *et al*. (2018) obtained better estimation for age and percentage at peak of egg production of 33 weeks of age and 73.14%, respectively.

Depending on compartmental model, age and percentage of egg production at peak ranged from 29.83 to 31.89 weeks of age and from 83.69% to 87.64%, respectively. While the aforementioned traits ranged from 26.62 to 27.94 weeks of age and from 73.64% to 87.55%, respectively based on modified compartmental model in two lines of Beijing White Leghorn chickens selected for egg production for several generations (Yang *et al*., 1989). Hence the two selected lines of Beijing White Leghorn chickens had better performance (age and percentage at egg production peak) than the studied Fayoumi strain may due to the different genetic background. The curve of modified compartmental showed more flexibility than the curve of compartmental model as it did not provide enough fit at the point of inflection to properly fit the egg production rate at the peak (Figure 1)

Comparison criteria of the four models were presented in Table 5. The four studied models have considerably high with similar R^2 values (close to 1) which ranged from 0.9666 to 0.9939 indicating that all models had good performance (fitting) in describing age-related changes in egg production. Similar high R^2values have been reported in several studies (Cason and Britton, 1988, Narinc *et al*., 2014, Otwinowska-Mindur *et al*., 2016 and Safari-Aliqiarloo *et al*., 2018). In this work, AIC values were -280.45, -282.15, -433.02 and -530.19, while estimates of BIC were -268.25,-266.90, -417.77 and -514.84 for Wood, McNally, compartmental and modified compartmental models, respectively. A wide range of AIC estimates were reported by some authors ranging from -225086 to 40.02 for modified compartmental model (Miyoshi *et al*., 1996, Savegnago *et al*. 2012 and Narinc *et al*. 2014) ranging from -224548 to 393 for compartmental model (Miyoshi *et al*., 1996, Savegnago *et al*. 2012, Otwinowska-Mindur *et al*., 2016) and ranging from (-223588to -195.2) for McNally model (Savegnago *et al*. 2012, Narinc *et al*.2013 and Narinc *et al*.2014) and ranging from -301.43 to 242 for Wood model (Miyoshi *et al*., 1996, Narinc *et al*.2013, Narinc *et al*., 2014 and

Otwinowska-Mindur *et al.*, 2016). Estimates of BIC were -171.02, -188.27 and -346.76 for Wood, McNally and modified compartmental models (Narinc *et al.*, 2014), respectively.

According to the four goodness of fit criteria (R^2 , AIC , BIC and MSE), modified compartmental model was the best model for describing the egg-laying pattern of Fayoumi layers which had the lowest AIC and BIC values and the highest R^2. Regarding the order of the egg production models based on the best fit modified compartmental model was ranking first followed by compartmental, McNally and Wood models, respectively (Table 5). The results of goodness of fit criteria in the current study are in agreement with the results of Yang *et al.* (1989) and Miyoshi *et al.* (1996) who reported that the modified compartmental model best fits the egg production data. On the other hand, the compartmental provided the best fit of egg production curves of Shaver white layers (Narinc *et al.*, 2014).

CONCLUSION

According to model goodness of fit criteria, the modified compartmental model was the best to fit the egg production data of Fayoumi layers by having the lowest values for (AIC), (BIC) and highest value for (R^2) followed by the compartmental, McNally and Wood models.

Table (1): The mathematical models that were fitted to egg production data:

Model	Equation	Reference
1. Wood	$y_t = a.\mathrm{t}^b . exp^{(-c.t\,)}$	Wood (1967)
2. McNally	$y_t = a.\mathrm{t}^b . exp^{(-c.t\, +\, d.t^{0.5})}$	McNally (1971)
3. Compartmental	$y_t = m\,[1 - exp^{-p(t-q)}]exp^{(-n.t\,)}$	McMillan *et al.* (1970a,b)
4.Modified compartmental	$y_t = \dfrac{A\ .\ exp^{-Bt}}{1 + exp^{-C(t-D)}}$	Yang *et al.* (1989)

y_t : hen day percentage at *t* weeks of laying, a: the initial production, b: the rate of increase to the peak, c : the rate of decrease from the peak, d: the proportional to the square root of time, m: a scale parameter, n: a measure of persistency of egg production, p: rate of sexual maturity , q : age at first egg, A : a scale parameter, B : the rate of decrease in laying ability, C : the reciprocal indicator of the variation in sexual maturity and D: the mean age of sexual maturity of the hens.

Table (2): The equations of egg production peak related traits:

Model	The week of peak production	Percentage at peak egg production	persistency of peak production	Cited by
Wood and McNally	b/c	-	[−(b + 1)ln c]	Narinc *et al*. (2014)
Compartmental	$q + (^{1}/_{p})\ ln[(p+n)/n]$	$[mpn^{(n/p)}]/exp^{nq}(p+n)^{(1+(^{n}/_{p}))}$	-	Safari-Aliqiarloo *et al*.(2018)
Modified compartmental	D + [ln(C-B) - ln(B)]/**C**	[AB exp$^{\{B[InB)-ln(C-B)-BC]\}/C}$]/C	-	Yang *et al*.(1989)

a: the initial production, b: the rate of increase to the peak, c : the rate of decrease from the peak, d: the proportional to the square root of time, m: a scale parameter, n: a measure of persistency of egg production, p: rate of sexual maturity , q : age at first egg, A : a scale parameter, B : the rate of decrease in laying ability, C : the reciprocal indicator of the variation in sexual maturity and D: the mean age of sexual maturity of the hens.

Table (3): Means and standard errors (SE) of hen day egg production% of Fayoumi hens during 13 months of production (21to 72 weeks of age).

Weeks of age	**Month of production**	**Hen day egg production rate**
21-24	1st month of production	6.42 ^{i}
25-28	2nd month of production	49.50 ^{f}
29-32	3rd month of production	63.50 ^{a}
33-36	4th month of production	56.50 ^{bc}
37-40	5th month of production	58.00 ^{b}
41-44	6th month of production	53.50 ^{e}
45-48	7th month of production	55.25 ^{cd}
49-52	8th month of production	58.00 ^{b}
53-56	9th month of production	58.00 ^{b}
57-60	10th month of production	58.00 ^{b}
61-64	11th month of production	54.00 ^{de}
65-68	12th month of production	47.75 ^{g}
69-72	13th month of production	41.00 ^{h}
S.E.		0.56
P value		0.0001

Table (4): Estimated parameters of egg production models ± SE and production peak related traits:

Functions	Parameter	Values
Wood	a, %	0.001±0.0002
	b	2.90±0.60
	c	0.08±0.01
	Age at peak production	36.25, wks of age
	Presistency of peak	9.85, wks
McNally	a, %	0.001±0.0001
	b	2.19±0.24
	c	0.06±0.01
	d	-0.08±0.02
	Age at peak production	36.5,wks of age
	Presistency of peak	8.79, wks
Compartmental	m	86.47±8.44
	n	0.01±0.003
	p	0.23±0.001
	q,wks of age	21.61±0.21
	Age at peak production	35.43,wks of age
	Peak production%	58.14%
Modified compartmental	A	75.26±3.32
	B	0.006±0.0008
	C, wks	1.14±0.17
	D, wks of age	24.96±0.16
	Age at peak production according to Yang *et al*. (1989)	29.44,wks of age
	Peak production% according to Yang *et al*. (1989)	64.16%

a: The initial egg production, b: The rate of increase to the peak of egg production c, the rate of decrease from the peak, d**:** the proportional to the square root of time, m: a scale parameter n: measure of persistency of egg production, p: rate of sexual maturity, q: age at first egg, A : a scale parameter, B: the rate of decrease in laying ability, C: the reciprocal indicator of the variation in sexual maturity, and D: the mean age of sexual maturity of the hens**.**

Table (5): The goodness of fit criteria for fitted egg production functions.

Criterion	Egg production functions			
	Wood	**McNally**	**Compartmental**	**Modified compartmental**
R^2	0.9666	0.9851	0.9888	0.9939
AIC	-280.45	-282.15	-433.02	-530.19
BIC	-268.25	-226.90	-417.77	-514.84
MSE	0.01	0.01	0.01	0.01

R^2: coefficient of determination, AIC: Akaike information criterion, BIC: Schwarz Bayesian information criterion and MSE: mean square error.

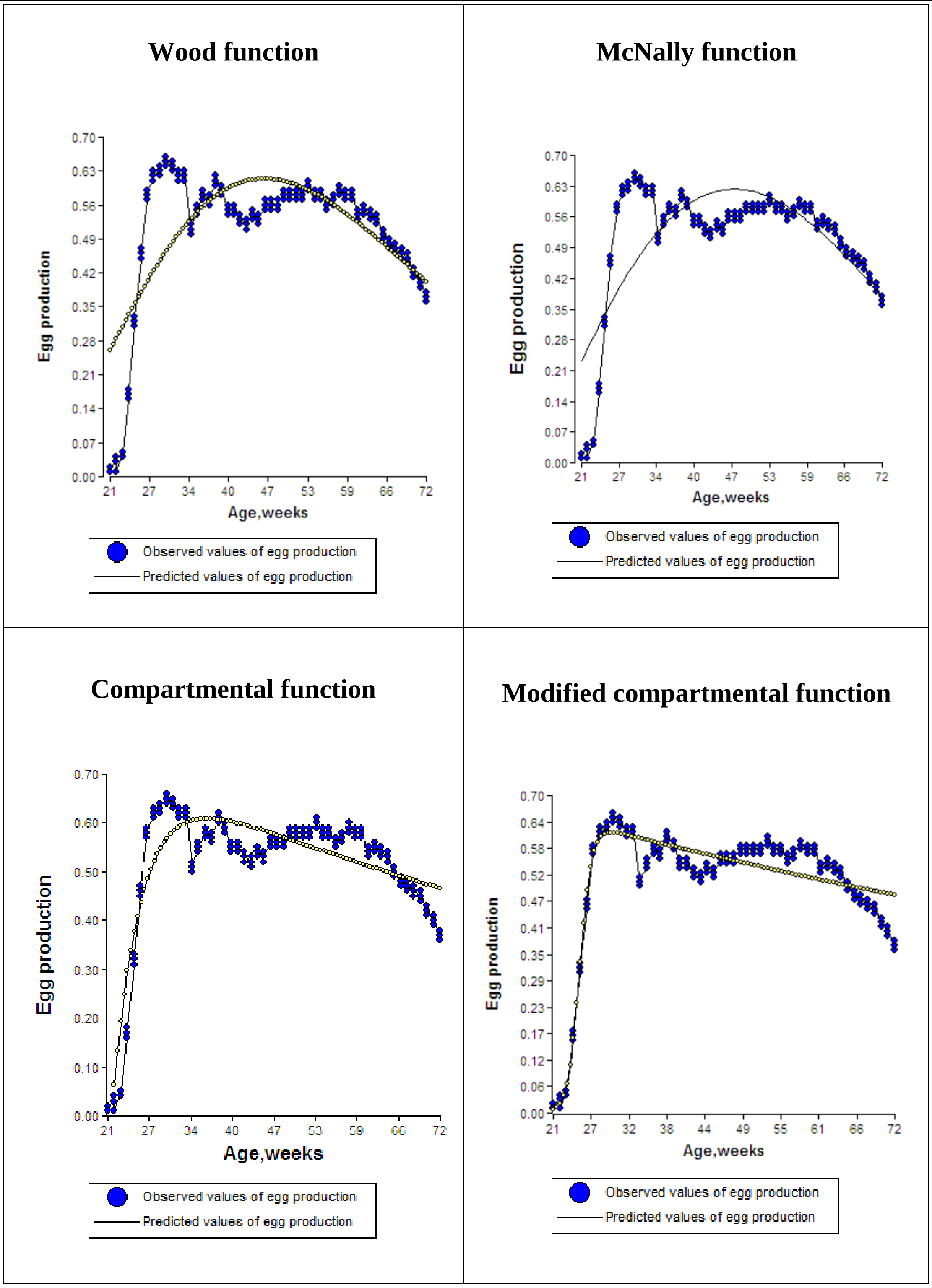

Figure (1): Fitted curves of hen day egg production using Wood, McNally, compartmental and modified compartmental functions.

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الملخص العربى

تقييم أربعة نماذج غير خطية لوصف منحنى إنتاج البيض للدجاج الفيومي البياض

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بيانات إنتاج البيض المستخدمة في هذا العمل تم الحصول عليها من سجلات قطيع دجاج الفيومي التابع لمشروع دواجن التكاملي بمنطقة العزب بمحافظة الفيوم. سجلات إنتاج البيض كانت لمدة ٥٢ أسبوعًا من فترة وضع البيض لعدد ١٩٠٠ دجاجة. جميع البيانات تم اعدادها على أساس أسبوعي في صورة عدد البيض لكل دجاجة في الأسبوع منسوب للدجاجات في اليوم (الحية). فيما يتعلق بنماذج Wood و McNally ، (a) تعني الإنتاج الأولي للبيض، كانت قيمة المعامل (a) لكلا النموذجين منخفضة جدًا (٠.٠٠١). كانت قيم معدل الزيادة لقمة إنتاج البيض (المعامل b) ٢.٩٠ لنموذج Wood و ٢.١٩ لنموذج McNally. وبالمثل ، تم تقدير المعامل c ، معدل التناقص بعد الوصول لقمة إنتاج البيض، بـ ٠.٠٨ لنموذج Wood و ٠.٠٦ لنموذج McNally. اعتمادًا على الدالة compartmental، m ، n ، p و q تمثل محدد المقياس، قياس ثبات إنتاج البيض، معدل النضج الجنسي والعمر عند أول بيضة على التوالي وكانت القيم المقدرة لهذه المعاملات ٨٦.٤٧ ، ٠.٠١ ، ٠.٢٣ و ٢١.٦١ أسبوع من العمرعلى التوالي، فيما يتعلق بالنموذج modified compartmental، تمثل المعاملات A ، B ، C و D محدد المقياس، ومعدل الانخفاض في القدرة انتاج البيض، ومؤشر متبادل للتباين في النضج الجنسي، ومتوسط عمر النضج الجنسي للدجاج، على التوالي. في هذا العمل، كانت القيم المقدرة للمعاملات المذكورة أعلاه ٧٥.٢٦، ٠.٠٠٦، ١.١٤ أسبوع و ٢٤.٩٦ أسبوع من العمر لـ A ، B ، C و D على التوالي. وفقًا لمعايير جودة الملاءمة، كان النموذج modified compartmental هو أفضل نموذج لوصف نمط وضع البيض للدجاج الفيومي البياض حيث كانت ذات اقل قيم لمعيار معلومات Akaike ومعيار معلومات Bayesian وأعلى معامل تحديد. علاوة على ذلك، أظهر النموذج modified compartmental تطابقًا مع إنتاج البيض الفعلي للدجاجات الحية في نفس اليوم (كان العمر والنسبة المئوية عند قمة الانتاج ٢٩.٤٤ أسبوعًا و ٦٤.١٦٪ على التوالي).

الكلمات الدالة: منحنيات انتاج البيض، Wood، McNally، Compartmental، Modified compartmental والدجاج الفيومي البياض.