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Application of non-linear models in description of growth of dual purpose FUNAAB Alpha chickens

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Abstract

Growth is explained mathematically by models that have parameters with biological interpretations. This study was conducted to compare five non-linear growth models (Gompertz, Brody, Logistics, Von Bertalanffy and Negative exponential) in order to describe growth in the three genotypes (normal feather, naked neck and frizzle feather) of the dual purpose FUNAAB Alpha chickens (n = 332). Doesn't Use Derivative iterative method of nonlinear procedure in SAS was used to estimate the model parameters. Computational difficultly, goodness of fit and residuals of the five models were also evaluated. Negative exponential model predicted the highest mature weight for the three genotypes while Logistics model predicted the highest coefficient of intensity of growth. The fitting of the five models presented no computational difficulty for normal feather chickens while Logistics failed to converge for male, naked neck and frizzle feather chickens. Based on goodness of fit (coefficient of determination, Bayesian information criterion, mean square error and residuals), Gompertz model was observed to have the best fit for normal feather and naked neck chickens while Brody model have the best fit for frizzle feather chickens and Von Bertalanffy for male chickens. From subjective approach (comparison of observed and predicted body weights), Logistics and Negative exponential models fitted well for normal feather than other models while Negative exponential model was the fittest among the models for naked neck and frizzle feather chickens and Gompertz for female chickens. It can be concluded that choice of appropriate model in description of growth depends on genotype and sex of dual purpose FUNAAB Alpha chickens.

Keywords: brody, goodness of fit, genotype, growth, logistics, negative exponential.

1 Introduction

FUNAAB Alpha breed of chicken, which was developed at the Federal University of Agriculture, Abeokuta, Ogun State, Nigeria, was registered as a new breed in 2018. The selection process for the traits of interest (meat and egg) started in 1997 with more than 10 generations of selections for improved meat and egg production. There are two types of FUNAAB Alpha chickens: the meat line and the dual purpose line. The dual purpose type was developed through rigorous, systematic and selective breeding of Nigerian native chickens without eroding their tropical adaptive features. Also, the dual purpose FUNAAB Alpha chickens are phenotypically the same in term of feather colours with Nigerian native chickens (Adebambo *et al.*, 2018). The average chick weight at hatch of the dual purpose line is between 30-35 g while body weight at maturity can reach 1800 g (Ilori *et al.*, 2017). Dual purpose FUNAAB Alpha chicken has three genotypes which are normal feather, naked neck and frizzle feather. The most important traits in this chicken breed are disease resistance and tropical adaptation.

Growth is an increase in body size per unit time (Lawrence & Fowler, 2002). It is a continuous function during animal's life, from embryonic to adult ages and it is mathematically explained by growth models or functions that have parameters with biological interpretations (Aggrey, 2002).

Mathematical functions are used to model growth in avian species and majority of them are asymptotic and mechanistic (Narinc *et al.*, 2017). An asymptotic model allows for a point where growth is no more possible known as asymp-

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totic or matured point. A mechanistic model predicts the growth of an animal through some other known theories. These models are useful in identifying better strategies to improve livestock production such as estimation of daily nutrient requirements (Pomar *et al.*, 2009) and development of breeding strategies; explanation of growth pattern (Narinc *et al.*, 2017) and in selection studies (Mignon-Grasteau *et al.*, 2000). The most widely used mathematical growth models in chickens are Von Bertalanffy, Brody, Logistics, Richards, Gompertz, Weibull, Negative exponential, France, Morgan-Mercer-Flodin and Michaelis-Menten (Lawrence & Fowler, 2002; Aggrey, 2002; Ahmadi & Golian, 2008).

Yakupoglu & Atil (2001) compared Gompertz, Logistic and Richards functions in Cobb 400 and Hubbard chickens. Roush *et al.* (2006) modelled growth of Ross × Ross 308 chickens using Gompertz and neural network models. Norris *et al.* (2007) described the growth curve of South African indigenous Venda and naked neck chickens using Gompertz, Logistic and Richards functions. Topal & Bolukbasi (2008) modelled growth of Ross PM3 chickens using non-linear functions. Narinc *et al.* (2010) compared non-linear growth models to describe growth of Hubbard and JA57 × Redbro chickens. Rizzi *et al.* (2013) described growth of Italian local chickens using non-linear growth functions. Zhao *et al.* (2015) modelled the growth curve of Shaobo, Huaixiang and Youxi chickens using Logistic, Gompertz and Von Bertalanffy functions. Dumuner *et al.* (2017) compared non-linear growth functions in Cobb 500, Ros 308 and Hubbard Flex chickens. Iyiola *et al.* (2017) modelled growth in Nigerian indigenous normal feather chickens using Bayesian non-linear functions. Ogunpaimo *et al.* (2020) described the growth curve of meat type FUNAAB Alpha chickens using Gompertz and Von Bertalanffy functions. Although many authors have compared growth models in many chicken breeds, there are limited works on modelling of growth and comparison of non-linear growth models in dual purpose FUNAAB Alpha chickens. These models are useful for estimation of daily nutrient requirement, development of breeding strategies, explanation of growth pattern and prediction of body weight in dual purpose FUNAAB Alpha chickens. The aim of this study was to compare five mathematical non-linear growth models (Gompertz, Brody, Logistics, Von Bertalanffy and Negative exponential) in order to describe the growth of dual purpose FUNAAB Alpha chickens.

2 Materials and Methods

2.1 Experimental site

The experiment was carried out at the Poultry Breeding Unit of the Directorate of University Farms, Federal University of Agriculture, Abeokuta, Alabata, Ogun State, Nigeria. Alabata (latitude 7°10′ N and longitude 3°2′ E) is located in Odeda Local Government Area of Ogun State, Nigeria (Google Map, 2021). The area which lies in the South Western part of Nigeria has a prevailing tropical climate with a mean annual rainfall of about 1037 mm. The mean ambient temperature ranges from 28 °C in December to 36 °C in February with a yearly average relative humidity of about 82 % (Climate data, 2021). The vegetation represents an interphase between the tropical rainforest and the derived savannah (Ilori *et al.*, 2017).

2.2 Source, sample size and management of experimental birds

The experimental birds were obtained from Programme for Emerging Agriculture Research Leader Unit of the University farm. Three hundred and thirty-two (332) dual purpose FUNAAB Alpha chickens were used for the experiment. The birds comprised 111 Normal Feather (45 males and 66 females), 112 Naked Neck (46 males and 66 females) and 109 Frizzle Feather (56 males and 53 females) chickens. All the experimental birds were raised together in a 25 m × 25 m pen under intensive management system. The chicks were brooded in deep litter pen at the brooding stage. The birds were wing-tagged for proper identification. They were also subjected to the same management procedures throughout the experimental period. Commercial feeds were provided for the birds *ad libitum.* Chick starter mash containing 23 % crude protein and 11.1 MJ/ kg metabolizable energy was fed to the birds from 0 to 8 weeks of age. Grower mash containing 18 % crude protein and 10.48 MJ/ kg metabolizable energy was fed to the birds from 9-20 weeks of age. Potable water was provided for the birds without restriction. Marek's disease vaccine was administered at day 1, Newcastle disease vaccine was administered at days 14, 35, 90 and 120. Infectious bursal disease vaccine was administered at day 21 while fowl pox disease vaccine was administered at day 70. Adequate sanitation was practised to prevent occurrence of diseases. The protocol for the experiment was approved by Animal Care and Use Committee of College of Animal science and Livestock production of the Federal University of Agriculture, P.M.B. 2240, Abeokuta, Ogun State Nigeria with approval reference FUNAAB/AEWC/2020/0021.

2.3 Data collection

Live weights of dual purpose FUNAAB Alpha chickens were recorded individually on a weekly basis from day old till 20 weeks of age using Avery Berkel scale (Model G220), United Kingdom with a maximum capacity of 15 kg and sensitivity of 1 g.

2.4 Statistical analysis

The GLM procedure of SAS version 9 (2002) was used to evaluate the effect of genotype and sex on body weight of dual purpose FUNAAB Alpha chickens. Mean separation was done using Tukey's test. Five non-linear growth models were fitted to the weight-age data from day old till 20 weeks of age for each bird using nonlinear procedure of SAS version 9 (2002). Doesn't Use Derivative iterative option of nonlinear procedure in SAS was used to estimate parameters of the models. The Doesn't Use Derivative method circumvents specification of model derivatives by choosing a fitting algorithm that approximates the derivatives by their differences. The models used, their relevant statistics and explanation of their biological parameters were described in Supplementary Table 1 (annex). The growth parameters used in this study were estimated using unadjusted body weights. As such, they are representative of growth under a given set of conditions. The environment often has a large effect on single weight or gain over a short period of time, but compensatory effects tend to reduce the net effect of the environment on lifetime weight-age parameters. The reason for using unadjusted weight in this study was because serial measurements are concurrently considered in estimation of parameters. Lifetime parameters such as those estimated in this study are not free from environmental effects but such parameters become adjusted in the least squares fitting of the data pattern (Brown *et al.*, 1976). The Computational difficulty was based on whether the models used converge or not and the number of iteration for each model using Best 30 when writing the syntax for each model. The time taken for each model to run was also considered. Key non-linear model descriptors such as inflection time, inflection point, relative growth rate and correlation coefficients among the model parameters were also evaluated. The goodness of fit for each model was assessed using coefficient of determination (R^2), Akaike's information criterion (AIC), Bayesian information criterion (BIC), mean square error (MSE), root of mean square error (RMSE) and residuals. The goodness of fit parameters as described by Lambe *et al.* (2006) are shown in Supplementary Table 2 (annex). The effects of genotype and sex on body weight of the dual purpose FUNAAB Alpha chickens were also evaluated.

3 Results

3.1 Effect of genotype, sex and their interaction on body weight

The effect of genotype, sex and their interaction on body weight of dual purpose FUNAAB Alpha chickens were shown in Table 1. Body weight of the chicken was significantly ($p < 0.05$) affected by genotype at all ages. The highest body weight was observed in normal feather chickens at weeks 1, 12, 16 and 20. Sex as well as interaction between genotype and sex had no significant ($p > 0.05$) effect on the body weight of the chickens except at week 16. There was no significant difference in the body weight of female naked neck and female frizzle feather chickens at week 16.

3.2 Model parameters

The growth models parameters based on genotype and sex of the birds were presented in Table 2 while the growth models parameters and computational difficulty based on genotype by sex interaction were shown in Table 3. For the

Table 1: *Effect of genotype, sex and their interaction on body weight of dual purpose FUNAAB Alpha chicken*

	Week 1	Week 4	Week 8	Week 12	Week 16	Week 20
Genotype						
Normal feather	88.42± 1.51^a	400.84± 9.01^b	896.05± 45.79^b	1260.95± 18.18^a	1317.76± 11.94^a	1491.19± 16.05^a
Naked neck	81.66± 1.50^b	375.81± 8.95^c	1053.94± 45.64^a	1155.18± 18.01^b	1286.89± 11.83^b	1444.13± 15.95^b
Frizzle feather	81.71±1.51^b	480.65± 10.64^a	942.45± 54.76^b	1140.74± 21.98^b	1235.62± 14.56^b	1427.18± 19.69^b
Sex						
Male	83.63± 1.30	413.80± 8.12	995.30± 41.30	1171.56± 16.30	1394.97± 10.70^a	1491.19±16.05
Female	84.24± 1.16	424.40± 7.49	932.94± 38.54	1165.69± 15.50	1199.21± 10.26^b	1444.13±15.95
Genotype by sex interaction						
Normal feather × male	86.47± 2.33	391.07± 13.89	888.92± 70.39	1220.38± 27.78	1394.54± 18.24^a	1529.70± 24.44
Normal feather × female	90.38± 1.92	410.62± 11.47	903.19± 58.57	1240.98± 15.41	1301.52± 23.47^b	1452.68± 20.82
Naked neck × male	81.54± 2.30	377.57± 13.74	1133.91± 70.39	1164.42± 27.78	1423.07± 18.24^a	1456.71± 24.72
Naked neck × female	81.77± 1.92	374.25± 11.47	973.98± 58.12	1145.94± 22.93	1150.71± 15.06^c	1431.55± 20.18
Frizzle feather × male	82.88±2.09	472.97± 14.55	963.22± 73.74	1129.89±29.10	1367.31± 19.11^a	1488.38± 25.60
Frizzle feather × female	80.55± 2.19	488.32± 15.53	921.67± 80.98	1151.60± 32.94	1163.94± 21.97^c	1365.98± 29.93

^{abc} Means within the same column for different ages having different superscript are significantly different ($p < 0.05$).
Mean separation was done using Tukey's test

Table 2: *The growth models parameters and computational difficulty based on genotype and sex.*

		Parameter					
	Model	*A*	*B*	*K*	*Convergence*	*Iteration*	*CT*
Genotype							
NF	Gompertz	1478.20	3.50	0.25	Converged	18	0.7
	Brody	1764.50	1.07	0.10	Converged	13	1.89
	Logistics	1419.30	13.46	0.39	Converged	11	0.49
	Von Bertalanffy	1520.10	-0.77	0.20	Converged	17	0.72
	Negative exponential	1941.40	-	0.07	Converged	16	0.52
NN	Gompertz	1362.50	4.15	0.31	Converged	15	0.68
	Brody	1581.40	1.10	0.12	Converged	12	1.88
	Logistics	843.00	3105.60	1.83	Not converged	100	2.92
	Von Bertalanffy	1395.20	-0.88	0.25	Converged	17	0.74
	Negative exponential	1729.30	-	0.09	Converged	13	0.42
FF	Gompertz	184.50	1.23	0.00	Not converged	100	2.79
	Brody	1581.70	1.06	0.11	Converged	10	1.82
	Logistics	1179.30	36.85	2.77	Not converged	100	2.83
	Von Bertalanffy	1418.50	-0.72	0.21	Converged	15	0.69
	Negative exponential	1705.40	-	0.09	Converged	11	0.48
Sex							
Male	Gompertz	1488.00	3.45	0.25	Converged	16	0.75
	Brody	1756.90	1.07	0.10	Converged	12	1.86
	Logistics	1087.10	-10957.30	5.51	Not converged	100	2.24
	Von Bertalanffy	1529.30	-0.77	0.20	Converged	16	0.72
	Negative exponential	1931.20	-	0.08	Converged	14	0.60
Female	Gompertz	1353.80	3.56	0.28	Converged	13	0.62
	Brody	1560.40	1.08	0.11	Converged	12	2.09
	Logistics	1307.50	13.92	0.44	Converged	16	0.51
	Von Bertalanffy	1387.40	-0.78	0.22	Converged	16	0.53
	Negative exponential	1691.70	-	0.09	Converged	12	0.42

NF: normal feather; NN: naked neck; FF: frizzle feather; CT: Computation time (sec).

normal feather chickens, the highest mature weight was predicted by Negative exponential model while the least mature weight was predicted by Logistics model. The average estimates of mature weight differ as much as 522.10 g across the models while the range of estimate of k varied from 0.07 in Negative exponential model to 0.39 in Logistics model.

For the naked neck genotype, the highest mature weight was predicted by Negative exponential model while the least was predicted by Logistics model. The estimate of constant of integration was highest in Logistics model while the least *B* was observed in Von Bertalanffy model.

For the frizzle feather chickens, the predicted mature weight ranged from 184.50 g to 1705.40 g. The range of estimate of *k* varied from 0.00 in Gompertz model to 2.77 in Logistics model. For the male chickens, the highest mature weight was predicted by Negative exponential model while the lowest was predicted by Logistics model. Negative *B* value was predicted by Von Bertalanffy model for female chickens. The predicted *k* for female chickens ranged from 0.09 to 0.44. K ranged from 0.09 to 5.51 in the two sexes.

3.3 Computational difficulty

For the normal feather chickens, the fitting of the five models showed no computational difficulty (Table 2). The five models attained convergence with a low number of iterations ranging from 11 to 18. All the models converged for naked neck chickens except Logistics model. In the frizzle feather chickens, the fitting of Gompertz and Logistics models failed to converge for the description of weight-age relationship.

Computation time ranged from 0.60 seconds to 2.24 seconds for male chickens. All the growth models converged for female chickens. The longest computation time was observed in Von Bertalanffy model for male naked neck chickens. Also, Von Bertalanffy model did not converge for male naked neck and male frizzle feather chicken (Table 3).

3.4 Goodness of fit measures

Goodness of fit measures for the five growth models based on genotype and sex were reported in Table 4. In normal feather chickens, the (R^2) was considerably high in Gompertz and Von Bertalanffy models while the least value was recorded in Negative exponential model. The AIC values of the five models ranged from 3490.64 in Gompertz model to 3546.09 in Negative exponential model. The highest MSE and RMSE values were observed in Negative exponential model.

Table 3: *The growth models parameters and computational difficulty based on genotype by sex interaction.*

			Parameters					
Genotype	*Sex*	*Model*	*A*	*B*	*K*	*Convergence*	*Iteration*	CT
NF	Male	Gompertz	1571.30	3.37	0.22	Converged	12	0.31
		Brody	1967.70	1.06	0.08	Converged	11	0.30
		Logistics	1494.90	12.40	0.35	Converged	12	0.33
		Von Bertalanffy	16.26.40	-0.75	0.18	Converged	51	0.32
		Negative exponential	2207.10	-	0.06	Converged	11	0.29
NF	Female	Gompertz	1420.70	3.64	0.27	Converged	14	0.29
		Brody	1649.10	1.08	0.11	Converged	12	0.39
		Logistics	1374.50	14.31	0.42	Converged	14	0.27
		Von Bertalanffy	1454.80	-0.80	0.22	converged	16	0.32
		Negative exponential	1794.60	-	0.09	Converged	15	0.23
NN	Male	Gompertz	1417.90	4.78	0.34	Converged	21	0.35
		Brody	1634.10	1.11	0.13	Converged	12	0.40
		Logistics	1373.90	23.92	0.56	Converged	13	0.27
		Von Bertalanffy	10.11	1.65	-0.04	Not converged	100	0.50
		Negative exponential	1787.90	-	0.09	converged	13	0.25
NN	Female	Gompertz	1326.10	3.81	0.29	Converged	15	0.39
		Brody	1552.40	1.08	0.11	Converged	11	0.41
		Logistics	577.10	-1268.7	1.67	Not converged	100	0.46
		Von Bertalanffy	1362.00	-0.8177	0.23	Converged	17	0.32
		Negative exponential	1695.30	-	0.09	Converged	11	0.31
FF	Male	Gompertz	1484.30	3.07	0.23	Converged	12	0.34
		Brody	1737.20	1.05	0.10	Converged	11	0.31
		Logistics	1084.40	623919	10.85	Converged	14	0.37
		Von Bertalanffy	39.28	0.48	-0.01	Not converged	100	0.41
		Negative exponential	1882.60	-	0.08	Converged	11	0.28
FF	Female	Gompertz	1261.70	3.31	0.30	Converged	13	0.33
		Brody	18.02	-6.33	-0.05	Not converged	100	0.42
		Logistics	987.50	960.25	13.66	Converged	13	0.42
		Von Bertalanffy	1287.90	-0.7429	0.24	Converged	15	0.39
		Negative exponential	1501.20	-	0.11	Converged	10	0.30

NF: normal feather; NN: naked neck; FF: frizzle feather; CT: Computation time (sec).

Table 4: *Goodness of fit measures for the five growth models based on genotype and sex*

	Model	*(R^2)*	*AIC*	*BIC*	*MSE*	*RMSE*
Genotype						
NF	Gompertz	0.983	3490.64	3502.06	36496.87	190.18
	Brody	0.981	3522.59	3534.00	40183.58	199.55
	Logistics	0.982	3508.49	3519.91	38513.32	195.36
	Von Bertalanffy	0.983	3491.19	3502.61	36557.58	190.33
	Negative exponential	0.980	3546.09	3553.70	43259.85	207.36
NN	Gompertz	0.902	4098.60	4110.02	227794.48	475.12
	Brody	0.900	4105.03	4116.44	232244.55	479.74
	Logistics	0.607	4558.31	4569.73	909696.05	949.46
	Von Bertalanffy	0.902	4098.75	4110.17	227895.13	475.22
	Negative exponential	0.900	4109.76	4117.37	236284.52	484.62
FF	Gompertz	0.909	3899.08	3910.49	124893.62	351.80
	Brody	0.974	3479.10	3490.51	35249.88	186.90
	Logistics	0.643	4352.92	4364.34	490030.40	696.85
	Von Bertalanffy	0.974	3488.37	3499.78	36247.74	189.53
	Negative exponential	0.973	3494.14	3501.75	36994.07	191.76
Sex						
Male	Gompertz	0.999	1938.59	1947.56	523093.31	256208.97
	Brody	0.999	1939.51	1948.48	526356.01	257807.30
	Logistics	0.676	2059.53	2068.50	1190902.78	583299.32
	Von Bertalanffy	0.999	1937.92	1946.89	520709.95	255041.61
	Negative exponential	0.999	1940.29	1946.27	532724.85	262738.45
Female	Gompertz	0.999	2177.36	2187.02	127187.04	62562.28
	Brody	0.988	2185.44	2195.10	132864.88	63355.16
	Logistics	0.999	2187.20	2196.86	134135.85	65980.34
	Von Bertalanffy	0.989	2176.30	2186.04	126514.67	62231.54
	Negative exponential	0.999	2195.66	2202.10	141167.55	69820.71

NF: normal feather; NN: naked neck; FF: frizzle feather.

Table 5: *Goodness of fit measures for the five growth models based on interaction between genotype and sex.*

Genotype	*Sex*	*Model*	*(R^2)*	*AIC*	*BIC*	*MSE*	*RMSE*
NF	Male	Gompertz	0.979	2592.78	2603.58	14644.90	7241.09
		Brody	0.946	2613.75	2624.55	15827.52	7825.83
		Logistics	0.969	2622.13	2632.92	16326.43	8072.52
		Von Bertalanffy	0.925	2589.20	2600.00	14451.96	7145.70
		Negative exponential	0.970	2634.08	2641.28	17128.17	8500.65
NF	Female	Gompertz	0.950	3812.73	3824.59	19839.48	9842.44
		Brody	0.899	3859.09	3870.95	22378.45	11102.04
		Logistics	0.959	3821.42	3833.28	20292.31	10067.09
		Von Bertalanffy	0.955	3817.51	3829.37	20087.26	9965.37
		Negative exponential	0.995	3887.83	3895.74	24175.32	12024.86
NN	Male	Gompertz	0.963	3354.37	3365.18	234858.50	116129.30
		Brody	0.979	3359.21	3370.02	239092.70	118222.90
		Logistics	0.963	3355.45	3366.25	235794.20	116592.00
		Von Bertalanffy	0.963	3568.74	3579.55	518022.4	256143.90
		Negative exponential	0.963	3361.17	3368.37	241704.60	119960.40
NN	Female	Gompertz	0.961	4040.28	4052.22	26773.50	13285.33
		Brody	0.971	4055.22	4067.16	27802.95	13796.16
		Logistics	0.961	5262.35	5274.29	586081.40	290820.70
		Von Bertalanffy	0.972	4038.04	4049.99	26622.97	13210.64
		Negative exponential	0.996	4076.60	4048.56	29419.12	12024.86
FF	Male	Gompertz	0.973	2678.43	2689.12	28303.90	13989.28
		Brody	0.993	2661.21	2671.91	26496.97	13096.20
		Logistics	0.963	3068.55	3079.25	126181.30	62365.49
		Von Bertalanffy	0.977	3559.71	3570.40	828449.60	409463.60
		Negative exponential	0.972	2670.09	2677.22	27518.30	13653.72
FF	Female	Gompertz	0.988	2108.02	2118.11	18706.32	9222.04
		Brody	0.982	2327.80	2337.90	52241.71	25754.67
		Logistics	0.955	2429.32	2439.42	83956.03	41389.54
		Von Bertalanffy	0.823	2101.45	2111.55	18141.19	8943.44
		Negative exponential	0.982	2115.36	2122.09	19448.64	9633.44

NF: normal feather; NN: naked neck; FF: frizzle feather.

For the naked neck chickens, the AIC values of the five models ranged from 4098.60 in Gompertz model to 4558.31 in Logistics model. The lowest BIC was also observed in Gompertz model and the highest was predicted by Logistics model. The highest MSE and RMSE were observed in Logistics model while the lowest MSE and RMSE were observed in Gompertz model.

For the frizzle feather chickens, the lowest BIC was also observed in Brody model while the highest was predicted by Logistics model. The highest MSE and RMSE were observed in Logistics model while the lowest MSE and RMSE were observed in Brody model. All the growth models have the same (R^2) value in male chickens except Logistics model. The AIC value ranged from 1937.92 to 2195 in both sexes. The lowest BIC was predicted by Negative exponential model for male dual purpose FUNAAB Alpha chickens. Also the BIC of all the models were higher in female chickens than male chickens.

Goodness of fit measures for the five growth models based on interaction between genotype and sex were presented in Table 5. For the interaction between genotype and sex, the lowest (R^2), AIC, BIC and RMSE were observed in Von Bertalanffy model.

3.5 Correlation among the growth model parameters

The correlation among the growth model parameters based on genotype and sex is presented in Table 6. Negative correlation coefficient was observed between A and B in the three genotypes for all the non-linear models except in Von Bertalanffy model. The correlation between A and K was not estimated by Logistic model for naked neck and frizzle feather birds. Positive correlation was also observed between parameters B and K in female birds for all the models except Von Bertalanffy model.

The correlation among the growth model parameters based on the interaction between genotype and sex is shown in Table 7. The highest correlation between A and B was predicted by Brody model in female frizzle feather chickens.

Table 6: *Correlation among the growth model parameters based on genotype and sex*

	Model	*A and B*	*A and K*	*B and K*
Genotype				
NF	Gompertz	-0.46	-0.76	0.85
	Brody	-0.65	-0.96	0.77
	Logistics	-0.28	-0.55	0.88
	Von Bertalanffy	0.53	-0.88	-0.84
	Negative exponential	-	-0.98	-
NN	Gompertz	-0.43	-0.67	0.88
	Brody	-0.62	-0.93	0.77
	Logistics	-0.04	NE	NE
	Von Bertalanffy	0.51	-0.76	-0.86
	Negative exponential	-	-0.97	-
FF	Gompertz	-0.38	-0.74	0.81
	Brody	-0.60	-0.94	0.75
	Logistics	NE	NE	NE
	Von Bertalanffy	0.44	-0.81	-0.78
	Negative exponential	-	-0.96	-
Sex				
Male	Gompertz	-0.44	-0.75	0.84
	Brody	-0.64	-0.95	0.77
	Logistics	-0.45	0.45	-1.00
	Von Bertalanffy	0.51	-0.82	-0.82
	Negative exponential	-	-0.97	-
Female	Gompertz	-0.42	-0.71	0.85
	Brody	-0.61	-0.94	0.76
	Logistics	-0.23	-0.50	0.88
	Von Bertalanffy	0.48	-0.79	-0.83
	Negative exponential	-	-0.95	-

NF: normal feather; NN: naked neck; FF: frizzle feather; NE: not estimated.

3.6 Body weight at inflection, inflection time and relative growth rate

Body weight at inflection, inflection time and relative growth rate based on genotype and sex were shown in Table 8.

709.65 g and week 6.67 were predicted as body weight at inflection and inflection time by Logistics model for normal feather chickens. Also, 453 g to 547.06 g was predicted as body weight at inflection for male chickens while 411.08 g to 653.75 g was predicted as body weight at inflection for female chickens. For the three genotypes, a relative growth rate range of 0.00 to 0.78 was predicted by the five non-linear models with the lowest value predicted by Gompertz model for frizzle feather chickens.

Body weight at inflection, inflection time and relative growth rate based on interaction between genotype and sex were presented in Table 9. The body weight at inflection ranged from 2.99 g in male naked neck chickens by Von Bertalanffy model to 747.45 g in male normal feather chicken by Logistics model. Logistics model could not predict inflection time for female naked neck chickens.

Table 7: *Correlation among the growth model parameters based on interaction between genotype and sex*

GT	*Sex*	*Model*	*A and B*	*A and K*	*B and K*
NF	M	Gompertz	-0.48	-0.81	0.84
		Brody	-0.68	-0.97	0.78
		Logistics	-0.31	-0.62	0.87
		Von Bertalanffy	0.55	-0.87	-0.83
		Negative exponential	-	-0.98	-
NF	F	Gompertz	-0.44	-0.73	0.86
		Brody	-0.63	-0.95	0.77
		Logistics	-0.25	-0.52	0.88
		Von Bertalanffy	0.51	-0.80	-0.85
		Negative exponential	-	-0.96	-
NN	M	Gompertz	-0.43	-0.64	0.91
		Brody	-0.61	-0.92	0.77
		Logistics	-0.22	-0.42	0.91
		Von Bertalanffy	-0.99	-0.99	0.99
		Negative exponential	-	-0.96	-
NN	F	Gompertz	-0.43	-0.69	0.87
		Brody	-0.62	-0.94	0.77
		Logistics	-0.27	0.26	-0.99
		Von Bertalanffy	0.50	-0.78	-0.85
		Negative exponential	-	-0.97	-
FF	M	Gompertz	-0.40	-0.78	0.80
		Brody	-0.62	-0.96	0.74
		Logistics	0.04	NE	NE
		Von Bertalanffy	-0.99	-0.99	0.99
		Negative exponential	-	-0.97	-
FF	F	Gompertz	-0.34	-0.67	0.82
		Brody	0.99	-0.99	-0.99
		Logistics	0.05	NE	NE
		Von Bertalanffy	0.40	-0.75	-0.79
		Negative exponential	-	-0.95	-

GT: genotype; NF: normal feather; NN: naked neck; FF: frizzle feather; M: male; F: female; NE: not estimated.

3.7 Pairwise comparison between observed and expected predicted body weight

The pairwise comparison between observed and predicted body weight for the models were reported as sigmoid growth curves in Figures 1-11 (annex) while the residuals between the observed and the predicted weights were presented in Table 10.

For the normal feather chickens, Logistics model predicted a closer body weight values to the observed value in all the weeks. The worst predictions were gotten from Von Bertalanffy model.

For the naked neck chickens, Brody model predicted a closer body weight value to the observed values while the worst predictions were observed in Von Bertalanffy model and Logistics model. The worst prediction was observed in Gompertz model for fizzle feather chickens. For female chickens, the best prediction was observed in Gompertz model except at week 16.

Table 8: *Body weight at inflection (BWI), inflection time (IT) and relative growth rate (RGR) based on genotype and sex*

GT	*Model*	*BWI (g)*	*IT (weeks)*	*RGR*
NF	Gompertz	543.46	5.01	0.04
	Brody	DE	DE	0.04
	Logistics	709.65	6.67	0.02
	Von Bertalanffy	450.40	5.49	0.78
	Negative exponential	DE	DE	0.48
NN	Gompertz	500.92	4.59	0.02
	Brody	DE	DE	0.03
	Logistics	421.50	4.39	0.33
	Von Bertalanffy	413.39	4.40	0.76
	Negative exponential	DE	DE	0.40
FF	Gompertz	67.83	NE	0.00
	Brody	DE	DE	0.03
	Logistics	589.50	1.30	0.06
	Von Bertalanffy	420.30	5.23	0.78
	Negative exponential	DE	DE	0.42
Sex				
Male	Gompertz	547.06	4.95	0.02
	Brody	DE	DE	0.04
	Logistics	543.55	NE	0.60
	Von Bertalanffy	453.13	5.43	0.80
	Negative exponential	DE	DE	0.43
Female	Gompertz	497.72	4.55	0.04
	Brody	DE	DE	0.04
	Logistics	653.75	5.99	0.02
	Von Bertalanffy	411.08	4.92	0.76
	Negative exponential	DE	DE	0.47

GT: genotype; NF: normal feather; NN: naked neck; FF: frizzle feather; DE: Does not exist; NE: not estimated.

Table 9: *Body weight at inflection (BWI), inflection time (IT) and relative growth rate (RGR) based on interaction between genotype and sex.*

GT	*Sex*	*Model*	*BWI (g)*	*IT (weeks)*	*RGR*
NF	M	Gompertz	577.68	5.52	0.03
		Brody	DE	DE	0.04
		Logistics	747.45	7.19	0.01
		Von Bertalanffy	481.30	6.28	0.82
		Negative exponential	DE	DE	0.49
NF	F	Gompertz	522.32	4.79	0.03
		Brody	DE	DE	0.04
		Logistics	687.25	6.34	0.02
		Von Bertalanffy	431.05	4.99	0.77
		Negative exponential	DE	DE	0.50
NN	M	Gompertz	521.29	4.60	0.01
		Brody	DE	DE	0.02
		Logistics	686.95	5.67	0.01
		Von Bertalanffy	2.99	-27.46	-1.00
		Negative exponential	DE	DE	0.33
NN	F	Gompertz	487.54	4.62	0.04
		Brody	DE	DE	0.04
		Logistics	288.55	NE	0.50
		Von Bertalanffy	403.56	4.78	0.76
		Negative exponential	DE	DE	0.49
FF	M	Gompertz	545.70	4.88	0.02
		Brody	DE	DE	0.03
		Logistics	542.00	1.22	0.02
		Von Bertalanffy	11.64	-109.861	-1.00
		Negative exponential	DE	DE	0.41
FF	F	Gompertz	463.86	3.99	0.04
		Brody	DE	DE	0.05
		Logistics	493.75	1.18	0.04
		Von Bertalanffy	381.60	4.58	-0.75
		Negative exponential	DE	DE	0.48

GT: genotype; NF: normal feather; NN: naked neck; FF: frizzle feather; DE: Does not exist; NE: not estimated.

4 Discussion

The significant effect of genotype on body weight observed in this study revealed that genotypic differences existed in body weight of dual purpose FUNAAB Alpha chickens. The effects of sex as well as interaction between genotype and sex on body weight were only significant at week 16 and this implied that sexual dimorphism is only evident in dual purpose FUNAAB chickens at week 16. The values of body weight observed for FUNAAB Alpha chickens used in this study fall in the range reported by Bashiru *et al.* (2020). Higher body weight was observed by Ogunpaimo *et al.* (2020) in their study and this may be due to the line of FUNAAB Alpha chickens used, Ogunpaimo *et al.* (2020) used meat line FUNAAB Alpha chickens while dual purpose line was used in this study. The disparity observed in the body weight of the three genotypes could have implication on management decision of the dual purpose FUNAAB Alpha chickens and it can be suggested that the three genotypes should be reared separately.

Growth is explained mathematically by models that have parameters with biological interpretations. These parameters are used to describe growth pattern over time and to calculate the expected weight of animals at specific ages (Selvaggi *et al.*, 2015). Non-linear growth model parameters are also used in selecting the appropriate growth models. Predicted matured weight offered the best opportunity to make direct comparisons among models since other parameters such as constant of integration and coefficient of intensity of growth measure slightly different phenomena (Aggrey *et al.*, 2002). Matured body weight parameter represents the maximum growth response of the birds (Narinc *et al.*, 2010). There were some differences among estimated matured weight by the five mathematical non-linear models used in our study. The larger estimate of matured weight is generally associated with small estimate of coefficient of intensity of growth and this was corroborated with the negative correlation coefficients observed between matured weight and coefficient of

Table 10: *The residuals (g) for the growth models at different ages based on genotype and sex.*

		Growth models				
	Age (Weeks)	*Gompertz*	*Brody*	*Logistics*	*Von Bertalanffy*	*Negative exponential*
Genotype						
NF	1	-248.19	-89.99	-51.58	-2389.49	-42.46
	4	-243.73	-210.90	31.69	-1643.07	-71.43
	8	-106.13	-116.46	6.49	-858.83	64.90
	12	8.52	-7.15	5.58	-358.41	164.43
	16	-84.40	-140.17	-78.18	-262.75	-3.00
	20	40.82	-71.12	73.52	-56.41	22.41
NN	1	-255.20	-113.10	80.09	-2269.46	-67.06
	4	-243.79	-271.37	98.86	-1471.06	-147.28
	8	27.30	9.64	196.95	-522.34	151.25
	12	-84.83	-101.64	310.43	-302.78	11.39
	16	-62.95	-127.43	418.13	-156.50	-58.45
	20	90.45	-25.83	598.61	38.16	-1.84
FF	1	-0.97	-92.14	-275.05	-2164.49	-49.48
	4	397.41	-108.94	-698.49	-1379.03	6.03
	8	861.65	-14.39	-234.91	-664.26	111.94
	12	1056.66	-51.38	-39.90	-361.14	36.12
	16	1171.17	-82.46	74.61	-199.99	-54.05
	20	1353.92	8.92	257.36	2.89	-26.00
Sex						
Male	1	-18.10	29.14	108.75	4.23	-61.23
	4	-6.18	-85.36	-673.30	-22.88	-103.64
	8	59.91	78.42	-91.79	62.46	99.05
	12	-83.37	-24.30	84.47	-68.17	-2.00
	16	-2.86	12.78	307.88	-0.50	18.41
	20	37.33	-15.04	404.51	22.85	-33.58
Female	1	-6.74	26.76	-47.21	11.34	-60.11
	4	6.92	-69.13	37.3	-11.18	-83.22
	8	15.04	48.13	3.17	23.34	88.08
	12	8.95	67.09	-22.94	24.37	88.08
	16	-132.41	-124.29	-126.97	-132.44	-120.47
	20	81.75	27.87	111.87	66.60	9.23

NF: normal feather; NN: naked neck; FF: frizzle feather.

intensity of growth observed in this study. This was true for normal feather, naked neck and male chickens but not for frizzle feather chickens as the smallest growth intensity observed in Gompertz model has a small A value in frizzle feather chickens. This could have resulted from the fact that gene and environment which influence the slope of the weight-age curve or the asymptotic weight also influence the estimates of rate of maturing (Brown *et al.*, 1976). The highest constant of integration observed in Logistics model implied that the model predicted more weight gain after hatching in the birds when compared with other models though this didn't reflect in the mature weight predicted by this model.

The values obtained for constant of integration obtained in our study were similar to the ones obtained by Bashiru *et al.* (2020) with matured weight higher in Bashiru *et al.* (2020) work which may be due to the difference in location and sample size. There was also a similar pattern in the correlation coefficients value among the model parameters obtained for female chickens in this study and the one obtained by Bashiru *et al.* (2020). The higher matured weighed observed by Ogunpaimo *et al.* (2020) may be due to the line of FUNAAB Alpha chickens used as meat line was used by Ogunpaimo *et al.* (2020) in their study. Failure to converge of Logistics model for male, naked neck and frizzle feather chickens as well as Gompertz model for frizzle feather chickens maybe an indication of lack of usefulness of these two models in male and these two genotypes. These two models have some limitations in fitting weight-age data (Lopez de Torre *et al.*, 1992) in these genotypes of dual purpose FUNAAB Alpha chickens. Non-convergence of iterative solution is the greatest difficulty of some models due to negative correlation among their parameters (Lambe *et al.*, 2006). The lower number of iterations observed in the converged model implied that they are useful when describing growth in dual purpose FUNAAB Alpha chickens.

Modelling of growth in dual purpose FUNAAB Alpha chickens provides a technique for reducing the number of variables describing the growth of the birds. The value of any technique depends on the accuracy with which it describes the observed body weight (Brown *et al.*, 1976). Highest coefficient of determination observed in Gompertz and Von Bertalanffy models for the normal feather and naked neck chickens indicated overall good fits of the age-weight data in these genotypes using these two models. The coefficient of determination is a good measure of goodness of fit but some of the mathematical models have same value. To differentiate the models in order to pick the best fitting model, other goodness of fit measures were used. The Akaike's information criterion and Bayesian information criterion were also calculated to determine the best model because likelihood ratio tests tend to favour models with few parameters whereas these criteria penalize models with many parameters. Gompertz model had the lowest AIC, BIC, MSE and seemed to have the best fit for normal feather and naked neck chickens. The growth parameters estimated by Gompertz model have been reported by Barbato (1991) and Mignon-Grasteau *et al.* (1991) to be suitable for inclusion in genetic improvement programmes in chickens due to their medium-high values of heritability. Also the AIC and BIC reported in our study were higher than the ones reported by Bashiru *et al.* (2020) and Ogunpaimo *et al.* (2020) and these differences may be attributed to the sample size, location and line of FUNAAB Alpha used.

The highest coefficient of determination observed in Brody model suggested overall good fits of the age-weight data in frizzle feather chickens. The highest (R^2) indicated that the proportion of variation explained was high for the model when fitting the growth of frizzle feather dual purpose FUNAAB Alpha chickens. Brody model also had the lowest AIC, BIC, MSE and seemed to have the best fit for frizzle feather chickens. Based on coefficient of determination, any of the models could be used for the two sexes except Logistics model.

We also subjected the models to subjective approach (comparison of observed and predicted body weight values) as the tests of goodness of fit may be inaccurate. A subjective evaluation of the goodness of fit is useful in detecting systematic overestimation or underestimation of body weights at any specific time. Both Logistics and Negative exponential models fitted well for normal feather chickens than other models while Negative exponential model was the fittest among the models for naked neck and frizzle feather chickens. The Fit of different models varies over different time periods and this is an important consideration from the standpoint of choosing an appropriate model. A model which yields differences between predicted and actual weight and tends to alternate in sign at short intervals is preferable to a model which yields deviation and tends to alternate in sign at longer interval (Brown *et al.*, 1976). From all the observations and results derived from this study, it could be well understood that there is a relationship between the genotype and the growth model as different models fitted well for different genotypes of the dual purpose FUNAAB Alpha chickens. The usefulness of this study to the local farmers going into rearing practice is that the live weight of the birds can be determined right from their first week of age. This is done by inserting the age (in weeks) of the bird to the parameter t in the best fitting model for the genotype of interest. With the help of the models, farmers will be able to determine the attainable weight of the chicken at every point in time especially for marketing.

5 Conclusions

Based on goodness of fit, it can be concluded that Gompertz is most appropriate model for describing the growth of normal feather and naked neck while Brody model is best for frizzle feather chickens and also Von Bertalanffy for male chickens. From subjective approach (comparison of observed and predicted body weights), both Logistics and Negative exponential models fitted well for normal feather chickens while Negative exponential was the fittest among the models for naked neck and frizzle feather chickens and Gompertz for female chickens.

Supplement

The supplement related to this article is available online on the same landing page at: https://doi.org/10.17170/kobra-2021xxxxxxx .

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Conflict of interest

We certify that there is no conflict of interest with any financial, personal, or other relationships with other people or organisation related to the material discussed in the manuscript.

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