Modeling the growth of four commercial broiler genotypes reared in the tropics

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Abstract
Genetic improvement in commercial broilers worldwide is heavily focused on selection for higher final body weight at a given age. Although commercial broilers are mostly sold by their final body weight, it is important to carefully consider how this weight is attained and at what cost. The cost of feeding broilers, which constitutes about 70% of the total cost of broiler production, varies considerably at different stages of the bird. Careful consideration of the growth curve of broilers and the parameters of the growth curve is critical to optimize profitability of commercial broiler production. The objective of this study was to model the variations of the growth curves of 4 commercial broiler genotypes reared in Ghana using the Gompertz and polynomial growth functions. Data on body weights at 1, 7, 14, 21, 28, 35, and 42 days for 4 unsexed commercial broiler genotypes were used to model both the Gompertz and polynomial growth functions. The 4 genotypes ranked differently for Gompertz predicted early (1-28 days), late growth (28–42 days), and body weight at 42 days. Gompertz function predicted growth better for broiler chicken than the polynomial as the parameters of the Gompertz function are biologically meaningful and heritable. Selection of broiler genotypes for production based on their growth curve (slower early growth and faster late growth) could minimize cost of production and thereby increase the profitability of commercial broiler production in the tropics.

Keywords  Gompertz function · Polynomial function · Body weight · Growth · Ghana

Introduction
The rate of genetic improvement in poultry is relatively faster than most livestock species due to their short generation interval and higher reproductive rate. The global broiler breeding industry, over the years, has focused on genetic improvement of growth through selection for higher body weight and feed conversion rate at a fixed age (Anthony 2007; Siegel and Dunnington 1987). The extensive genetic modification of the body weight of broilers has partly contributed to some adverse effects on the birds such as increased feed intake (Barbato et al. 1983), body fat (Griffith 1996; Katanbaf et al. 1988), and a general decrease in reproductive performance of broiler parents (Barbato 1999; Dunnington and Siegel 1985; Pollock 1999). In addition, there are also problems of ascites (Pakdel et al. 2005) and leg lameness (Kestin et al. 2001) which have been attributed to selection solely for increased body weight or growth rate. Havenstein et al. (2003) reported that fat in 43-day-old broilers accounted for about 10-15% of total carcass weight.

In broiler breeding, growth or live body weight at usually 38 or 42 days of age is considered traits of interest in selective breeding programs (Dixon 2020). The selection of animals on only superior body weight at a fixed age may be partly deceptive as this does not give information on how the weight was attained (Anthony et al. 1991). The growth curve of an animal could give information on how it attained its body weight and at what cost. Variations in the growth curve could have implication on the maintenance cost of a given animal and the eventual profitability of keeping such an animal. For instance, the financial cost of maintaining an animal that has a slower growth early in life and subsequently picks up later in life is quite lower than a rapidly fast-growing animal at an earlier age. This is because the
metabolic activity of a slower-growing animal is not as high as the later; hence, the cost of feeding the former is relatively low. It is therefore important not to select meat-type chickens using only their final body weight without taking into account their growth curve.

Selection for growth curve parameters can be employed to solve some of the problems associated with selection for final body weight since the mathematical parameters of the growth curve have moderate heritability (Barbato 1991) and could be used to change the growth trajectory of broilers.

A variety of logistic, polynomial, and other sigmoidal curves have been fitted to the growth curves of chickens (Bashiru et al. 2020; Grossman and Bohren 1982; Narinç et al. 2017; Osei-Amponsah et al. 2014). The Gompertz equation has been reported to have a best fit with its parameters being biologically meaningful (Aggrey 2002; Ricklefs 1985). Other importance of mathematical growth functions are prediction of the daily energy, protein, and mineral dietary requirements of birds; appropriate slaughter age; and age of sexual maturity (Kaplan and Gürcan 2018). The objective of this study was to model the variations of the growth of four commercial broiler chicken genotypes reared in Ghana using the Gompertz and polynomial growth functions. The outcome of this work may be useful to industry, research, and education.

Materials and methods

Study area

The study was conducted on the Katamanso station of the Animal Research Institute of the Council for Scientific and Industrial Research (CSIR-ARI). The area is located at latitude 5° 44′ and longitude 0° 8′ in the Accra Plains of Ghana. The annual rainfall ranges from 600 to 1000 mm and the mean annual temperature is between 20 and 34°C.

Genotypes and husbandry

Four exotic commercial broiler chicken genotypes marketed in Ghana, namely Ross 308, Cobb 500, Hybro, and Cobb 700 designated as genotypes A, B, C, and D, respectively, were obtained from hatcheries as unsexed day old chicks. Two hundred (200) chicks of each genotype were wing-banded, weighed, and randomly placed into 16 floor pens covered with wood shavings in groups of 50 thus constituting 4 replicates per stock. Genotypes were not intermingled in a pen. Chicks were fed a starter diet of 12.12 MJ/kg Metabolisable energy and 23% crude protein for 3 weeks, followed by a finisher diet 13.2 MJ/kg of Metabolisable energy and 19.98% crude protein until the end of the experiment when broilers were 6 weeks of age. Both feed and water were provided for ad libitum access.

Data

The body weights of each of the four unsexed broiler genotypes were recorded at 1, 7, 14, 21, 28, 35, and 42 days of age. The observed body weights of the broiler genotypes were analyzed for the mean body weights at 28 and 42 days of age. These traits are important in the broiler industry as broiler chickens are usually fed on finisher diet from 28 days onwards and experience their late growth from that period and are finished at 42 days of age.

Growth functions

The Gompertz and polynomial growth functions were used to describe the growth patterns of the four commercial broiler genotypes marketed in Ghana. Each growth function was fitted to the body weights of each bird at 1, 7, 14, 21, 28, 35, and 42 days of age to estimate the predicted body weights of the birds. The Gompertz predicted mean body weights at 28 and 42 days of age for each bird in each genotype were then estimated.

Observed and Gompertz predicted early and late growths for each individual bird of the four broiler chicken genotypes were computed by the formulae below:

\[ \text{Observedearlygrowth(grams)} = \text{BW}_{28} - \text{BW}_1 \]
\[ \text{Observedlategrowth(grams)} = \text{BW}_{42} - \text{BW}_{28} \]

where \( \text{BW}_1, \text{BW}_{28}, \) and \( \text{BW}_{42} \) are the observed body weights of broiler chickens at days 1, 28, and 42, respectively.

\[ \text{Gompertzearlygrowth(grams)} = \text{GBW}_{28} - \text{GBW}_1 \]
\[ \text{Gompertzlategrowth(grams)} = \text{GBW}_{42} - \text{GBW}_{28} \]

where \( \text{GBW}_1, \text{GBW}_{28}, \) and \( \text{GBW}_{42} \) are the Gompertz predicted body weights of broiler chickens at days 1, 28, and 42, respectively.

Broiler genotypes were then ranked based on the observed and Gompertz predicted early and late growths. The Gompertz predicted growth curve parameters for each of the birds were estimated using the Microsoft Excel Macros (Microsoft Corporation 2013). The Gompertz function was used to describe the age-weight relationships for each bird. In the function, the body weight of the \( t \)th animal at the \( t \)th age was computed as (Aggrey 2002)

\[ \text{BW}_{it} = A_i \times \exp (-Bi(\exp (-Ki))) \]

where \( \text{BW}_{it} = \) body weight of the \( i \)th broiler at time \( t \),
\( A = \) asymptotic final body weight of the \( i \)th broiler,
\( B = \) transformed initial body weight of the \( i \)th bird,
\( K = \) rate of growth.

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The estimated values of the Gompertz parameters (A, B, and K) of each of the birds of the genotypes, BW28, BW42, GBW28, and GBW42 were analyzed using general linear model procedure of SAS version 9.4 (SAS 2013) with Model 1 below:

\[ Y_{ij} = \mu + G_i + e_{ij} \]  
(Model 1)

where \( Y_{ij} \) = observation on a bird in the \( i \)th genotype (A, B, K, BW28, BW42, GBW28, or GBW42);

\( G_i \) = fixed effect of the \( i \)th genotype;

\( e_{ij} \) = the random residual \( \sim N(0, \sigma^2_e) \) where \( \sigma^2_e \) is the residual variance.

Differences between means were separated using Tukey’s test.

Pearson correlations among observed body weights at 28 and 42 days of age and the parameters of the Gompertz growth curve were also estimated. Correlations among early growth, late growth, and body weights at 42 days of age for observed and Gompertz predicted body weight were estimated.

The polynomial growth function was also fitted to the body weights and the parameters of the growth function were also estimated for each individual bird in each genotype and the mean parameters for each of the four broiler genotypes were determined.

\[ BW_t = B_0 + B_1t + B_2t^2 + B_3I_s + B_4I_s \]  
(Walmsley 2007)

where \( BW_t \) = body weight at age \( t \);

\( t \) = age in days from hatch;

\( I_s \) = feed intake of time period;

\( B_0, B_1, B_2, B_3, \) and \( B_4 \) are unknown coefficients.

The polynomial predicted body weights at 1, 35, and 42 days of age were estimated. These were used to calculate the predicted early and late growths for each bird using the formulae below.

Polynomialearlygrowth = PBW_{35} − PBW_1
Polynomiallategrowth = PBW_{42} − PBW_{35}

where PBW1, PBW35, and PBW42 are the polynomial predicted body weights of broilers at day 1, 35, and 42, respectively.

The polynomial predicted body weights at 35 and 42 days, early and late growths, were analyzed using GLM procedure of SAS version 9.4 (SAS 2013).

Differences between means were separated using the Tukey’s test.

Correlations among the parameters of the polynomial function and observed body weights at 42 days of age were estimated. Correlations among early, late, and body weight at 42 days were also estimated.

Results

Comparison of observed and Gompertz predicted body weights

The BW28, BW42, GBW28, and GBW42 of the four commercial broiler genotypes are presented in Table 1. Ranking of genotypes based on body weight at 28 and 42 days of age followed the same trend for both observed and Gompertz predicted body weight were estimated.

The polynomial growth function was also fitted to the body weights and the parameters of the growth function were also estimated for each individual bird in each genotype and the mean parameters for each of the four broiler genotypes were determined.

| Genotype | BW28   | BW42   | GBW28  | GBW42  |
|----------|--------|--------|--------|--------|
| A        | 1.0323 ± 0.046ab | 1.8831 ± 0.063 | 1.0116 ± 0.040ab | 1.8868 ± 0.063 |
| B        | 0.9368 ± 0.047b   | 1.7627 ± 0.065 | 0.9421 ± 0.041b   | 1.7619 ± 0.065 |
| C        | 1.0000 ± 0.046b   | 1.8940 ± 0.063 | 0.9960 ± 0.040ab  | 1.8940 ± 0.063 |
| D        | 1.1947 ± 0.047a   | 1.9249 ± 0.065 | 1.1466 ± 0.041a   | 1.9363 ± 0.065 |
| Overall  | 1.0404 ± 0.036    | 1.8668 ± 0.058 | 1.0236 ± 0.032    | 1.8703 ± 0.032 |

Means in a column with different superscripts are significantly different (\( p < 0.05 \))
Comparison of stages of growth (Gompertz function)

Table 3 shows the magnitude of growths for the two stages of growth dubbed early and late growths for both observed and predicted growths. Ranking of genotypes based on the growth (early and late growths) followed a similar pattern for both the observed and Gompertz predicted. For early growth, genotypes are ranked D, A, C, and B while for late growth genotypes ranked C, A, B, and D in descending order of magnitude. With the exception of genotype A which retained its rank for both early and late growths, all other genotypes had a different pattern of growth. Genotype D recorded the largest early growth but a slower growth as it approached maturity. Genotype C, on the other hand, was slow growing in its early life and picked up later in life.

Comparison of stages of growth (polynomial function)

The ranking of the genotypes based on the observed early and late growths and polynomial predicted early and late growths followed similar trends (Table 4). However, the patterns of growth of the genotypes were different. Genotype D recorded the highest growth at the first stage of growth but the slowest growth at the later stage of life.

The parameters of the Gompertz and Polynomial functions were different for the different broiler genotypes (Tables 5, 6, 7). Genotype D had the highest \( P < 0.05 \) maturation rate, \( K \) compared to the other genotypes even though it came up with the lowest asymptotic body weight, \( A \). There was a strong negative correlation between \( K \) and transformed initial body weight, \( B \); and a weak correlation between \( K \) and \( B_{W42} \) (Table 8). There was a weak positive correlation between \( B_{W42} \) and parameter \( A \) though not...
The opposite seems to be the case for BW28 and the Gompertz growth curve parameters. There was a significant positive correlation between B and K; and between B and BW28 (Table 8). However, a negative correlation existed between BW28 and A. A significant positive correlation exists between B and K while a negative correlation exists between A and B; and between A and K.

The coefficients of the polynomial functions and the observed body weights for the four broiler genotypes are presented in Table 6. For all broiler genotypes, the polynomial coefficients decreased from B0 to B3. Parameter B3 remained negative for all broiler genotypes.

The observed growth curves of the broiler genotypes looked similar at the early stage of growth (first 28 days) after which genotype D increased slightly (Figure 1). However, at the end of growth, all genotypes attained similar body weights with the exception of genotype B which lacked behind but not statistically significant ($P > 0.05$).

The Gompertz predicted growth curves of the four broiler genotypes showed similar pattern as those of the observed growth curves; however, the observed growth curves separated at an early stage of 3 weeks of age (21 days) (Figure 2). Genotype B still lacked behind in the Gompertz predicted growth compared to the other genotypes.

The $R^2$ and residual errors for the growth functions of each broiler genotype are presented in Table 7. The goodness of fit of Gompertz growth functions was higher than those of the polynomial functions (Table 7). On the other hand, the residual errors of the Gompertz function were lower than that of the polynomial function. For the Gompertz function, genotypes B and C had lower residuals compared to genotypes A and D. However, the residuals of the polynomial functions for genotypes C and D were lower than those of genotypes A and B.

The correlations among observed body weight at 42 days, polynomial parameters $B_0$, $B_1$, and $B_2$, were all positive and significant (Table 9). Parameter $B_3$ was negatively correlated with all other parameters ($B_0$, $B_1$, and $B_2$). There were strong positive correlations between the observed body weights at different ages and their

| Genotype | BW28 | BW42 | A | B | K |
|----------|------|------|---|---|---|
| A        | 1.0323 ± 0.046$^{ab}$  | 1.8831 ± 0.063  | 11.77 ± 5.89 | 8.10 ± 0.89$^b$  | 0.365 ± 0.03$^b$  |
| B        | 0.9368 ± 0.047$^b$  | 1.7627 ± 0.065  | 12.70 ± 6.05 | 7.35 ± 0.91$^b$  | 0.334 ± 0.03$^b$  |
| C        | 1.0000 ± 0.046$^b$  | 1.8940 ± 0.063  | 14.47 ± 5.89 | 7.31 ± 0.89$^b$  | 0.293 ± 0.03$^b$  |
| D        | 1.1947 ± 0.047$^a$  | 1.9249 ± 0.065  | 3.11 ± 6.05 | 12.39 ± 0.91$^a$  | 0.515 ± 0.03$^a$  |
| Overall  | 1.0404 ± 0.046  | 1.8668 ± 0.058  | 10.58 ± 5.72 | 8.76 ± 0.87  | 0.376 ± 0.02 |

Means in a column with different superscripts are significantly different ($p < 0.05$)

| Genotype | B0   | B1   | B2   | B3   | BW42 |
|----------|------|------|------|------|------|
| A        | 551.42 ± 7.62$^c$  | 50.34 ± 1.16$^{bc}$  | 1.51 ± 0.08$^b$  | −0.017 ± 0.002$^a$  | 1.8831 ± 0.063  |
| B        | 569.05 ± 7.84$^{bc}$  | 46.46 ± 1.20$^c$  | 0.94 ± 0.08$^c$  | −0.015 ± 0.002$^a$  | 1.7627 ± 0.065  |
| C        | 613.05 ± 7.84$^a$  | 51.97 ± 1.20$^b$  | 1.15 ± 0.08$^d$  | −0.016 ± 0.002$^a$  | 1.8940 ± 0.063  |
| D        | 592.80 ± 7.60$^{ab}$  | 62.02 ± 1.16$^a$  | 2.06 ± 0.08$^d$  | −0.042 ± 0.002$^b$  | 1.9249 ± 0.065  |
| Overall  | 581.32 ± 7.35  | 52.81 ± 1.04  | 1.43 ± 0.07  | −0.023 ± 0.04  | 1.8668 ± 0.058 |

Means in a column with different superscripts are significantly different ($p < 0.05$)

| Genotype | Coefficient of determination | Residual error |
|----------|------------------------------|----------------|
|          | Gompertz | Polynomial | Gompertz | Polynomial |
| A        | 0.999767 | 0.9689 | 1.2820 | 21.7214 |
| B        | 0.999826 | 0.8979 | 0.0798 | 14.4944 |
| C        | 0.999678 | 0.9562 | 0.1720 | 9.7638 |
| D        | 0.999780 | 0.9732 | 6.1740 | -0.2595 |
| Pooled   | 0.999943 | 0.9668 | 1.8830 | 11.4131 |

Table 5 Mean (± standard deviation) observed body weights (kg) at 28 and 42 days of age and Gompertz growth parameters for four commercial broiler genotypes

Table 6 Mean (± standard deviation) polynomial growth parameters and the observed body weight at 42 days of age for four commercial broiler genotypes

Table 7 Coefficients of determination ($R^2$) and residual errors of Gompertz and polynomial growth functions of the four broiler genotypes

Table 8 Phenotypic correlation among observed body weights at 42 and 28 days of age (BW42, BW28, and Gompertz predicted growth parameters (A, B, and K)
Fig. 1 Observed growth curves of four broiler genotypes

Fig. 2 Gompertz predicted growth curves of four broiler genotypes

corresponding Gompertz predicted body weights at different ages (Table 10) with all the correlations being significant. The overall mean observed body weight at 42 days was similar to polynomial predicted body weight at 42 days but not Gompertz predicted 42 days’ body weight.

Table 9 Phenotypic correlation between observed body weight at 42 days of age (BW_{42}) and polynomial predicted growth parameters

|      | B₀     | B₁     | B₂     | B₃     |
|------|--------|--------|--------|--------|
| BW_{42} | 0.635  | 0.500  | 0.234  | −0.103 |
| B₀    | 0.471  | −0.050 | −0.229 |
| B₁    | 0.777  | −0.891 |
| B₂    | −0.744 |

Table 10 Correlations between observed body weights and Gompertz predicted (GBW) and polynomial predicted body weights (PBW) at days 1, 7, 14, 21, 28, 35, and 42

| Observed body weight | GBW  | PBW  |
|----------------------|------|------|
| BW₁                  | 0.793| 0.552|
| BW₇                  | 0.402|      |
| BW₁₄                 | 0.832|      |
| BW₂₁                 | 0.884|      |
| BW₂₈                 | 0.982|      |
| BW₃₅                 | 0.197|      |
| BW₄₂                 | 0.992| 0.150|
Ranking on body weight

The similarity in the ranking of broiler genotypes by their observed body weights and Gompertz predicted body weights could be due to the use of only actual body weights by the Gompertz function in predicting the body weights of chicken. However, the differences in ranking observed in broiler genotypes using polynomial predicted body weights could be attributed to the incorporation of feed intake in the function (Walmsley 2007). Praharaj et al. (1996) reported that ranking of sire families of broilers is significantly different under full and restricted feeding regimes or program. The appreciable variations within body weights suggest that further genetic improvement could be achieved within the genotypes through selection.

Ranking using growth functions (Gompertz and polynomial)

The use of asymptotic body weight, A, ranks genotypes in descending order of C, B, A, and D. Parameter A estimates the weight of bird at an infinite age. In commercial broiler chicken production, birds are ready for slaughter between 6 and 8 weeks of age hence hardly reach this matured body weight; therefore, parameter A is unimportant. Transformed initial body weight, B, and exponential rate of decay of specific growth rate, K, both ranked genotypes in the same order of D, A, B, and C. This could be due to the strong positive correlation between the two parameters. Parameter K is however the most biologically meaningful of the three parameters and has a greater effect on the growth curve. Genotype D which had the highest K value also had the lowest value for late growth. The overall estimated K for the pooled data, 0.376, was higher than that reported by Barbato (1991) but lower than that of Mignon-Grasteau et al. (2000) which were 0.037 and 2.15, respectively. The variations within the estimate for this work were, however, lower. A lower K has a favorable growth curve of low early growth and a high late growth. Barbato (1991) has reported a heritability of 0.28 for this parameter. This trait can therefore be passed on from parents to their progeny. Parameter K has a negative correlation with BW_{42} but a positive correlation with BW_{28}. This is expected since as animals grow, the rate of deterioration of growth increases hence the negative correlation between K and BW_{42}. The phenotypic correlation between BW_{28} and K (0.701) was similar to that of Barbato (1991) who reported 0.74 at 14 days. Rapid progress for a trait can be achieved by selecting on a highly correlated trait if the trait under consideration is difficult to measure with precision. Parameter K can therefore be selected for by indirectly selecting for BW_{28}. However, there was a big difference between the correlation at 42 days reported by Barbato (1991) and that of this work at the same age. Environmental and genetic variations could have influenced the trait in the present study. There were also negative correlations between the growth

| Genotype | BW_{42Obs} | BW_{42Gomp} | BW_{42Poly} |
|----------|------------|-------------|-------------|
| Overall mean | 1866.83 | 1870.28 | 1825.04 |
| Minimum | 643.60 | 1330.00 | 643.97 |
| Maximum | 2652.40 | 2658.00 | 2652.64 |
| Standard deviation | 296.90 | 283.24 | 296.75 |

Table 11 Mean body weights at 42 days, minimum, maximum body weights, and standard deviations (grams) for observed, Gompertz, and polynomial predicted using pooled data.
curve parameters, A and K. This could be from the rapid decrease in growth rate after inflection point resulting in a lower asymptotic body weight (Mignon-Grasteau et al. 2000).

The polynomial parameters ranked the broiler genotypes differently. The parameter, $B_2$, however, gave a similar ranking as those of $BW_{42}$. With the exception of $B_3$, all the parameters of the polynomial function have a positive correlation with $BW_{42}$. Aggrey (2002) explained that polynomial function has a better fit for poultry data but the parameters of this function have no biological interpretation because they give no insight into the growth process. Although the $R^2$ for the polynomial functions in this study were lower than those of the Gompertz functions, the values were largely higher than those reported by Osei-Amponsah et al. (2014) in local chicken populations in Ghana. The use of polynomial function seems to be more suitable for predicting early body weight rather than late growth in broilers.

Chambers (1990) observed that the correlations between weights at a given age and previous gain were high. Gompertz predicted growth could thus be employed to give a better prediction of body weight than polynomial since Gompertz function gives largely higher goodness of fit and lower residual error.

In addition, the standard deviation of a given estimation method could be used to predict the robustness of the method for estimation. Although the Gompertz function slightly overestimates the mean body weights at 42 days for the pooled data, the Gompertz function is a better predictor of body weights at later age than the polynomial function due to their lower residual values.

There was an interesting trend for the correlations between observed body weights at fixed ages and their predicted weights at the same ages. While the correlations between observed and Gompertz predicted body weight generally increased with age, the reverse was observed for the polynomial function.

It is possible to predict weight of broiler chickens using the Gompertz and polynomial growth functions. However, the Gompertz function is a better estimator of growth since it has a number of advantages over the polynomial. Among these are its parameters are biologically meaningful and inheritable, lower variation between the parameters it estimates, and the high correlations between its predicted weights and those of the observed. Nonetheless, a simple method of slow early growth and fast late growth could also be employed in a broiler breeding program to rank animals for selection. This will modify the growth curve and minimize the problems related to selection solely on final body weight.

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**Author contribution** Bernard Ato Hagan – conceived the idea for this work; analyzed the data; wrote the manuscript. Christian Asumah – wrote the manuscript. Ernest Darkwah Yeboah – wrote the manuscript. Vida Korkor Lamptey – data collection; wrote the manuscript.

**Availability of data and material** The data for this work is available upon request.

**Code availability** Not applicable.

**Declarations**

**Ethics approval** The manuscript does not contain clinical studies.

**Consent to participate** Not applicable.

**Consent for publication** There are consents from CSIR-Animal Research Institute barring the publication of this work.

**Conflict of interest** The authors declare no competing interests.

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