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RESEARCH ARTICLE

Predictive model evaluation for growth, feed intake and under-wing temperature in two broiler chicken strains under two housing conditions

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ABSTRACT

This study evaluated the performance of Arbor Acres Plus and Marshall chicken strains. The birds were reared under two management systems (without access or with access to pasture) in Nasarawa State, Nigeria in an 8-week trial. Data for body weight, primary feather length, under-wing temperature were collected weekly while feed intake was taken daily. Five mathematical models (3P and 4P Gompertz; 3P, 4P and 5P Logistic) were used to model the performance of birds using the J.M.P (SAS) software. Parameters used to evaluate the models were the adjusted coefficient of determination (Adj. R^2), Akaike's information criterion (AIC), Bayesian information criterion (BIC) and root mean square error (RMSE). The age of maximum growth rate for body weight, feather length, under-wing temperature and feed intake was four weeks. Overall, Logistic 4P with (without access to pasture; Adj R^2 of 0.959) and Gompertz 3P (with access to pasture; 0.894) were the best models for Marshall strain in the prediction of body weight while Logistic 4P model was the best for Arbor Acres Plus (Adj R^2 0.951 and 0.916, respectively). Also, in Marshall and Arbor Acres Plus, Logistic 4P outperformed others in the prediction of feather length. However, Logistic 4P and 5P appeared better than other models in both management systems for the prediction of under-wing temperature of Marshall while the performance of Gompertz 3P was better in Arbor Acres Plus. The feed intake of Marshall and Arbor Acres Plus in both management systems was better predicted by Logistics 3P. In conclusion, the present non-linear models may guide subsequent management decisions to improve the performance of the birds.

Keywords: Broilers, Strain, Pasture, Modelling, Growth.

INTRODUCTION

In the tropics, poultry production possesses the quickest potential to bridge the protein supply-demand gap (Yakubu *et al.*, 2010) and plays a formidable role in employment generation and as a source of revenue to both farmers and government. The modern commercial lines of broiler chickens have become more demanding in terms of housing, feeding, and handling conditions. This is due to the very rapid weight gains and very good feed conversion per kilogram weight gain (Skomorucha and Muchacka, 2007; Sanchez-Casanova *et al.*, 2021). There is a growing demand for the use of mathematical models in predicting the growth parameters in broiler chickens. Modelling in poultry production has a fundamental role in helping to maximize the system by producing high-precision estimates that may be applied by researchers and farmers (Júnior *et al.*, 2023). This will enable farmers to predict ahead the production and productivity of their farms thereby cutting wastage especially in feed allocation which accounts for more than 70% of the total cost of production. Body weight (BW) is a veritable measure of growth with its successive measurements forming a growth curve. Modelling BW is paramount because of the direct relationship between weight and feed consumption (Hagan *et al.*, 2022). Feather length can also be used as an indicator of growth (Chen *et al*., 2020).

A large body of literature aims at identifying growth models that fit best to given mass-at-age data (Kühleitner *et al.*, 2019). Growth curves are the most appropriate models for describing growth patterns and can be used to predict growth rate and estimate body weight or body part changes over time. Growth curves are sigmoidal with an inflection point where the rate of growth is maximal with an upper asymptote. Growth curve parameters have been widely exploited in poultry selection studies as they have been reported to be highly heritable (Raji *et al*., 2014; Mouffok *et al*., 2019) for the prediction of future growth at any age (Yakubu and Madaki, 2017). Mathematical models may help to define more appropriate feeding regimens in order to adequately address the high nutritional requirements during the various growth phases (Selvaggi *et al*., 2015). They can also be used for the improvement of feed conversion achieved primarily by reducing the growing period, which has been accomplished by selection for growth rate and feed conversion (Marks, 1995).

Linear and quadratic models are traditional regression approaches that have been applied in the poultry industry. However, their robustness is not enough and regression coefficients may be prone to large standard errors. According to Burnham and Anderson (2002), linear predictive equations may be biased in the estimation of parameters and inconsistent among the model selection algorithms. These days, models such as the Gompertz and Logistic amongst others are frequently used sigmoid models fitted to growth data (Aggrey, 2002; Selvaggi *et al*., 2015). In Nasarawa State, Nigeria, there is dearth of information on suitable growth models and appropriate housing design for broiler chickens. This study, therefore aimed at developing mathematical models for the prediction of body weight, feed intake, primary feather length and under-wing temperature in broiler chickens in Nasarawa State.

MATERIALS AND METHODS

Study Area

The experiment was carried out at the Livestock Unit of the Teaching and Research Farm of the Faculty of Agriculture, Shabu-Lafia Campus, Nasarawa State University, Keffi (NSUK), Nasarawa State, North Central Nigeria. The Farm is located within the Nasarawa South agro-ecological zone of the State. The geographical coordinates of the Farm are 8 29' 30" North, 8 31' 0" East, respectively. In the Guinee savanna zone of North central. It is found in latitude 08 – 33 E. The mean monthly minimum and maximum temperatures are 20.16ºC and 35.06ºC respectively while the mean monthly relative humidity and rainfall are 74.7% and 168-190mm respectively between July and September (NIMET, 2021).

Experimental Design

A total of two hundred (200) day-old chicks (DOC) comprising equal number of Arbor Acres Plus (Amo Brand) (100) and Marshall broilers (100) were used for the experiment. While Arbor Acres Plus was sourced from Amo Farms, Awe, Oyo State, Marshall Strain was purchased at Zartech Farm, Ibadan, Nigeria. 100 randomly selected birds were kept indoors without access to pasture while 100 birds were kept indoor but had access to pasture (*Mucuna pruriens*). Housing was in two forms: A standard poultry house without a run and standard poultry house with a run area. A 2x2 factorial experiment in a completely randomized design (CRD) was adopted. Each treatment group was replicated two times. There were 25 birds per replicate. The birds were randomly allocated to the experimental pens (14.3 birds/m^2) in a completely randomized design based on their strain and housing condition.

Experimental Birds' Management

All the birds in each system of housing were tagged individually and assigned an identification number. The initial weight of each bird that was housed on deep litter was taken. From day-old to 4 weeks of age, the birds were raised on starter ration (22.00% crude protein, 2,800 kcal/ kgME, 8.50% fat, 5.00% crude fiber, 1.20% calcium, and 0.45% phosphorus). From weeks 4 to 8 weeks, the birds were fed commercial broiler finisher ration, (20.00% crude protein, 2,900 kcal/kg ME, 8.60% fat, 5.40% crude fiber, 1.20% calcium, and 0.41% phosphorus). However, from week 5 to week 8, birds in the standard poultry house with a run had access to pasture. Routine vaccination and other management practices were strictly adhered to. There was also administration of antibiotics, vitamins and coccidiostat (Amprolium) in the drinking water when appropriate. Standard biosecurity measures were also strictly taken. International Council for Laboratory Animal Science and NC3Rs ARRIVE (Animals in Research: Reporting In Vivo Experiments) guidelines on research ethics were strictly followed. The trial lasted eight (8) weeks.

Data Collection

In both housing conditions, data were collected on weekly basis, on body weight of each bird using an electronic scale. Feed intake was measured daily by subtracting the amount of feed left from the known amount that was given and by dividing with the number of birds in each pen (feed intake/bird/day). The primary feather length of each selected bird was taken on a weekly basis using a measuring tape. Under-wing temperature of the selected birds was taken using a clinical thermometer.

Statistical Analysis

Growth models (3P and 4P Gompertz; 3P, 4P and 5P Logistics) were fitted to the measurements of actual body weight, primary feather length, under-wing temperature and feed intake related to age via a non-linear procedure of J.M.P. (SAS) statistical software (2021). The models' performances were compared based on the Adj. R^2, RMSE, AIC and BIC (Akinsola *et al*., 2021).

RESULTS

Growth curve parameters for body weight in Marshall strain

The estimated growth curve parameters for body weight of Marshall strain without access or with access to pasture are presented in Table 1 and Figures 1 and 2, respectively. The age of maximum growth rate was 4 weeks. Overall, based on the AIC, BIC and RMSE lower values, Logistic 4P with Adj. R^2 of 0.959 (without access to pasture) and Gompertz 3P with Adj R^2 of 0.894 (with access to pasture) were the best models for Marshall strain in the prediction of body weight. Gompertz 4P recorded the highest value of 0.960 (96%) for adjusted coefficient of determination (Adj. R^2) for Marshall strain without access to pasture whereas for Marshal strain with access to pasture, Logistics 5P model recorded the highest value of 0.895 (89.5%) for adjusted coefficient of determination (Adj. R^2).

Growth curve parameters for body weight in Arbor Acres Plus

The estimated growth curve parameters modeling of Arbor Acres Plus without access or with access to pasture is presented in Table 2 and Figures 3 and 4, respectively. The age of maximum growth rate was 4 weeks. Overall, based on the AIC, BIC and RMSE lower values, Logistic 4P with Adj. R^2 of 0.951 (without access to pasture) and Logistic 4P with Adj R^2 of 0.916 (with access to pasture) were the best models for Arbor Acres Plus in the prediction of body weight.

Table 1. Estimated growth curve parameters of Marshall strain without access and with access to pasture.

Model	a	b	c	d	e	Age and weight at inflection point	AIC	BIC	RMSE	Adj. R^2
Without Access										
Logistics 3P	0.44	8.67		4453.34		4.0;510.7064	4838.236	4853.965	124.640	0.959
Logistics 4P	0.29	15.62	-162.80	21080.87		4.0;530.4511	4831.519	4851.154	123.397	0.959
Logistics 5P	-0.29	32.10	11239.75	-162.86	224.66	4.0;530.3578	4833.577	4857.107	123.557	0.959
Gompertz 3P	0.09	0.09		20.61		4.0;520.7959	4832.954	4848.683	123.793	0.959
Gompertz 4P	0.02	164.99	-151.40	9.65		4.0;531.5372	4831.612	4851.247	123.412	0.960
With Access										
Logistics 3P	0.44	8.21		2890.95		4.0;388.8217	4979.517	4995.246	149.600	0.894
Logistics 4P	0.35	10.31	-70.31	4635.46		4.0;398.7626	4980.182	4999.817	149.527	0.894
Logistics 5P	1.99	8.33	-108.14	1625.19	0.14	4.0;397.1381	4981.495	5005.024	149.577	0.895
Gompertz 3P	0.10	18.12		19607.12		4.0;397.3158	4978.933	4994.662	149.487	0.894
Gompertz 4P	0.06	32.01	-50.50	100096.33		4.0;401.58	4980.601	5000.235	149.608	0.894

a=maturity index; b=scale parameter; c= asymptotic weight; d=upper asymptote; e=power; AIC=akaike information criterion; BIC=bayesian information criterion; RMSE=root mean square error; Adj. R^2=adjusted coefficient of determination.

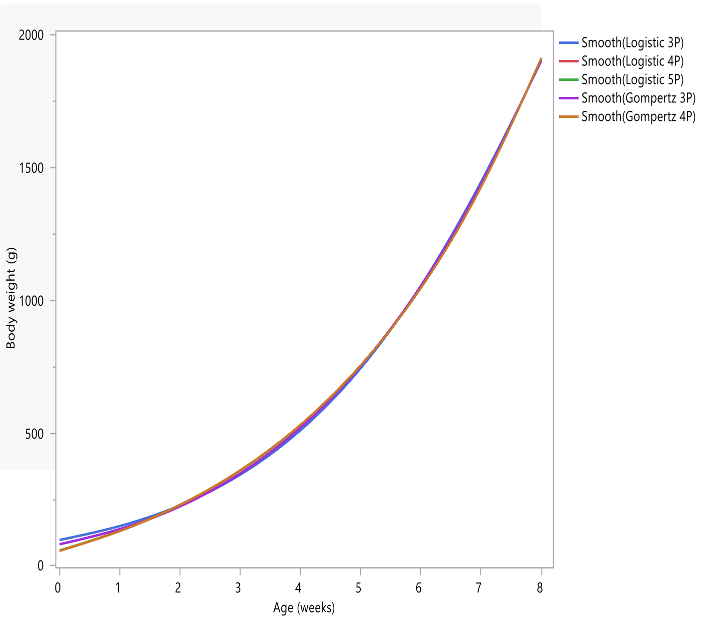

Figure 1. Estimated growth curve of Marshall without access to pasture

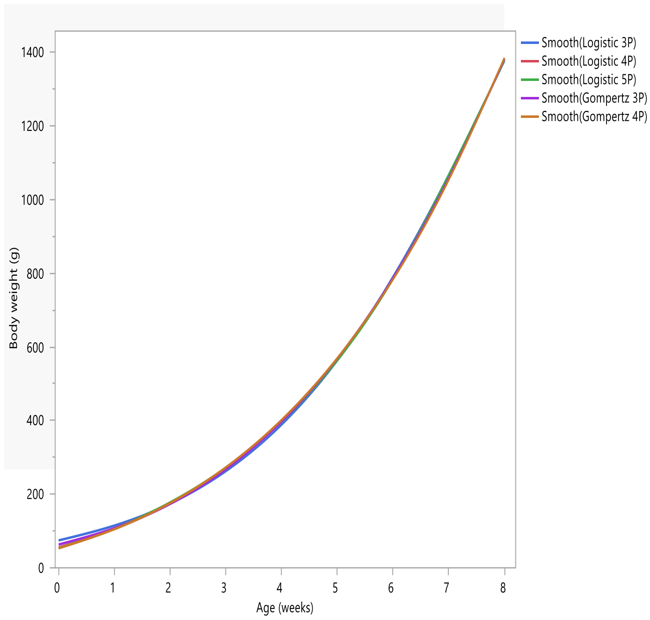

Figure 2. Estimated growth rate curve of Marshall with access to pasture

Table 2. Estimated growth curve modeling of Arbor Acres Plus without access and with access to pasture.

Model	a	b	c	d	e	Age and weight at inflection point	AIC	BIC	RMSE	Adj. R^2
Without Access										
Logistics 3P	0.38	10.52		6802.51		4.0;521.3273	5593.57	5609.831	136.621	0.948
Logistics 4P	0.26	39.75	-193.22	7652.52		4.0;540.4233	5570.82	5591.128	132.986	0.951
Logistics 5P	6.65	8.04	-378.17	1870.53	0.0321	4.0;568.6505	5604.189	5628.530	137.950	0.947
Gompertz 3P	0.06	31.56		154843.13		4.0;528.3952	5584.466	5600.730	135.219	0.949
Gompertz 4P	0.00	0.00	45.00	45.00		4.0;45	7257.810	7278.118	900.484	-1.268
With Access										
Logistics 3P	0.36	9.87		4027.33		4.0;435.2031	4871.569	4887.298	130.125	0.911
Logistics 4P	0.21	71.16	-246.78	7211.75		4.0;454.1546	4850.515	4870.149	126.463	0.916
Logistics 5P	-0.21	130.71	1.07	-249.964	13069.826	4.0;454.5364	4852.567	4876.096	126.626	0.916
Gompertz 3P	0.08	21.04		24481.784		4.0; 443.1864	4862.263	4877.992	128.570	0.913
Gompertz 4P	0.00	0.00	45.00	45.00		4.0;45	6147.323	6166.958	675.472	-1.393

a=maturity index; b=scale parameter; c= asymptotic weight; d=upper asymptote; e=power; AIC= akaike information criterion; BIC=bayesian information criterion; RMSE=root mean square error; AdjR^2=adjusted coefficient of determination

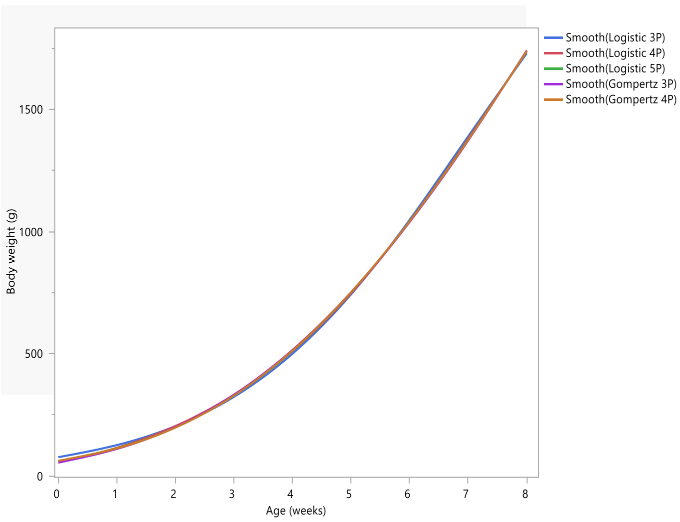

Figure 3. Estimated growth rate curve of Arbor Acres Plus with access to Pasture

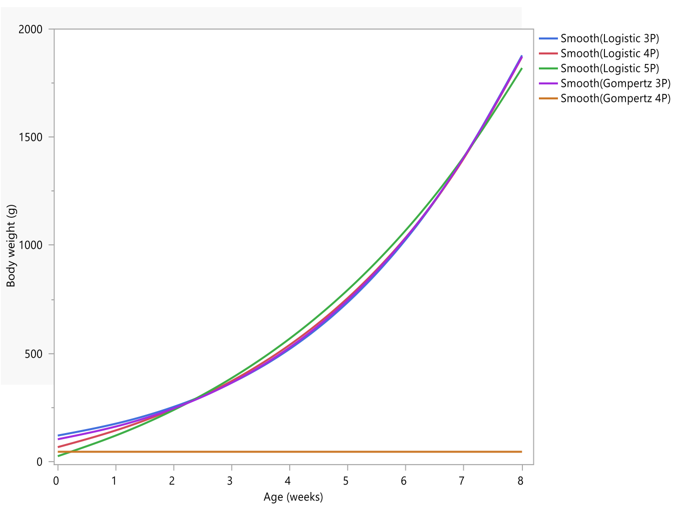

Figure 4. Estimated growth rate curve of Arbor Acres Plus without access to Pasture

Feather length curve parameters for Marshall strain

The result for the estimated feather length curve parameters of Marshall strain without access or with access to pasture is presented in Table 3 and Figures 5 and 6, respectively. The age of maximum growth rate was 4 weeks. Overall, based on the AIC, BIC and RMSE lower values, Logistic 4P with Adj. R^2 of 0.968 (without access to pasture) and Logistic 4P with Adj. R^2 of 0.988 (with access to pasture) were the best models for Amo Arbor Acres Plus in the prediction of feather length.

Feather length curve parameters for Arbor AcresPlus

The result for the estimated feather length curve modeling of Arbor Acres Plus without access or with access to pasture is presented in Table 4 and Figures 7 and 8. The age of maximum growth rate was 4 weeks. Overall, based on the AIC, BIC and RMSE lower values, Logistic 4P with Adj. R^2 of 0.985 (without access to pasture) and Logistic 4P with Adj. R^2 of 0.979 (with access to pasture) were the best models for Arbor Acres Plus in the prediction of feather length.

Wing temperature curve parameters of Marshall strain

The result for the estimated under-wing temperature curve modeling of Marshall strain without access or with access to pasture is presented in Table 5 and Figures 9 and 10. Adjusted coefficient of determination (Adj. R^2) for all models for the prediction of under-wing temperature of Marshall strain without access and with access to pasture were very low. However, Logistic 4P and 5P appeared better than other models in both management systems for the prediction of wing temperature of Marshall strain.

Table 3. Estimated feather length curve parameters of Marshall strain without access and with access to pasture.

Model	a	b	c	d	e	Age and weight at inflection point	AIC	BIC	RMSE	Adj. R^2
Without Access										
Logistics 3P	0.45	4.32		18.391		4.0;8.539912	1027.925	1043.654	0.907	0.961
Logistics 4P	0.001	-16783.36	-9.785e+8	2289.206		4.0;8.671462	960.189	979.823	0.830	0.968
Logistics 5P	0.001	-23444.81	-7.094e+9	1904.665	776.3667	4.0;8.672631	962.239	985.768	0.831	0.968
Gompertz 3P	0.23	3.90		22.989		4.0;6.49198	987.125	1002.854	0.861	0.966
Gompertz 4P	0.001	-6493.704	-347662.0	2292.738		4.0;6.7144	960.189	979.824	0.830	0.968
With Access										
Logistics 3P	0.47	3.85		18.57		4.0;9.618119	990.097	1005.826	0.864	0.969
Logistics 4P	0.05	-301.12	-53148.15	50.112		4.0;9.775242	789.093	808.727	0.665	0.982
Logistics 5P	-0.81	-57.42	50.112	-637.80	0.0572	4.0;9.775243	791.156	814.686	0.666	0.982
Gompertz 3P	0.26	3.14		21.598		4.0;9.74771	898.854	914.583	0.768	0.975
Gompertz 4P	0.002	-6943.85	-1.26e+10	792.85		4.0;9.50275	834.514	854.148	0.706	0.979

a=maturity index; b=scale parameter; c= asymptotic weight; d=upper asymptote; e=power; AIC= akaike information criterion; BIC=bayesian information criterion; RMSE=root mean square error; Adj. R^2=adjusted coefficient of determination

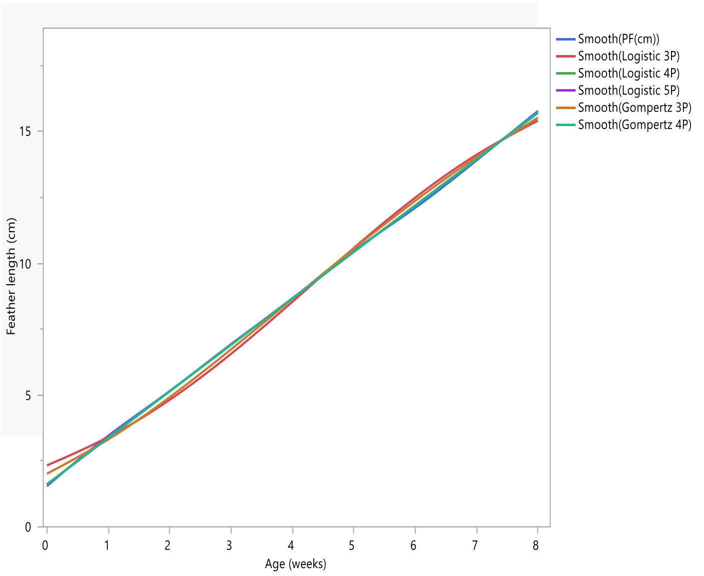

Figure 5. Estimated growth rate curve of Marshall feather length without access to pasture

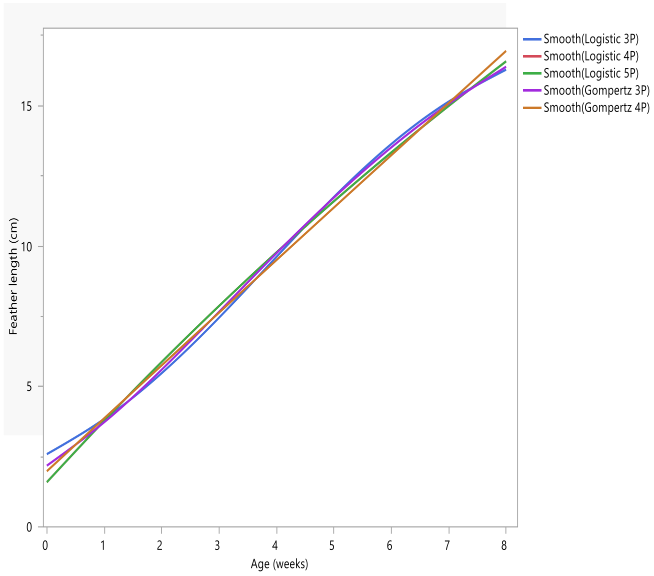

Figure 6. Estimated growth rate curve of feather length of Marshall with access to pasture

Table 4. Estimated feather length curve parameters of Arbor Acres Plus without access and with access to pasture.

Model	a	b	c	d	e	Age and weight at inflection point	AIC	BIC	RSME	Adj. R^2
Without Access										
Logistics 3P	0.49	4.20		18.504		4.0;8.789634	944.161	960.425	0.702	0.980
Logistics 4P	0.18	3.67	-14.02	30.577		4.0;8.913983	824.126	844.433	0.612	0.985
Logistics 5P	0.39	9.75	-41.70	23.714	0.109	4.0;8.9035	825.867	850.208	0.612	0.985
Gompertz3P	0.25	3.75		22.76		4.0;8.907608	862.426	878.691	0.640	0.983
Gompertz4P	0.12	3.50	-8.11	35.518		4.0;8.917802	824.426	844.733	0.612	0.985
With Access										
Logistics 3P	0.47	4.07		18.338		4.0;9.018029	920.247	935.879	0.812	0.972
Logistics 4P	0.02	-669.42	-1.083e+8	97.270		4.0;9.149623	801.033	820.547	0.692	0.979
Logistics 5P	0.02	-1495.84	-4.199e+8	101.985	2058812.3	4.0;9.086203	855.127	870.760	0.745	0.976
Gompertz3P	0.25	3.51		22.107		4.0;9.132692	855.127	870.760	0.745	0.976
Gompertz4P	0.02	-104.27	-938.99	93.274		4.0;9.149671	801.048	820.561	0.692	0.979

a=maturity index; b=scale parameter; c= asymptotic weight; d=upper asymptote; e=power; AIC= Akaike information criterion; BIC=Bayesian information criterion; RSME=Root means square error; Adj. R^2=adjusted coefficient of determination

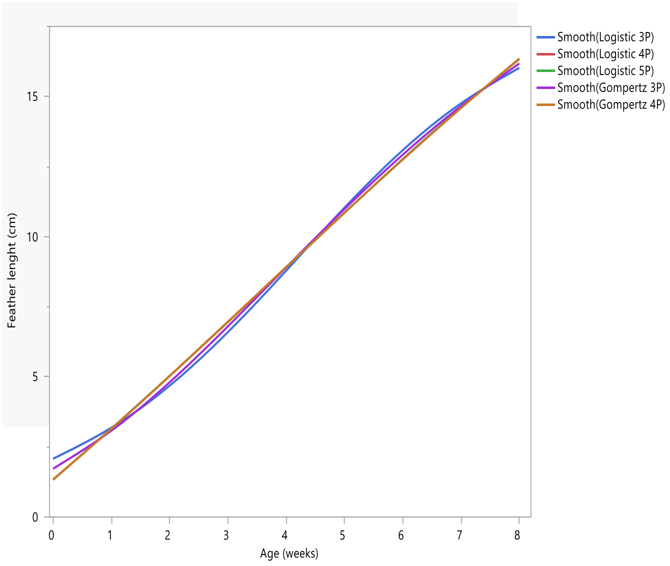

Figure 7. Estimated feather length curve of Arbor AcresPlus without access to pasture

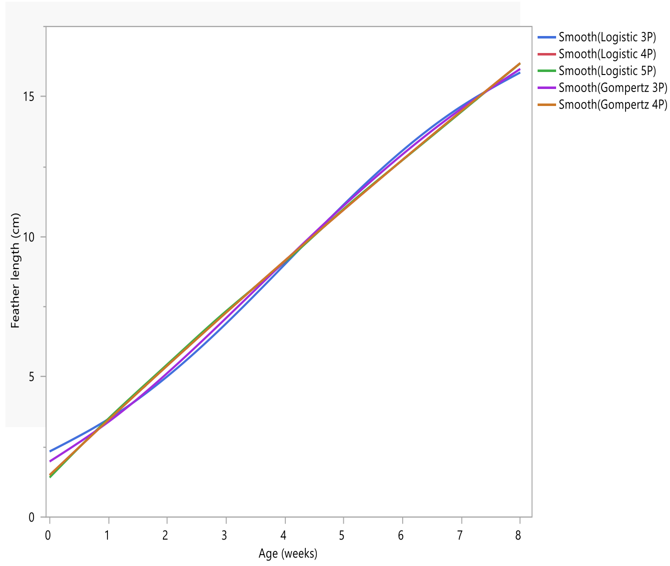

Figure 8. Estimated feather length curve ofArbor AcresPlus with access to pasture

Table 5. Estimated under-wing temperature curve parameters of Marshall strain without access or with access to pasture.

Model	a	b	c	d	e	Age and weight at inflection point	AIC	BIC	RSME	Adj. R^2
Without Access										
Logistics 3P	0.15	-17.86		41.657		4.0;40.27759	1190.551	1206.280	1.119	0.200
Logistics 4P	0.66	2.87	39.02	40.909		4.0;40.30093	1191.176	1210.811	1.119	0.204
Logistics 5P	7.12	6.20	4.60	40.819	0.001	4.0;40.24825	1192.195	1215.724	1.119	0.206
Gompertz 3P	0.15	-18.70		41.69		4.0;40.27722	1190.567	1206.296	1.119	0.201
Gompertz 4P	0.46	2.38	39.17	40.99		4.0;40.30346	1191.490	1211.124	1.119	0.203
With Access										
Logistics 3P	0.43	-4.24		43.70		4.0;42.50718	3933.504	3949.598	25.143	0.005
Logistics 4P	19.77	4.08	39.24	44.65		4.0;40.09361	3933.229	3953.322	25.104	0.010
Logistics 5P	138.03	4.19	39.41	44.65	44.649	4.0;39.41234	3935.331	3959.414	25.135	0.011
Gompertz 3P	0.41	-4.65		43.71		4.0;42.4934	3933.522	3949.616	25.144	0.005
Gompertz 4P	0.39	-17.06	-4637.32	43.73		40;42.47936	3935.588	3955.681	25.174	0.005

a=maturity index; b=scale parameter; c= asymptotic weight; d=upper asymptote; e=power; AIC= Akaike information criterion; BIC=Bayesian information criterion; RSME=Root means square error; Adj. R^2=adjusted coefficient of determination.

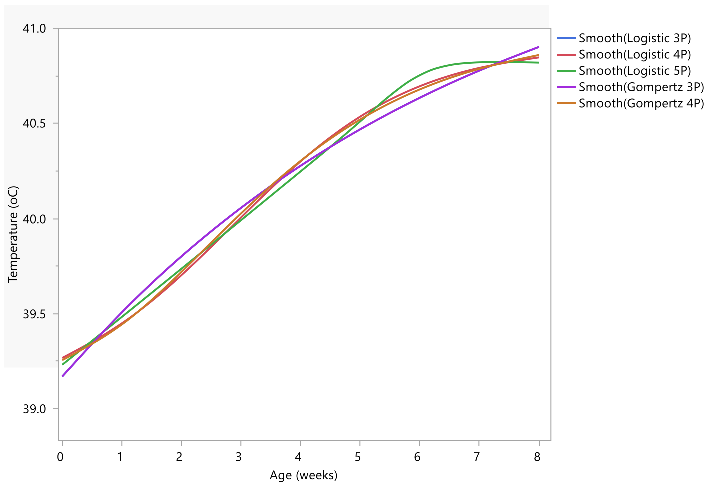

Figure 9. Estimated wing temperature curve of Marshall strain without access to pasture

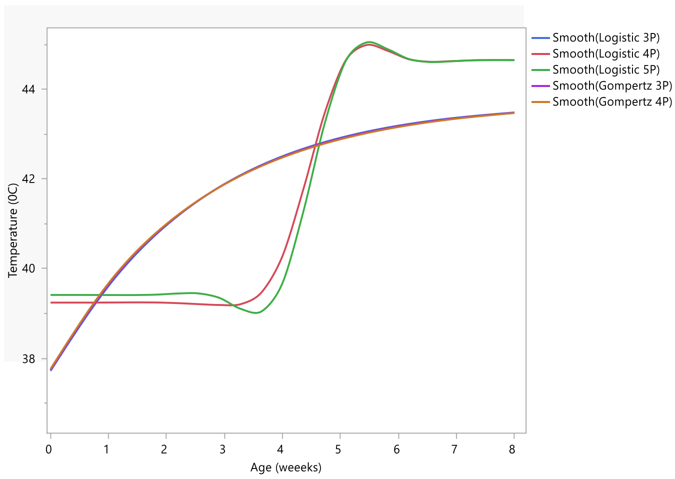

Figure 10: Estimated wing temperature curve of Marshall strain with access to pasture

Under-wing temperature curve parameters of Arbor Acres Plus

The result for the estimated under-wing temperature of Arbor Acres Plus without access or with access to pasture is presented in Table 6 and Figures 11 and 12, respectively. The age of maximum growth rate was 4 weeks. Overall, based on the AIC, BIC and RMSE lower values, Gompertz 3P with Adj. R^2 of 0.816 (without access to pasture) and Gompertz 3P with Adj R^2 of 0.853 (with access to pasture) were the best models for Arbor acres strain in the prediction of wing temperature.

Feed intake curve parameters of Marshall strain

The result for the estimated feed intake curve parameters of Marshall strain without access or with access to pasture is presented in Table 7 and Figures 13 and 14, respectively. The age of maximum growth rate was 4 weeks. Adjusted coefficient of determination (Adj. R^2) for all models for the prediction of estimated feed intake/bird of Marshall strain without access and with access to pasture were very low. However, based on the AIC, BIC and RMSE lower values, Logistics 3P with Adj. R^2 of 0.361 (without access to pasture) and Logistics 3P with Adj. R^2 of 0.228 (with access to pasture) were the best model for Marshall strain in the prediction of feed intake.

Feed intake curve parameters of Arbor Acres Plus

The result for the estimated daily feed intake/ bird curve modeling of Arbor Acre Plus without access or with access to pasture is presented in Table 8 and Figures 15 and 16. Adjusted coefficient of determination (Adj. R^2) for all models for the prediction of estimated feed intake of Arbor acre without access and with access to pasture were very low. However, Logistics 3P with Adj. R^2 of 0.325 (without access to pasture) and Logistics 3P with Adj. R^2 of 0.198 (with access to pasture) were the best models for Arbor Acres Plus in the prediction of feed intake.

Table 6. Estimated wing temperature curve parameters of Arbor Acres Plus without access or with access to pasture.

Model	a	b	c	d	E	Age and weight at inflection point	AIC	BIC	RMSE	Adj. R^2
Without Access										
Logistics 3P	0.07	-23.99		46.078		4.0;40.02247	528.979	545.243	0.438	0.816
Logistics 4P	0.05	-239.59	-131.870	47.136		4.0;40.02266	530.941	551.248	0.439	0.816
Logistics 5P	0.05	-444.29	-100.185	47.137	34983.676	4.0;40.02264	532.996	557.337	0.439	0.816
Gompertz 3P	0.06	-28.23		46.550		4.0;40.02257	528.936	545.201	0.438	0.816
Gompertz 4P	0.00	0.00	37.5	37.5		4.0;37.50000	2126.535	2146.842	2.678	-5.848
With Access										
Logistics 3P	0.17	-15.09		41.629		4.0;40.07843	279.769	298.228	0.290	0.853
Logistics 4P	0.16	-103.73	-393.211	41.682		4.0;40.07918	279.366	302.427	0.290	0.853
Logistics 5P	0.16	-140.95	-358.000	41.681	396.368	4.0;40.07924	281.397	309.054	0.290	0.853
Gompertz 3P	0.164	-15.83		41.654		4.0;40.07882	278.558	297.017	0.290	0.853
Gompertz 4P	0.143	-115.029	-458.142	41.853		4.0;40.06739	280.240	303.300	0.290	0.853

a=maturity index; b=scale parameter; c= asymptotic weight; d=upper asymptote; e=power; AIC= akaike information criterion; BIC=bayesian information criterion; RSME=root mean square error; Adj. R^2=adjusted coefficient of determination.

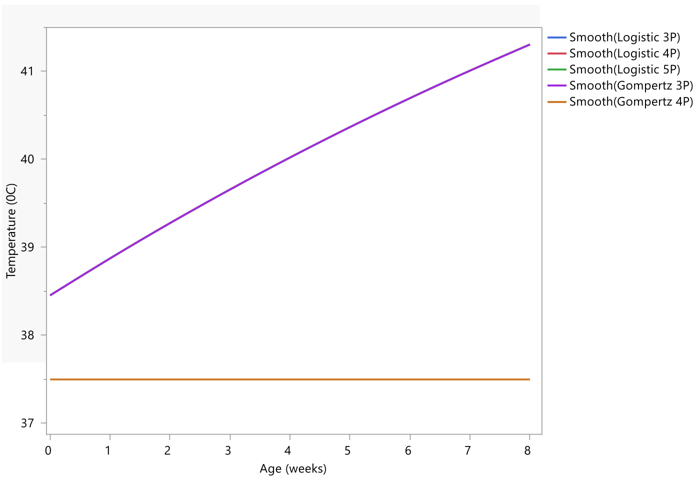

Figure 11: Estimated wing temperature curve of Arbor Acres Plus without access to pasture

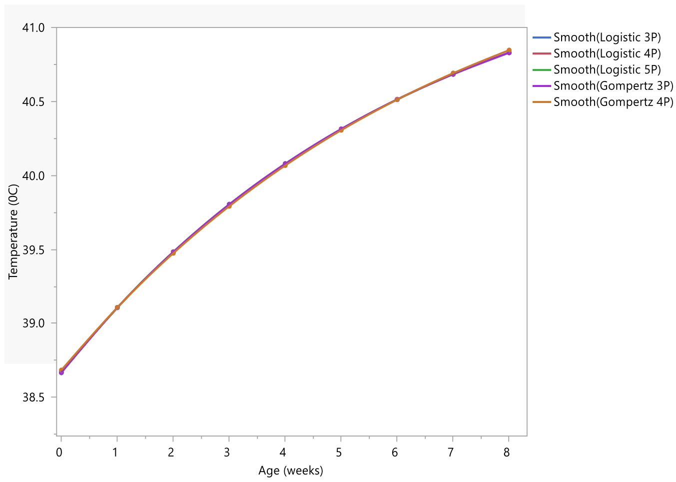

Figure 12. Estimated wing temperature curve of Arbor Acres Plus with access to pasture

Table 7. Estimated feed intake curve parameters of Marshall strain without access and with access to pasture.

Model	a	b	c	d	e	Age and weight at inflection point	AIC	BIC	RSME	Adj. R^2
Without Access										
Logistics 3P	0.07	-11.30		305.245		4.0;223.6596	117.987	116.098	11.834	0.361
Logistics 4P	0.37	3.45	198.356	244.379		4.0;223.6933	123.036	118.731	12.409	0.361
Logistics 5P	0.30	-18.64	206.131	246.122	664.969	4.0;223.7274	129.534	121.369	13.080	0.361
Gompertz 3P	0.05	-16.90		322.955		4.0;223.6568	117.987	116.099	11.834	0.361
Gompertz 4P	0.30	3.33	206.143	246.126		4.0;223.7275	123.034	118.730	12.408	0.361
With Access										
Logistics 3P	0.14	-5.73		92.2000		4.0;72.93621	109.282	107.394	8.672	0.228
Logistics 4P	2.49	3.59	67.075	76.984		4.0;74.34584	114.054	109.750	9.004	0.243
Logistics 5P	1.64	-1.26	67.215	77.189	1941.661	4.0;74.22785	120.539	112.373	9.486	0.244
Gompertz 3P	0.10	-8.44		95.811		4.0;72.92162	109.285	107.397	8.673	0.228
Gompertz 4P	1.64	3.36	67.21	77.189		4.0;74.22782	114.039	109.734	8.999	0.244

a=maturity index; b=scale parameter; c= asymptotic weight; d=upper asymptote; e=power; AIC= akaike information criterion; BIC=bayesian information criterion; RMSE=root mean square error; Adj. R^2=adjusted coefficient of determination.

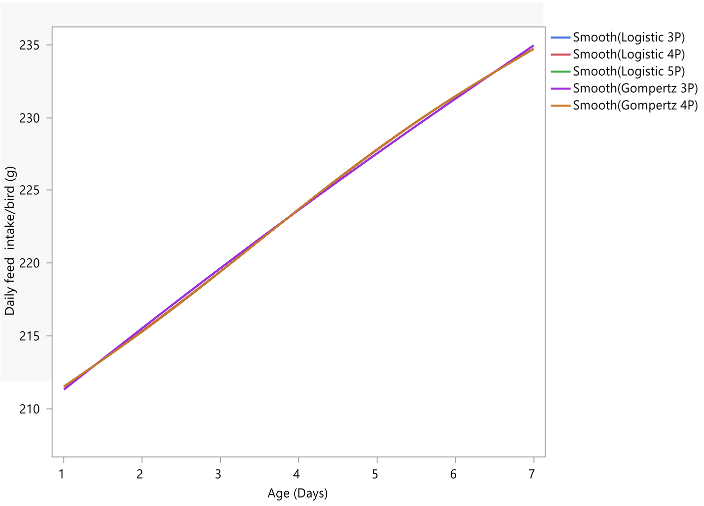

Figure 13: Estimated feed intake curve of Marshall without access to pasture

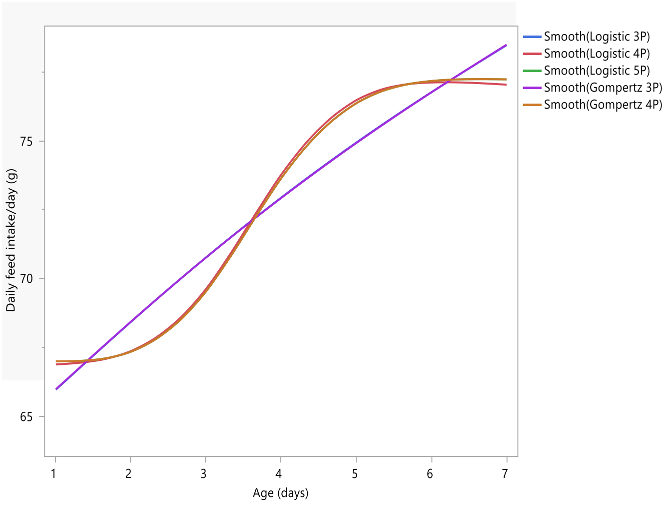

Figure 14. Estimated feed intake curve of Marshall with access to pasture

Table 8. Estimated feed intake/ bird curve modeling of Arbor Acres Plus without access and with access to pasture.

Model	a	b	c	d	e	Age and weight at inflection point	AIC	BIC	RSME	Adj. R^2
Without Access										
Logistics 3P	0.08	-12.02		247.272		4.0;196.6072	116.195	114.307	11.101	0.325
Logistics 4P	0.72	3.62	182.928	207.328		4.0;196.7984	121.200	116.895	11.622	0.327
Logistics 5P	-2.02	2.03	212.097	186.034	0.139	4.0;197.0282	127.685	119.519	12.244	0.328
Gompertz 3P	0.07	-16.25		255.320		4.0;196.6008	116.196	114.308	11.101	0.325
Gompertz 4P	0.54	3.34	185.704	208.249		4.0;196.9136	121.192	116.887	11.618	0.328
With Access										
Logistics 3P	0.32	-3.36		90.144		4.0;82.25819	116.614	114.726	11.268	0.198
Logistics 4P	1.28	2.80	71.265	85.950		4.0;83.35975	121.599	117.295	11.789	0.202
Logistics 5P	1.14	-4.03	72.811	85.918	1963.885	4.0;83.53520	128.068	119.903	12.413	0.203
Gompertz 3P	0.281	-4.23		90.712		4.0;82.23170	116.618	114.729	11.270	0.197
Gompertz 4P	1.14	2.60	72.812	85.919		4.0;83.53515	121.568	117.264	11.776	0.203

a=maturity index; b=scale parameter; c= asymptotic weight; d=upper asymptote; e=power; AIC= akaike information criterion; BIC=bayesian information criterion; RMSE=root mean square error; Adj. R^2=adjusted coefficient of determination.

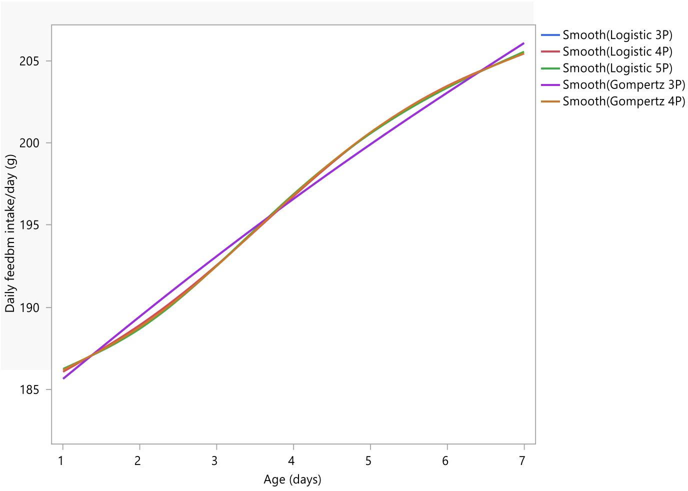

Figure 15. Estimated feed intake curve of Amo Arbor Acres Plus without access to pasture

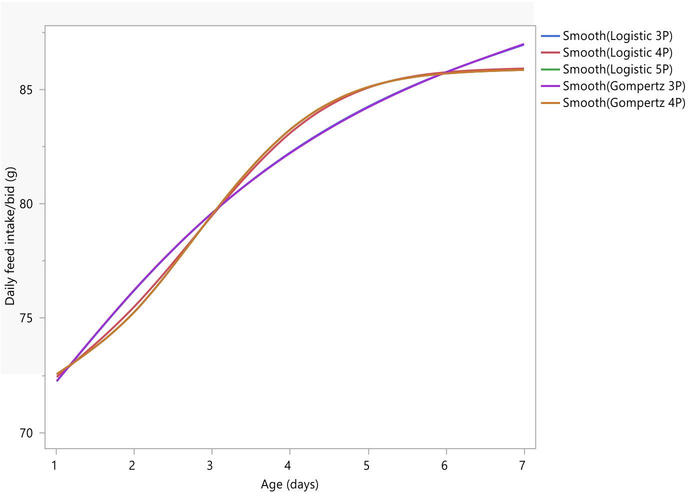

Figure 16. Estimated feed intake curve of Amo Arbor Acres Plus with access to pasture

DISCUSSION

Body weight changes over time can be described using growth models. This allows the information from longitudinal measurements to be combined into a few parameters with better biological interpretation (Afrouziyeh *et al*., 2021). The lowest AIC, BIC and RMSE values obtained in the current study explain better the change in body weight of the birds. This is in agreement with the results of Zárate-Contreras *et al*. (2022). Such low AIC, BIC and RMSE values will help in choosing the appropriate model. The range of Adj. R^2values recorded for Marshall strain and Arbor Acres Plus (without access and without access to pasture) in the present study are comparable to the range of 93.1% to 99.9%earlier reported (Safari *et al*., 2021; Quintana-Ospina *et al*., 2023). Selvaggi *et al*. (2015) found that Gompertz function fitted live weight data very well in chickens, being the best model for studying the growth of birds. Koushandeh *et al*. (2019) showed that the performance prediction of broiler chicks using the Gompertz function (R^2 =0.9989) was more accurate than the artificial neural network (R^2 = 0.95839). In a related study, Mancinelli *et al*. (2023) reported that the growth performance of chickens could be accurately predicted with Gompertz parameters. Also, Abe *et al*. (2022) reported that the output of predicted growth curve was more consistent in Logistic and Gompertz models.The age at inflection point was 4 weeks (28 days) in the present study. However, it is lower than the 32 days (Freitas *et al*., 2023) and 31 days (Nogueira *et al*., 2019) reported for broiler chickens. The maturity index varied with respect to the strain, management system and model used in the present study. This is congruous to the submission of Safari *et al*. (2021), where growth rate differed between strains and the Gompertz and Logistic functions.It has been reported that a low rate of maturation depicts delayed maturity while a high value is an indication of accelerated maturity (Aggrey, 2002; Adenaike *et al*., 2017; Mata-Estrada *et al*., 2020).

The differential feather length curves in Arbor Acres Plus and Marshall strain are in agreement with the report of Noubandiguim *et al*. (2021) where the length of the primary feathers significantly differed among the broiler pure lines through eight weeks old. The 0.001-0.05 (Logistic 4P) and 0.001-0.002 (Gompertz 4P) maturity index in Marshall strain and 0.02-0.18 (Logistic 4P) and 0.12 (Gompertz 4P) maturity index in Arbor Acres Plus in the two management systems can be compared with a wide range of rates of maturing (0.0250-0.0907/d) obtained by Vargas *et al*. (2020) in commercial broilers. The under-wing temperature has been reported to correlate with primary feather length (Noubandiguim *et al*. 2021). However, it was better predicted in Arbor Acres Plus than in Marshall strain in the present study. The age at inflection point was also 4 weeks (28 days) for both under-wing temperature and primary feather length in both strains and management systems. The Adj. R^2 values of the prediction models for daily feed intake/bird were low. This may not be unconnected with the fact that data for grouped birds were used. It is possible that better prediction models would be obtained if feed intake is taken from individual birds.

An opportunity to make selection strategies by changing feeding practices or genetic make-up of growth curve shape can be provided by the growth curve parameters (slower early growth and faster late growth) (Selvaggi *et al*., 2015; Hagan *et al*., 2022). Therefore, the estimated growth parameters obtained in the present study could be appropriately included in genetic improvement programme. This is in consonance with the submission of Zárate-Contreras *et al*. (2022) that growth models are important in chickens for management decisions and genetic improvement. Similarly, Nematzadeh *et al*. (2022) reported that genetic improvement of chickens for rapid growth rate could be achieved by fitting growth curve parameters in the selection index. However, the varying growth parameters obtained in the current study and the previous ones could be attributed to genetics, nutrition, management system, sex, ecology and climatic condition and model.

CONCLUSION

The models used in the present study were able to predict (with varying accuracy) the body weight, feed intake, feather length and wing temperature of Marshall and Arbor Acres Plus broiler chickens reared in two management systems. Overall, Logistic 4P (without access to pasture) and Gompertz 3P (with access to pasture) were the best models for Marshall strain in the prediction of body weight while Logistic 4P model was the best for Arbor Acres Plus. Also, Logistic 4P performed better than others in the prediction of feather length in Marshall and Arbor Acres Plus. However, Logistic 4P and 5P appeared better than other models in both management systems for the prediction of wing temperature of Marshall while the performance of Gompertz 3P was better in Arbor Acres Plus. Logistics 3P was found as best model to predict feed intake of Marshall and Arbor Acres Plus in both management systems. The optimal models obtained in this study may be used by farmers to work out the best feeding to improve the performance of the birds.

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