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ORIGINAL ARTICLE

POULTRY

Genetic variance components of the growth curve for Isfahan indigenous chicken

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Abstract

Background: Being able to model a growth curve using three or four non-linear functional parameters could help explain the growth phenomenon in a precise way and would allow the comparison of an animal's development rate, optimize management and feeding strategies and guide animal production strategies.

Objective: The goal of this study was to estimate the genetic parameters of growth traits of Isfahan indigenous chicken in Iran and to determine the best non-linear model describing the growth curve.

Methods: The prediction of additive genetic parameters was performed using the REML method by WOMBAT. Direct heritability of the studied traits and genetic correlations between them were obtained. The Logistic, Gompertz, von Bertalanffy, Brody, Negative exponential, Weibull, Janoschek and Bridges models were compared based on the coefficient of determination (R^2), mean square error (MSE) and akaike information criterion.

Results: The Gompertz model was identified as the best model for describing the growth curve for Isfahan native chicken. The heritability of maturity weights (*A*), initial weight (*B*) and maturity rate (*K*) parameters were 0.223 ± 0.002, 0.016 ± 0.005 and 0.087 ± 0.001, respectively.

Conclusion: This study shows that Isfahan indigenous chicken has the genetic potential for improving growth and reproduction based on their desirable heritabilities and correlations using appropriate models.

KEYWORDS
genetic correlation, heritability, indigenous chicken, non-linear model

1 | INTRODUCTION

It is widely accepted that indigenous animals are considered valuable capital and strategic reserves of local regions, and their preservation and development are of great value and importance (Hartmann et al., 2003). In many developing countries, the genetic improvement of indigenous flocks still forms the basis of the core poultry breeding system. The genetic resources of indigenous chickens can play an essential role in establishing suitable breeds for production and adaptation to environmental conditions (Hoffman, 2005). The introduction of chickens to ancient Persia from the Indian subcontinent goes back to 2000–2500 BC (Nasr Esfahani et al., 2012). Isfahan indigenous chickens are found in central parts of Iran, such as in Chaharmahal Bakhtiari and Isfahan provinces. Genetic studies of Isfahan indigenous chicken production systems date back only three decades.

Half of the global chicken population is concentrated in Asia and indigenous breeds represent the majority of poultry genetic diversity. These breeds are classified depending on whether they can be registered in a single country (native), in several countries in a region (regional cross-border), or several regions (international cross-border). Knowledge of the growth patterns of indigenous breeds can only be achieved if the limitations that characterize these populations are considered and treated accordingly (González Ariza et al., 2021). The loss of indigenous breeds is not only a serious threat from the point of view of the loss of genetic resources but also leads to the irreversible loss of social, cultural and hereditary resources. These breeds are an integral part of the evolutionary diversity (González Ariza et al., 2021). Therefore, to understand the socio-economic characteristics, genetics, management and feed constraints faced by farmers rearing Isfahan indigenous chickens, a systematic recording system was developed decades ago to address growth and economic traits in these chickens.

Estimating growth curve parameters with reasonable accuracy is crucial in describing the production system, mainly when the rations include different food additives (Abbas et al., 2014). Most real-life growth curve systems are nonlinear. Therefore, non-linear models (NLMs) are often the preferable choice for describing biological systems under study. The shape and trend of the growth curve are generally affected by the diet constituents. Then, NLMs such as Brody, von Bertalanffy, Gompertz, Logistic and Richards methods have been used to address the animal growth phenomenon (Kum et al., 2010). However, there is no one-size-fits-all rule here, and the comparison of NLMs is generally taken into account when selecting the best fitted models even for the same species, strains and different lines (Narinc et al., 2010). Researchers have applied NLMs to explore growth curve estimation in different bird species (Table 1). As can be seen, studies on the analysis of growth data in indigenous chickens are very scant. Therefore, the main objective of this study was to estimate the growth parameters of Isfahan indigenous chicken and their genetic components due to best fitted NLMs. Awareness the genetic parameters of this trait is one of the first steps in designing breeding programmes and estimating heritability. As the genetic and phenotypic trends of studied traits change over time, another objective of the current study was also to delineate genetic trends in Isfahan indigenous chicken.

2 | MATERIALS AND METHODS

2.1 | Data

The Isfahan indigenous chicken breeding centre is located 25 km Southeast of Isfahan City, Kaboutarabad village. The centre was established in 1983 to preserve, expand and revive the genetic resources of Isfahan indigenous chickens. Some traits recorded in the centre were used in the current study, including body weight at hatch (BW1), body weight at 8 weeks of age (BW8), body weight at 12 (BW12) weeks of age, age at sexual maturity (ASM), weight at sexual maturity (WSM), egg number (EN) in the first 12 weeks of production, egg weight at the 84th day of laying (EW84), egg weight at the first day of laying (EW1) and average egg weight (AEW) at 28, 30 and 32 weeks of the laying period. The data were saved as ASCII files and edited by Excel 2020. Pedigree software was used to study and troubleshoot the pedigree structure. Table 2 contains the pedigree information used in this study. The study did not need IACUC or ethics committee approval because the study did not involve direct contact with animals but rather the utilization of records collected during routine activities.

2.2 | Statistical analysis

The outlier data (with more than three standard deviations around the mean) were removed from the data set. The general linear model method in SAS 9.2 software (2009) was used to calculate the least squares means of growth traits and parameters. The fixed effects (sex, generation and hatching number) were considered on all growth traits, and parameters and significant effects were included in the final animal model. A Duncan test was used to compare the means of traits at different levels of fixed effects. The (co)variance components of growth traits were estimated by REML using WOMBAT software. The following simple additive genetic animal model was used to estimate the genetic parameters of growth traits: $y = Xb + Zu + e$, with the assumptions of $E(y,u,e)' = (Xb,0,0)'$, and $Var(u,e)' = (G,R)'$ $var(y) = V = ZGZ' + R$, where y is the vector of observation, X is incidence matrix of fixed effects, b is vector of fixed effects, Z is incidence matrix of random effects, u is the vector of random effects, and e is residuals vector. To determine genetic correlation among the traits, we also used the following genetic bivariate animal additive model:

$[y_1 y_2] = [X_1 0 0 X_2][b_1 b_2] + [Z_1 0 0 Z_2][u_1 u_2] + [e_1 e_2]$, where $var(u_1) = A\sigma^2_{A1}$, $var(u_2) = A\sigma^2_{A2}$, $cov(u_1,u_2) = A\sigma_{A12}$, $var(e_1) = I\sigma^2_{e1}$, $var(e_2) = I\sigma^2_{e2}$. This assumed that errors are uncorrelated with each other and with random effects in the model. The other terms in the model are obvious. The genetic trends of traits were estimated using the average breeding values of animals and drawn using Excel 2020. The following eight NLMs, for example Logistic, Gompertz, von Bertalanffy, Brody, Negative exponential, Weibull, Janoschek and Bridges (Table 3), were used to fit the growth curve in Isfahan indigenous chicken. In the models, W is live weight at t (age in days), A is asymptotic weight, B is the rate of gain from birth to asymptotic weight (A), K is maturity rate, and M is the trajectory shape determinant. The growth parameters were estimated using the NLIN procedure of SAS 9.2 software, and A, B and K parameters were calculated. The goodness of fit criteria, including coefficient of determination ($R^2 = 1 - \frac{RSS}{TSS}$, where RSS and TSS were residual and total sum of squares, respectively), akaike information criterion ($AIC = n ln(\frac{SSE}{n}) + 2p$, where n is the number of observations, p is the number of parameters and SSE is error sum of squares) and mean squares error ($MSE = \frac{RSS}{n-p-1}$) were used to compare the fitted models (Sharif et al., 2021). The model

TABLE 1 Non-linear model studies for growth parameter estimation.

Species	Models	Best fitted model	Reference
Athens-Canadian chicken	Richards, Gompertz and Logistic, spline linear regression	Richards	Nahashon et al. (2006)
Indigenous chicken in China	Logistics, Gompertz and von Bertalanffy	Gompertz	Zhao et al. (2015)
Mazandaran native fowl	Gompertz, Logistics; Brody, Verhulst, Richards and von Bertalanffy	Gompertz	Barapour et al. (2021)
Japanese quail	Richards, Gompertz, Logistic, von Bertalanffy Hyperbolastic growth functions, including H1, H2 and H3	Richards	Beiki et al. (2013)
Japanese quail	Gompertz, Logistic, von Bertalanffy, Richards, Levakovich and Janoschek	Richards	Narinc et al. (2010) and Kaplan and Gurcan (2018)
Native Kazakh chicken	Gompertz, Richards, Lopez, Logistic and von Bertalanffy	Richards	Faraji Arough et al. (2023)
Vietnamese Ri chicken	Gompertz, Brody, Logistic, Richards, Bridges and Janoschek	Richards	Nguyen et al. (2023)
Vietnamese indigenous Mia chicken	Logistic, Gompertz, Richards and Bridges	Gompertz	Nguyen et al. (2021)
Local Italian chicken	Gompertz, Logistic and Richards	Richards	Rizzi et al. (2013)
Thai native chickens	von Bertalanffy, Gompertz Logestic	Gompertz	Boonkum et al. (2021)

TABLE 2 Brief structure of the pedigree of Isfahan indigenous chicken.

Parameter	Value
Total number of chickens	8334
Sires	336
Dams	2226
Chickens with progeny	2562
Chickens without progeny	5772
Founders in sires	336
Founders in dams	610

TABLE 3 Non-linear models used for growth curve description.

Model	Function	Number of parameters
Logistic	$W_t = A(1 + Be^{-kt})^{-1} + \varepsilon$	3
Gompertz	$W_t = Ae(-Be^{-kt}) + \varepsilon$	3
von Bertalanffy	$W_t = A(1 - Be^{-kt})^3 + \varepsilon$	3
Brody	$W_t = A(1 - Be^{-kt}) + \varepsilon$	3
Negative exponential	$W_t = A-(Ae^{-kt}) + \varepsilon$	2
Weibull	$y = a - b(e^{-kt^m}) + \varepsilon$	4
Janoschek	$y = a - (a - BW_0) \times e^{-kt^m} + \varepsilon$	4
Bridges	$y = BW_0 + a \times (1 - e^{-kt^m}) + \varepsilon$	4

with the greatest R^2 and the smallest mean square error (MSE) and akaike information criterion (AIC) values was selected as the best fit for growth data in Isfahan indigenous chickens (Sharif et al., 2021).

TABLE 4 Descriptive statistics of studied traits in indigenous chickens of Isfahan.

Trait	Number of records	Mean	SD
BW1 (g)	24,401	37.12	3.22
BW8 (g)	24,394	863.46	174.30
BW12 (g)	23,822	1377.14	271.23
ASM (d)	7372	166.96	14.92
WSM (w)	7460	2003.61	194.48
EN (*n*)	7363	51.67	16.31
EW1 (g)	7366	41.52	5.10
EW84 (g)	7368	48.40	3.47
AEW (g)	7113	51.22	3.15

Abbreviation: AEW, average egg weight at weeks of 28, 30 and 32 in laying period; ASM, age at sexual maturity; BW1, body weight at hatch; BW8, body weight at 8 weeks of age; BW12, body weight at 12 weeks of age; EN, egg number in the first 12 weeks of production; EW1, egg weight at the first day of laying; EW84, egg weight at the 84 first day of laying; WSM, weight at sexual maturity.

The variance components of growth parameters were estimated by a mixed model of WOMBAT and considering the influences of fixed effect, including sex, generation and hatch number.

3 | RESULTS AND DISCUSSION

Descriptive statistics of Isfahan indigenous chickens are presented in Table 4. The main factor determining the body weight of a 1-day old

TABLE 5 Summary of previous studies in Iranian indigenous chickens.

Native fowl (generations)	BW1 (g)	BW8 (g)	BW12 (g)	ASM (d)	EN (*n*)	AEW (g)	Reference
West Azerbayjan (21)	42.45	812.78	1388.37	176.47	33.94	52.54	Ghorbani and Zakizadeh (2021)
Yazd (6)	–	401.29	692.05	172.91	39.74	41.61	EmamgholiBegli et al. (2010)
Khorasan (3)	–	684.16	1243.75	164.21	38.86	50.36	Ghadamgahi et al. (2017)
Fars (25)	34.55	592.48	909.16	157.30	50.72	46.62	JelokhaniNiaraki et al. (2021)
Isfahan (21)	37.79	863.59	1398.34	171.35	47.5	50.16	JelokhaniNiaraki et al. (2021)
Fars (3)	34.51	633.93	1028.82	137.25	50.10	50.04	Jafari et al. (2015)
Yazd (15)	33.35	455.18	794.24	171.79	36.62	45.64	Non-published
Isfahan (3)	37.12	863.51	1375.49	166.57	52.47	51.22	Present study

chicken is the weight of the egg from which it is hatched. The average of this trait in Isfahan indigenous chickens was 37.12 ± 0.020 g, which was similar to the range of 1-day body weight values of native chickens from China (36.16) (Liu et al., 2006) but lower than native birds of Azerbaijan (Ghorbani & Zakizadeh, 2021). The average weight of 1-day-old chickens in the current study was higher than the average of the other native breeds of Iran (Mazandaran, Fars, Yazd) (Table 5), as well as Ethiopian chickens (24.9 g) (Dana et al., 2011). It seems the differences could be due to environmental conditions and the genetic background of native birds. If the hen does not eat well, the laid egg is poorly nourished, and the chicken is born with low weight, with some breeds laying much larger eggs than others. One of the most important economic traits in the breeding of indigenous chickens is the BW8. The mean of this trait in the current study (863.46 ± 1.11 g) was higher than the mean of Chinese indigenous chickens (631.05 g) (Liu et al., 2006) and the highest one among Iranian native chickens (Table 5). Emamgholi Begli et al. (2010) and Ghadamgahi et al. (2017) reported the average BW8 for Yazd and Khorasan chickens as 401.29 g and 684.16 g, respectively. They reported a lesser average of BW8 for Isfahan indigenous chickens, similar to the current study. Selection based on BW8 seems to have increased the mean due to the high genetic potential of this trait. The average BW12 of Isfahan indigenous chickens obtained was 1375.49 ± 1.74 g, which was lower than indigenous chickens of Azerbaijan (Ghorbani & Zakizadeh, 2021) and the other study of Isfahan native chickens (JelokhaniNiaraki et al., 2021) (Table 5). The difference between the 2 studies might be due to the lower amount of available data (4 generations in the present study vs. 21 generations in the previous one). On the other hand, these findings were higher than the reported values for native chickens in Mazandaran, Khorasan Razavi, Fars and Yazd (Table 5). In this study, the ASM was estimated to be 166.57 ± 0.165 days, which was similar to reported values for chickens in Fars (except the study of Jafari et al., 2015), Khorasan Razavi and Mazandaran (Table 5). Isfahan indigenous chickens reach sexual maturity sooner than the indigenous chickens of Yazd (Emamgholi Begli et al., 2010) and West Azerbaijan (Ghadamgahi et al., 2017). Decreasing the age of puberty is desirable, and indicating the genetic development of ASM in indigenous chickens. The EN of indigenous chickens in the present study was estimated to be 52.47 ± 0.177. The EN in this population was higher than the reported values for all other indigenous chickens in Iran. According to previous studies, it seems that Isfahan indigenous chickens have more significant genetic potential for egg production compared to other indigenous chickens in Iran.

3.1 | Non-genetic effects

The analysis of variances of production and reproduction traits is presented in Table 6. All the non-genetic factors had a significant effect ($p < 0.05$) on traits, which were consistent with the results of other studies (Ghadamgahi et al., 2017; Salehi Nasab et al., 2013; Yousefi Zonuz et al., 2013). In this study, the body weight of roosters and hens differed on the first day of hatch (37.36 vs. 36.90), BW8 (957.90 vs. 769.69) and BW12 (1524.70 vs. 1212.17). Abaszadeh et al. (2019) reported a significant effect of sex on the body weight of chickens from 2 to 12 weeks. Sex hormones or physiological characteristics may have an essential role in the differences between the two sexes. The hatching number had a significant effect on most studied traits except EN, whereas the average body weight of BW1 increased after the first hatch. The average body weights of BW8 and BW12 showed a downward trend in subsequent hatches, but the BW1 weight trend was upward. The weight loss in hatches can be due to the smaller egg size from hatches 1 to 4. The average body weights of BW1, BW8, BW12 and WSM in the 13th, 14th, 15th and 16th generations showed a fluctuation over generations. As this population is under selection for increasing the EN, decreasing the EW1, EW84 and AEW could be likely due to negative genetic correlations between the number and weight of eggs (Tables 6 and 7).

3.2 | Estimation of genetic parameters

The heritability of traits is presented in Table 7. The highest and lowest heritability was estimated for BW1 (0.61) and the EN during the first 12 weeks of the laying period (0.18), respectively. Ghadamgahi et al. (2017) reported a heritability of 0.11 for EN in indigenous chickens of Khorasan Razavi. The heritability of BW1 was higher than Ethiopian native chickens (0.40) (Abaszadeh et al., 2019). Khalil et al. (2004)

TABLE 6 Least square means (LSM) of studied traits for indigenous chickens.

Factors	BW1	BW8	BW12	ASM	WSM	EN	EW1	EW84	AEW
Gender	*	*	*	–	–	–	–	–	–
1	37.36^{a}	957.90^{a}	1524.70^{a}	–	–	–	–	–	–
2	36.90^{b}	769.69^{b}	1212.17^{b}	–	–	–	–	–	–
Generation	*	*	*	*	*	*	*	*	*
13	37.72^{a}	961.91^{a}	1518.23^{a}	184.17^{a}	2008.36^{a}	45.66^{a}	44.54^{a}	49.66^{a}	51.71^{a}
14	37.83^{b}	924.96^{b}	1441.13^{b}	162.09^{b}	2022.40^{a}	56.07^{b}	40.92^{bc}	48.46^{b}	51.29^{b}
15	36.87^{c}	696.46^{c}	1110.27^{c}	165.86^{c}	1920.59^{b}	52.30^{c}	41.08^{c}	47.92^{cd}	50.81^{c}
16	36.33^{d}	871.85^{d}	1404.13^{d}	158.35^{d}	2001.69^{a}	48.12^{d}	39.63^{d}	47.77^{d}	51.51^{ab}
Hatch	*	*	*	*	*	*	*	*	*
1	36.62^{a}	889.17^{a}	1425.65^{a}	167.05^{a}	2041.59^{a}	52.67^{a}	41.73^{a}	48.66^{a}	51.26^{a}
2	37.09^{b}	858.36^{b}	1391.18^{b}	167.52^{a}	1967.88^{bd}	51.79^{a}	41.29^{bc}	48.30^{bc}	51.25^{a}
3	37.49^{c}	862.77^{c}	1377.04^{b}	163.93^{bc}	2011.90^{c}	51.19^{a}	41.15^{c}	48.03^{c}	51.00^{b}
4	37.55^{d}	844.88^{d}	1279.89^{b}	171.98^{ac}	1931.67^{d}	46.50^{a}	42.01^{abc}	48.83^{ad}	51.81^{c}

Note: The mean within each group, except for those with similar letters, is statistically significantly different at $p < 0.05$.
*Significance at $p < 0.05$.
Abbreviation: AEW, average egg weight at weeks of 28, 30 and 32 in laying period; ASM, age at sexual maturity; BW1, body weight at hatch; BW8, body weight at 8 weeks of age; BW12, body weight at 12 weeks of age; EN, egg number in the first 12 weeks of production; EW1, egg weight at the first day of laying; EW84, egg weight at the 84 first day of laying; WSM, weight at sexual maturity.

TABLE 7 Heritability (diagonal), genetic (above the diagonal) and phenotypic (below the diagonal) correlations for investigated traits of Isfahan indigenous chickens.

Trait	BW1	BW8	BW12	ASM	WSM	EN	EW1	EW84	AEW
BW1	**0.61** ± **0.01**	0.23 ± 0.024	0.238 ± 0.02	0.24 ± 0.04	0.24 ± 0.04	−0.28 ± 0.06	0.56 ± 0.06	0.38 ± 0.02	0.62 ± .03
BW8	0.11 ± 0.01	**0.31** ± **0.02**	0.96 ± 0.01	0.38 ± 0.06	0.66 ± 0.04	−0.43 ± 0.07	0.16 ± 0.09	−0.05 ± 0.002	0.25 ± 0.05
BW12	0.130 ± 0.008	0.74 ± 0.003	**0.27** ± **0.01**	0.38 ± 0.06	0.74 ± 0.03	−0.38 ± 0.08	0.22 ± 0.01	0.01 ± 0.002	0.25 ± 0.06
ASM	0.07 ± 0.014	−0.02 ± 0.001	−0.06 ± 0.01	**0.36** ± **0.02**	0.43 ± 0.05	−0.88 ± 0.02	0.13 ± 0.01	0.16 ± 0.02	0.18 ± 0.05
WSM	0.06 ± 0.01	0.40 ± 0.01	0.43 ± 0.01	0.06 ± 0.01	**036** ± **0.02**	−0.48 ± 0.06	0.33 ± 0.07	0.20 ± 0.01	0.39 ± 0.04
EN	−0.04 ± 0.01	0.006 ± 0.001	0.004 ± 0.001	−0.57 ± 0.01	−0.08 ± 0.001	**0.18** ± **0.02**	−0.37 ± 0.05	−0.19 ± 0.01	0.20 ± 0.02
EW1	0.08 ± 0.01	0.04 ± 0.01	0.04 ± 0.01	0.18 ± 0.01	0.10 ± 0.01	0.09 ± 0.001	**0.13** ± **0.01**	0.84 ± 0.03	0.78 ± 0.05
EW84	0.17 ± 0.01	0.10 ± 0.01	0.11 ± 0.01	0.04 ± 0.01	0.15 ± 0.01	0.29 ± 0.01	0.60 ± 0.01	**0.38** ± **0.02**	0.95 ± 0.003
AEW	0.20 ± 01	0.13 ± 0.01	0.13 ± 0.02	0.08 ± 0.01	0.22 ± 0.01	0.10 ± 0.01	0.31 ± 0.01	0.90 ± 0.002	**0.51** ± **0.02**

reported heritability for egg production in the first 3 months as 0.31 and for annual egg production as 0.54, which are higher than the estimated values in the current study. The heritability of BW65 weight for native chickens of Iran was reported as 0.33 (Ghorbani et al., 2006). The heritability of traits was within the range of previous studies on Isfahan indigenous chickens (Ghorbani et al., 2006). It seems breed type, data amount, breeding environment, climatic conditions and feed quality can all contribute to differences in heritability. The results from the current study are comparable to others reported in the literature. The estimated heritability for ASM in our study was lower than Fars indigenous chickens (0.48) and more than indigenous chickens in Khorasan Razavi province of Iran (0.30) (Ghadamgahi et al., 2017; Jafari et al., 2015). Genetic and phenotypic correlations among traits are presented in Table 7. The genetic correlations among body weight traits (except the correlation between body weight in BW1 and BW8) ranged from moderate to strong and positive. The results suggest that selection for growth traits at a young age will lead to future weight gain. These results are consistent with other reports (Ghadamgahi et al., 2017; Niknafs et al., 2013). Medium and positive genetic correlations were obtained between body weight and age at puberty. Results suggest that planning to increase body weight can have adverse effects by increasing the age of puberty. Therefore, controlling body weight before puberty is essential. In indigenous chickens with high body weight before puberty, the selection to increase body weight results in fat storage and increases the age of puberty (Ghadamgahi et al., 2017).

Although body weight traits (BW1, BW8, BW12 and WSM) had medium negative genetic correlations with EN, they had positive correlations with age and WSM. On the other hand, a strong and negative

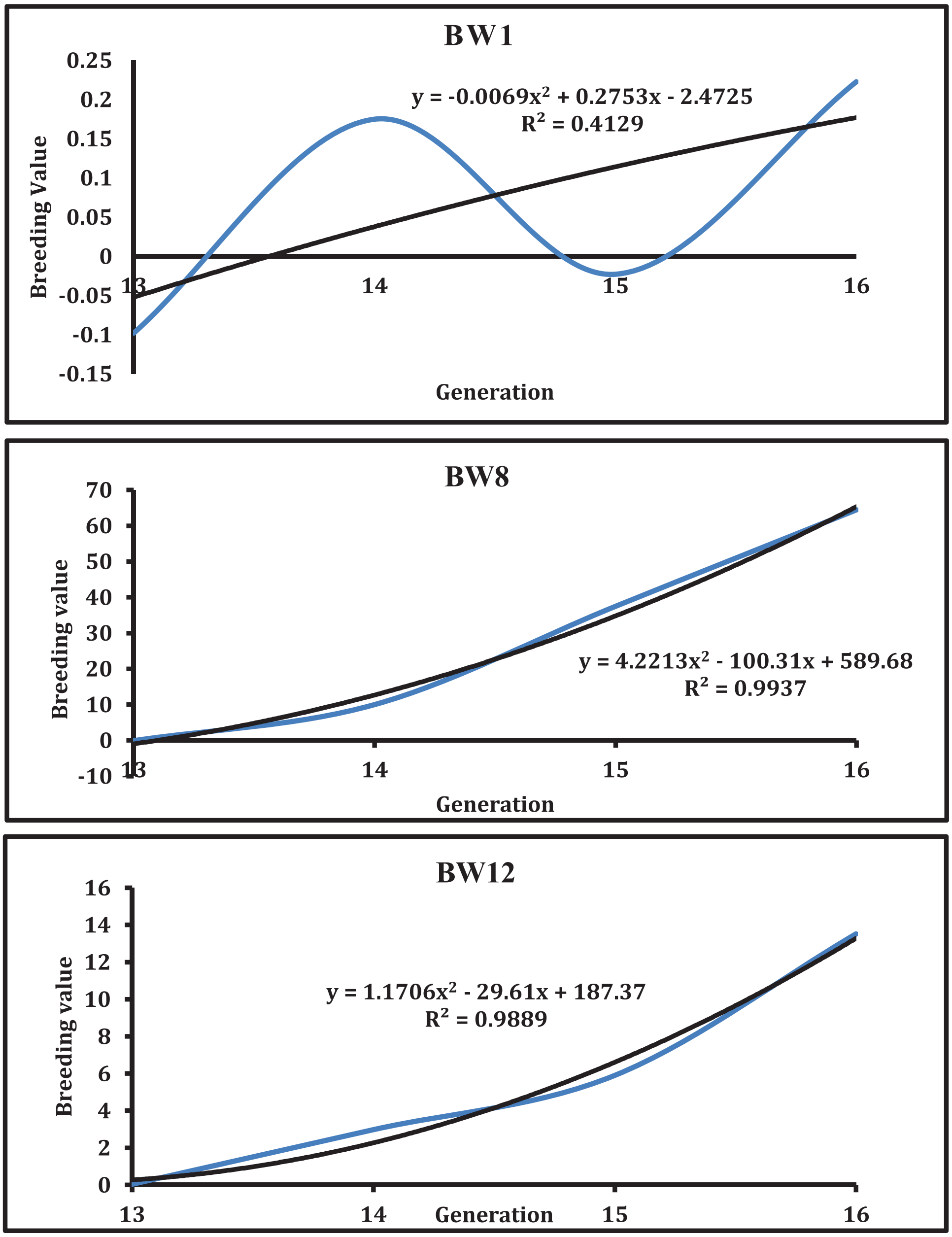

FIGURE 1 Genetic trend of body weight at hatch (BW1), body weight at 8 weeks of age (BW8), body weight at 12 (BW12), age at sexual maturity (ASM), egg number (EN), egg weight at the 84 first day of laying (EW84), average egg weight at weeks (AEW), weight at sexual maturity (WSM) and egg weight at the first day of laying (EW1) in Isfahan indigenous chickens.

genetic correlation (−0.88) was observed between the ASM and the EN. This negative correlation indicates that the selection to increase the EN reduces the age of puberty, which is desirable. These observations were consistent with the results from other reports (Ghadamgahi et al., 2017; Niknafs et al., 2013). Indeed, there was a moderate genetic correlation between the EN laid during the production period and growth traits (such as body weights at BW1, BW8 and BW12), and WSM (Table 7).

The genetic trends of BW1, BW8, BW12, ASM, EN, EW84, AEW, WSM and EW1 in Isfahan indigenous chickens are presented in Figure 1. The genetic trends of body weights (BW1, BW8, BW12 and WSM) were positive and upward, whereas ASM decreased. The negative genetic correlation (−0.88) between ASM and EN describes the shape of genetic trends. Egg numbers showed an upward trend and plateaued after a while, but the trend of egg weights at the 84th day of production (EW84), AEW and EW1 showed a declining trend. According to the results in Table 7, the genetic correlations between EN and egg weights (EW1, EW84 and AEW) were negative and moderate. Salehi Nasab et al. (2013) obtained positive genetic trends for body weights at BW8 and BW12 in Yazd's indigenous chickens during the first to seventh generations, which shows that the implementation of breeding programmes for these traits has been associated with favourable results. Although Isfahan indigenous chickens have the genetic potential for laying eggs, selection aims to increase the EN. Due

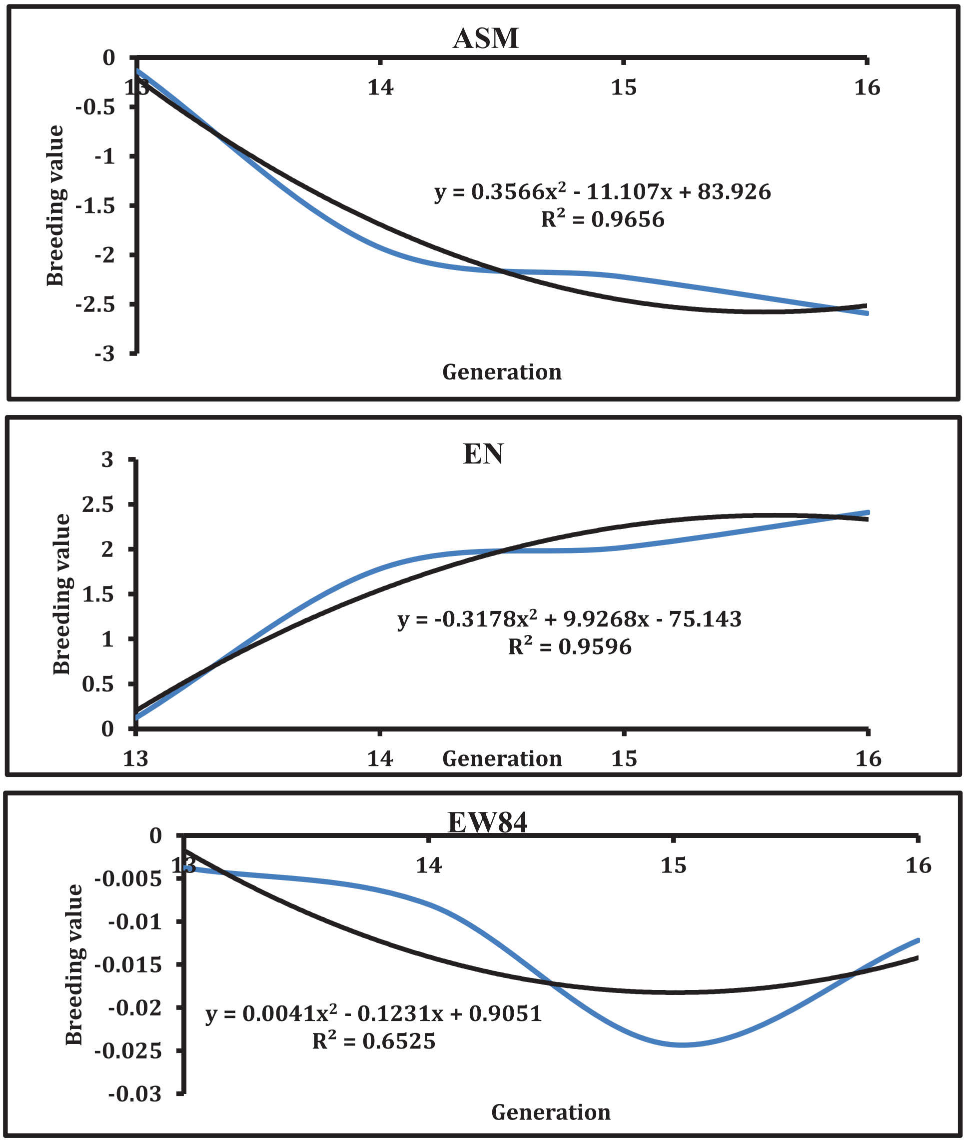

FIGURE 1 Continued

to the negative correlation between EN and growth traits and WSM, it seems that the egg plateau has led to increased body weights.

3.3 | Estimation of growth curve parameters

The estimated parameters of different NLMs for growth and goodness-of-fit criteria (MSE, AIC and R^2) are presented in Table 8. The Gompertz model had the highest value of R^2 and the lowest values of MSE and AIC and was selected as the best model to fit the growth curve of Isfahan indigenous chickens. The *A*, *B* and *K* parameters in the Gompertz model were estimated as 2149.4, 3.8695 and 0.0240, respectively. The von Bertalanffy model was the second best fitted model for growth traits in indigenous chickens. Our results agree with the previous studies that fitted NLMs to the growth pattern. Nahashon et al. (2006) reported that the Gompertz model fitted better to the growth pattern of native Guinea fowl. The Gompertz model also had a high degree of competence in describing the growth curve of native Chinese birds due to its lower error rate than the Logistic and von Bertalanffy models (Zhao et al., 2015). Similar results were reported in other studies (Barapour et al., 2021). It was also reported that the Gompertz model fitted as the best model for slow-growing Thai native chickens (Boonkum et al., 2021). Another study reported that flexible growth functions, such as Lopez, Richards and Weibull fit the live weight and age data better than the functions with a fixed point of inflection (such as the Gompertz and Logistic) based on goodness of fit criteria and statistical performance in Iranian native chickens and commercial broilers (Moharrery & Mirzaei, 2014). However, in quail, the Richards or generalized Logistic model had been reported as the best fitted model for the quail growth curve, which is contrary to the results of the current study (Beiki et al., 2013). In our study, the value of asymptotic weight (2037.3) agreed with the value reported by Barapour et al.

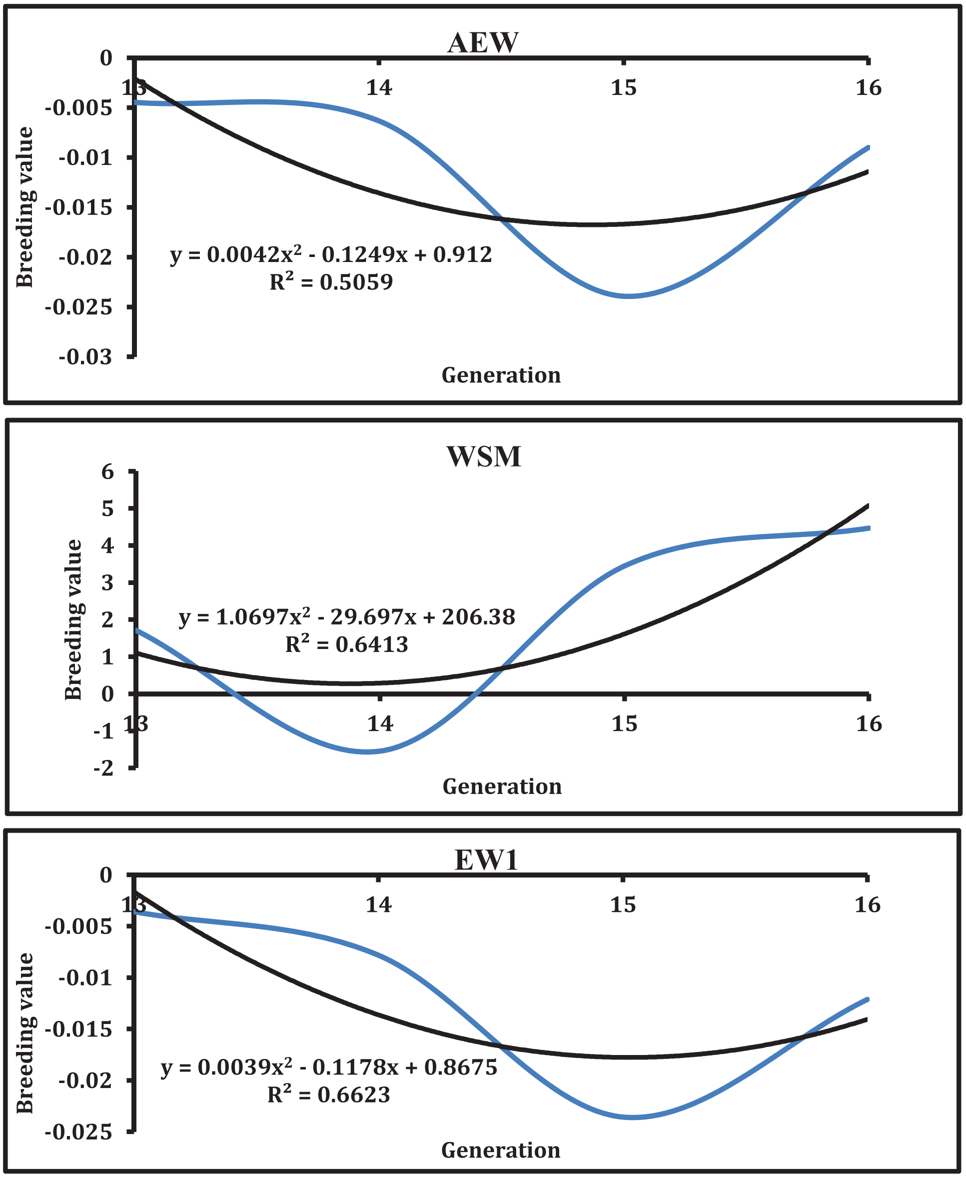

FIGURE 1 Continued

TABLE 8 Estimated values for parameters of non-linear models in Isfahan indigenous chickens.

	Parameters					
Model	A	B	K	MSE	AIC	R^2
Logistic	2037.30 ± 2.12	17.147700 ± 0.1700	0.0408 ± 0.00010	23165.9	211314.3	0.9855
Gompertz	2149.40 ± 3.10	3.8695 ± 0.024000	0.0240 ± 0.00010	20784.9	209922.1	0.9901
von Bertalanffy	2250.50 ± 4.42	0.8119 ± 0.004000	0.0184 ± 0.00010	21004.2	210130.5	0.9868
Brody	3400.60 ± 19.15	1.0000 ± 0.000500	0.0053 ± 0.00004	24690.8	212223.7	0.9844
Negative exponential	3400.20 ± 17.52	0.0053 ± 0.000003	–	24690.0	212221.7	0.9844
Weibull	2084.70 ± 2.56	1997.40 ± 2.15	0.00017	21850.2	215210.4	0.9732
Janoschek	2063.20 ± 3.12	–	0.00019	23945.3	215320.2	0.9728
Bridges	2039.30 ± 2.62	–	0.00012	24010.7	215941.7	0.9714

Abbreviation: AEW, average egg weight at weeks of 28, 30 and 32 in laying period; ASM, age at sexual maturity; BW1, body weight at hatch; BW8, body weight at 8 weeks of age; BW12, body weight at 12 weeks of age; EN, egg number in the first 12 weeks of production; EW1, egg weight at the first day of laying; EW84, egg weight at the 84 first day of laying; WSM, weight at sexual maturity.

TABLE 9 Estimated heritability (diagonal), genetic correlations (above the diagonal) and phenotypic correlations (below the diagonal) of Gompertz curve parameters.

Parameter	*A*	*B*	*K*
A	**0.223 ± 0.002**	0.147	−0.589
B	−0.195	**0.016 ± 0.005**	−0.389
K	−0.527	0.366	**0.087 ± 0.001**

(2021) for Mazandaran native chicken. The *B* and *C* parameters in the Gompertz model were 3.86 and 0.0240, respectively. It seems that growth curve parameters can be influenced by environmental and management factors, as well as breeding programmes (Kaplan & Gurcan, 2018). Heritability and correlation values between the growth curve parameters of indigenous chickens are presented in Table 9. The heritability of parameter *A*, as the asymptotic maturity weight of the bird, was estimated as 0.223 based on the Gompertz model. The heritability for *A* showed medium values (Aslam et al., 2011; Manjula et al., 2018). In the present study, the lowest heritability was estimated for *B*, which did not correspond to the values reported for native Korean chickens (Manjula et al., 2018). Genetic correlations between maturity weights *A*–*B* and *A*–*K* were positive (0.147) and negative (−0.589), respectively. There is an essential biological relationship between maturity weight parameters and maturity rate in growth models. The negative correlation among these parameters indicates that chickens with less maturity weight reached puberty sooner.

4 | CONCLUSION

Accounting for indigenous breeds and substructure within the breeding programme could be important when evaluating opportunities to accelerate genetic progress over time. The results from this study indicate there is a chance to increase the economic benefits of a poultry enterprise by increasing the contribution from indigenous breeds when designing the genetic programme with a $G \times E$ interaction focus. Isfahan indigenous chicken showed good genetic potential regarding egg lay during the production period. The strong and negative correlations were between EN and body weights, WSM and ASM. Although the negative correlation between EN and ASM is desirable, focusing on increasing the EN could lead to negative genetic trends for body growth traits. It is suggested to consider appropriate models in the selection programme to achieve simultaneous progress in both body weights and egg production. Indeed, it is also recommended to investigate the productive and reproductive performance of this breed in rural conditions.

AUTHOR CONTRIBUTIONS

Conceptualization; data curation; formal analysis; investigation; methodology; resources; software; validation: Mostafa Ghaderi-Zefrehei. *Data curation; formal analysis; software; writing—original draft*: Farjad Rafeie. *Data curation; formal analysis; resources; software; writing—original draft*: Sonia Zakizadeh. *Methodology; software*: Mahdi Elahi Torshizi. *Formal analysis; software*: Sunday O Peters. *Formal analysis; software*: Jacqueline Smith.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to disclose.

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None.

DATA AVAILABILITY STATEMENT

The datasets generated and analysed during the current study are not publicly available but are available from the corresponding authors on reasonable request.

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ETHICS STATEMENT

None.

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