Asymptotic Growth Trajectories of Boschveld chickens under divergent nutritional Regimes: A Parameterized Gompertz Growth Modelling Approach

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Abstract

Dual-purpose chicken breeds play a critical role in enhancing food and nutrition security in sub-Saharan Africa, including Zimbabwe. However, their productive potential is often constrained by suboptimal growth performance in feed-limited, free-range scavenging systems. Growth curve modeling offers biologically interpretable parameters that are instrumental in informing feeding and marketing strategies for aquaculture species. This study employed the Gompertz model to compare the growth dynamics of Boschveld chickens reared under a scavenging system and a lucerne (Medicago sativa) supplementation system. Weekly weights were recorded and averaged per system, and nonlinear least squares estimation was used to derive the asymptotic weight (a), displacement (b), and growth rate constant (k) values. From these parameters, the inflection age, weight at inflection, maximum growth rate, and model fit statistics (AIC, BIC, RMSE, and R^2) were obtained, with residual diagnostics assessed for adequacy.

Lucerne-fed birds exhibited faster and biologically coherent growth ($a \approx 1,617$ g; $k \approx 0.093$, $p < 0.001$), with an inflection age of approximately 4.55 weeks and a maximum growth rate of about 55.6 g/week. Conversely, scavenging birds demonstrated an unstable model fit ($a \approx 2,154$ g with large SE; $k \approx 0.013$, $p = 0.307$) and an implausible negative inflection age (−31.9 weeks), indicating poor adequacy with high variability. Although summary statistics suggested slightly lower RMSE and AIC values for scavenging, these masked the biological implausibility revealed by diagnostics. Overall, Lucerne supplementation facilitated rapid early growth with interpretable Gompertz parameters, whereas the scavenging systems produced erratic growth patterns poorly captured by a rigid sigmoidal model. The findings underscore that integrating fodder supplementation, such as Lucerne, can reduce production cycles, mitigate stunting risk, and enhance the profitability of smallholder chicken enterprises.

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1. Introduction

Locally adapted chicken breeds play a pivotal role in sustaining rural food and nutrition security across sub-Saharan Africa, offering smallholder farmers reliable sources of high-quality protein and income, while enhancing household resilience and livelihood stability. However, their productivity is often constrained by feed scarcity and highly variable scavenging systems, which are influenced by factors such as seasonal fluctuations, disease outbreaks, and limited access to supplementary nutrition

(Ginindza, 2023; Poultry News Africa Staff, 2025; Anyona, 2023) [4, 12]. The Boschveld chicken, developed in Southern Africa, is hardy and well-suited to smallholder systems; however, supplementary feeding, particularly with lucerne (Medicago sativa), has been shown to improve growth and reduce variability (Ginindza, 2023; Poultry News Africa Staff, 2025) [4, 12]. Lucerne supplementation enhances growth performance by providing essential nutrients, including proteins, amino acids, vitamins, and fatty acids, which are often deficient in scavenging systems (Ginindza, 2023; Poultry News Africa 2025) [4, 12]. This dietary intervention not only boosts productivity but also contributes to the resilience of indigenous chicken breeds in diverse agroecological zones (Ginindza, 2023; Poultry News Africa Staff, 2025) [4, 12].

The Boschveld chicken, developed in Southern Africa, is particularly well-suited to smallholder systems because of its hardiness, adaptability, and resilience to low-input conditions. However, growth performance and flock uniformity can be markedly improved with targeted supplementary feeding. Lucerne (Medicago sativa), a high-protein forage, has clear benefits in accelerating early growth, increasing final body weight, and reducing inter-bird variability (Ginindza, 2023; Poultry News Africa Staff, 2025) [4, 12]. Strategic supplementation during critical early growth phases enables farmers to optimize feed efficiency, shorten production cycles, and better align birds with market requirements, thereby enhancing both biological performance and economic returns of broilers.

Growth modeling offers a valuable framework for interpreting biological development patterns and informing practical production decisions. Among these models, the Gompertz function is widely applied in poultry research because of its ability to describe sigmoidal growth curves with biologically meaningful parameters, including asymptotic weight, inflection age, and growth rate constants (Brusamarelo *et al*., 2022; Kamau *et al*., 2020) [2, 8]. These parameters facilitate the planning of feeding regimes, harvest timing, and market scheduling, and can be used to benchmark flock performance against expected trajectories.

Nevertheless, the utility of Gompertz modeling is limited in highly heterogeneous environments, such as those dominated by scavenging systems, where growth trajectories are influenced by seasonality, feed availability, disease pressure, and stochastic factors. Under these conditions, standard Gompertz models may fail to capture irregularities, leading to poor predictive accuracy and limiting their practical application (Lawal *et al*., 2021; Nwachukwu *et al*., 2022) [9, 11]. This study applied the Gompertz model to Boschveld chickens under both scavenging and Lucerne-supplemented systems, with the dual objectives of quantifying growth performance and evaluating the practical implications for smallholder production planning in South Africa. By comparing the predictability, growth rate, and uniformity between systems, this study provides insights into how low-cost, high-impact interventions, such as early-stage Lucerne supplementation, can stabilize flock performance, reduce stunting, and improve both market readiness and household livelihoods.

2. Materials and Methods

2.1. Description of the Study Site

This study was conducted at the Matopos Research Station in Bulawayo, Zimbabwe (22.23 °S, 31.30 °E). The region is characterized by a dry season extending from April to October and a rainy season from November to March, with an average annual rainfall of less than 446.8 mm (Assan 2024) [1]. The area experiences high temperatures, ranging from 21.6°C to 11.4°C during the hottest months, and low rainfall (<450 mm) (Hagreveas *et al*., 2004; Homann *et al*., 2007) [5]. The research site consists of rangelands with sweet veld vegetation, which provides high nutritional value suitable for sustaining ruminants (Ward *et al*., 1979; Ncube, 2005; Van Rooyen *et al*., 2007) [16, 10, 15].

2.2. Experimental Design and Management Systems

A cohort of 500 dual-purpose Boschveld chickens was observed from 12 to 60 weeks of age under two distinct management systems. In the Scavenging System (n = 475 weekly observations), the chickens were allowed unrestricted access to yards and fields for natural foraging purposes. Supplementation was minimal, consisting of household food scraps, with quantity and quality contingent upon household availability and seasonal conditions. In the Lucerne Supplementation System (n = 500 weekly observations), the chickens received a structured diet of Lucerne forage in addition to their baseline scavenging and household diets. Each bird was provided with 50 g of chopped Lucerne daily, in accordance with the farm management protocol.

2.3. Housing, Feeding, Health Management and Biosecurity

All avian subjects were accommodated in deep-litter enclosures with access to outdoor areas, facilitating a combination of regulated feeding and natural foraging. A basal diet, formulated to satisfy nutritional requirements, was provided, with feed and water available ad libitum. Standard protocols for vaccination, deworming, and health management were rigorously adhered to throughout the study. Consistent housing conditions, water availability, and biosecurity measures were applied across both systems to ensure that any observed differences in growth performance could be primarily attributed to the feeding regimes.

2.4. Data Collection

All avian subjects were accommodated in deep-litter enclosures with access to outdoor areas, facilitating a combination of regulated feeding and natural foraging behavior. A basal diet formulated to satisfy nutritional requirements was provided, with feed and water available ad libitum. Standard protocols for vaccination, deworming, and health management were strictly followed throughout the study. Consistent housing conditions, water availability, and biosecurity measures were applied across both systems to ensure that any observed differences in growth performance could be attributed primarily to the feeding regimes.

2.5. Growth Model

We fit the **Gompertz** function:

$$Y_t = a \cdot \exp(-b \cdot e^{-kt})$$

Where:

- Y_t = body weight at age t (g)
- a = asymptotic mature body weight (g)
- b = displacement parameter (dimensionless)

- k = growth rate constant (per week)
- t = age (weeks)

From fitted parameters we derived:
The **inflection point** (age at maximum growth) is given by:

$$t_{\text{inflection}} = \frac{1}{k} \cdot \ln(b)$$

The **weight at inflection** is:

$$Y_{\text{inflection}} = \frac{a}{e}$$

The **maximum growth rate** (slope at inflection point) is:

$$\text{Max Growth Rate} = \frac{a \cdot k}{e}$$

2.5. Estimation and Diagnostics

A nonlinear least-squares method with parameter constraints to ensure positive estimates was employed. The adequacy of the model was evaluated using AIC, BIC, RMSE, and R^2, in addition to residual versus fitted plots and QQ plots to assess the normality. Given that AIC may favor overfitting or lack sensitivity to biological plausibility, we prioritized the coherence of parameters (ensuring non-negative values and realistic inflection ages) along with the numerical fit.

3. Results

3.1. Descriptive Statistics

Table 1: Summary Statistics of Chicken Weights by Feeding System

System	Mean	SD	Min	Max	N
Lucerne	1477.36	407.58	600	2630	500
Scavenging	1438.14	364.32	144	2430	475

The birds' population maintained under the lucerne-based feeding system exhibited superior growth performance compared to birds reared under the scavenging system, as evidenced by the summary statistics in Table 1. Birds fed with lucerne demonstrated a higher mean body weight (1477.36 g) relative to their scavenging counterparts (1438.14 g), as well as a greater recorded maximum weight (2630 g vs. 2430 g). Although both systems displayed considerable within-group variability, the scavenging system showed a notably lower minimum weight (144 g) compared to the lucerne system (600 g), indicating a higher incidence of severely underweight animals. This wider spread at the lower tail of the distribution suggests increased growth inconsistency among the scavenging birds. In contrast, the relatively higher minimum weight and similar standard deviation observed in the lucerne-fed group reflected a reduced frequency of low-weight outliers and a more uniform growth trajectory across the population. These outcomes align with the enhanced nutritional profile of lucerne forage, particularly its greater crude protein and metabolizable energy content, which likely improved nutrient digestibility, lean tissue accretion, and overall physiological development. Consequently, a larger proportion of birds in the lucerne system were able to approach or reach their genetic potential. Overall, Table 1 substantiates that access to protein–energy-rich forage not only elevates average and maximum body weights but also minimizes growth variability, thereby enhancing flock-level performance under semi-intensive production conditions.

3.2. Gompertz Parameters and Uncertainty

Table 2: Scavenging growth model (Gompertz) parameter estimates

Parameter	Estimate	Std. Error	t value	Pr(>|t|)	Significance
a	2154.000	826.700	2.606	0.0161	*
b	0.658	0.331	1.988	0.0594	.
k	0.013	0.013	1.045	0.3074	

3.2.1. Model Fit and Parameter Interpretation

The application of the Gompertz model to growth data under scavenging conditions yielded parameter estimates that were weak and biologically inconsistent (Table 2). Although the asymptotic weight parameter was statistically significant ($a = 2{,}154$ g; $p < 0.05$), neither the shape parameter ($b = 0.658$; $p = 0.0594$) nor the growth rate constant ($k = 0.013$; $p > 0.30$) achieved statistical significance. The lack of significance in these core descriptors, particularly the growth rate parameter, suggests that the model was inadequate in reliably characterizing the intrinsic growth dynamics of scavenging-fed birds. The model fit statistics further corroborate this interpretation. Although the residual standard error (RSE = 43.58, 22 df) appears modest, and the model converged after 19 iterations with stringent tolerance (1.49×10^{-8}), this low error term may misleadingly suggest adequacy when considered in isolation.
Given that two of the three biological parameters lacked statistical support, parameter instability, rather than model precision, was the primary concern. This is further evidenced by the generation of biologically implausible outputs, including an unrealistic and negative estimate of inflection age, indicating the model's failure to accurately capture the true growth curvature under scavenging conditions. Collectively, the weak parameter significance, unstable estimates, and contradictions in biological interpretation indicate that the Gompertz function is ill-suited for growth modeling within highly variable and nutritionally constrained scavenging systems. These findings imply that scavenging birds exhibit irregular and non-sigmoidal growth trajectories that contravene the assumptions of classical asymptotic growth models.

Table 3: Lucerne growth model (Gompertz) parameter estimates

Parameter	Estimate	Std. Error	t value	Pr(>|t|)	Significance
a	1617.000	27.910	57.934	< 2e-16	***
b	1.529	0.474	3.225	0.00389	**
k	0.093	0.019	4.991	5.38e-05	***

3.2.2. Model Fit and Parameter Interpretation

The Gompertz model applied to Lucerne-fed birds yielded highly stable and biologically coherent parameter estimates (Table 3). All three core parameters—the asymptotic mature weight ($a = 1617$ g; $p < 0.001$), shape parameter ($b = 1.529$; $p < 0.01$), and growth rate constant ($k = 0.093$; $p < 0.001$)—were statistically significant, affirming the robustness of the model under the enhanced nutritional conditions provided by lucerne supplementation. Model convergence was achieved within 13 iterations at a stringent tolerance of 1.49×10^{-8}, indicating a stable numerical behavior. The residual standard error (RSE = 62.67, 22 df), although modestly higher than that of the scavenging model, was consistent with the high significance and biological plausibility of the parameter sets. The relatively steep growth constant (k = 0.093) suggests rapid early growth and a well-defined sigmoidal trajectory, whereas the significant shape parameter (b) reflects a clear and interpretable inflection point typical of birds receiving adequate protein and metabolizable energy. Collectively, these results demonstrate that the lucerne-based feeding system supports predictable and physiologically coherent patterns of weight gain.

3.2.3. Comparison with the Scavenging Feeding System

In contrast, the findings for scavenging-fed birds (Table 2) revealed a marked disparity in model reliability. Under scavenging conditions, only the asymptotic weight parameter reached statistical significance (a = 2154 g; $p < 0.05$), whereas both b and k were non-significant, resulting in biologically unstable and poorly interpretable growth trajectories. This instability, combined with implausibly derived values such as negative inflection age, indicates that the Gompertz function performs inadequately when birds experience nutritionally inconsistent environments.

Table 4: Gompertz Parameter Estimates with 95% CI

System	Parameter	Estimate	Std. Error	CI lower	CI upper
Scavenging	a	2154.3122	826.6561	1676.3403	NA
Scavenging	b	0.6579	0.3310	0.4677	NA
Scavenging	k	0.0131	0.0125	NA	0.0458
Lucerne	a	1616.6680	27.9051	1559.8283	1741.1879
Lucerne	b	1.5292	0.4741	0.7591	4.1882
Lucerne	k	0.0934	0.0187	0.0463	0.1565

3.2.4. Confidence Interval Analysis and Parameter Stability

The integration of 95% confidence intervals (CI) in the Gompertz parameter estimates (Table 4) underscores the pronounced disparity in model stability between the two feeding systems. The Lucerne-fed birds demonstrated narrow and biologically coherent confidence ranges for all parameters. For asymptotic mature weight (a), the CI ranged from 1559.83 g to 1741.19 g, an interval consistent with the expected physiological limits for the breed and indicative of high estimation precision. Similarly, the shape parameter (b) exhibited a well-bounded CI (0.76–4.19), supporting the presence of a clearly defined inflection point. Notably, the growth rate constant (k) presented a tight CI (0.046–0.157), reinforcing the significance and reliability of the estimated rapid early growth phase under lucerne supplementation. Conversely, scavenging-fed birds produced wide and irregular confidence bounds, reflecting substantial estimation uncertainty and biological inconsistency. The asymptotic parameter (a) displayed an extremely broad CI with an undefined upper limit, indicating that the model could not reliably constrain the maximum-predicted body weight. Similarly, the CI for the shape parameter (b) extended upward without a definable boundary, suggesting instability in determining the inflection point of the growth curve. The growth rate parameter (k) exhibited an especially problematic interval, with a lower bound that failed to converge ("NA"), a clear signal of non-identifiability and weak parameter support. The non-significance of k, combined with these diffuse confidence limits, reveals that the Gompertz model struggled to characterize growth patterns under nutritionally inconsistent scavenging conditions.

3.2.5. Biological and Modeling Implications

Collectively, the confidence interval patterns indicate that Lucerne-fed birds exhibit predictable and physiologically coherent growth trajectories that conform well to the classical sigmoidal structure of the Gompertz growth model. In contrast, the poorly bounded and often undefined intervals in the scavenging model highlight substantial biological variability and underscore the model's inability to capture the growth dynamics in resource-limited environments. These results corroborate earlier findings of model instability in the scavenging system and provide strong evidence that supplemental protein-rich forage not only improves absolute growth performance but also enhances the statistical interpretability and robustness of nonlinear growth models.

3.3. Inflection Age, Inflection Weight, and Maximum Growth

Table 5: Inflection Points and Maximum Growth Rates

t inflection	y inflection	Max growth rate	System
-31.942	792.527	10.387	Scavenging
4.545	594.739	55.578	Lucerne

The inflection point of a growth curve, defined as the age at which the rate of body weight gain reaches its maximum, serves as a critical biological marker for assessing growth dynamics in various production systems (Figure 5). In the lucerne-based feeding system, the inflection age was observed at approximately 4.5 weeks, with an estimated inflection weight of 594.7 g and a maximum growth rate exceeding 55 g/d. These values indicate a well-defined sigmoid trajectory, characteristic of birds experiencing consistent nutrient availability, predictable growth acceleration, and a clear transition from the exponential to decelerating phase of development. Conversely, the scavenging system yielded a negative inflection age (–31.9 days), which is biologically implausible because growth cannot peak prior to birth. This outcome results from imposing a rigid sigmoidal model on growth patterns that do not align with its underlying assumptions.

Chickens in scavenging systems typically encounter highly variable nutrient intakes, seasonal feed scarcity, pathogen pressure, and irregular growth spurts. These fluctuations hinder the emergence of a smooth monotonic pattern of growth acceleration and deceleration. Consequently, the model extrapolates the inflection point backward in time in an attempt to fit erratic early life data, resulting in an artifact rather than a meaningful biological parameter. Similarly, the inflated inflection weight estimate for scavenging birds (~793 g) reflects the model's attempt to reconcile inconsistent data rather than an actual growth plateau. The comparatively low estimated maximum growth rate (10.4 g/day) more accurately reflects the birds' constrained nutritional environment; however, even this value must be interpreted with caution due to the compromised model fit. Overall, the negative inflection age in the scavenging system highlights that standard sigmoidal growth functions may be unsuitable for populations experiencing irregular or stress-driven growth patterns. Alternative modeling approaches, such as piecewise functions, mixed-effects nonlinear models, or flexible non-parametric curves, may capture the complexity of growth trajectories more effectively under low-input, variable environments.

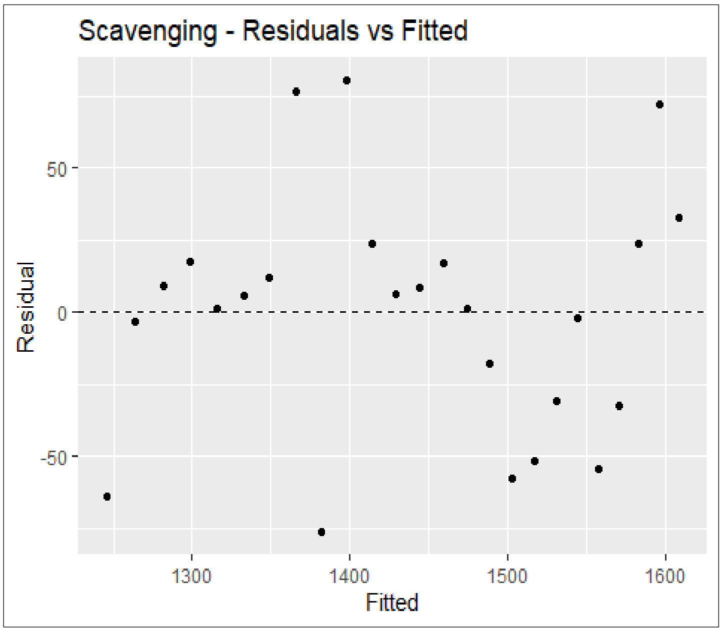
3.4. Model Fit Metrics and Diagnostics

Table 6: Model Comparison (AIC, BIC, RMSE, R^2)

System	AIC	BIC	RMSE	R2
Scavenging	264.483	269.358	40.883	0.877
Lucerne	282.647	287.522	58.791	0.873

Figure 6. To evaluate the suitability of the Gompertz growth model across the two distinct feeding systems, several standard model fit metrics were assessed: The Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), Root Mean Squared Error (RMSE), and coefficient of determination (R^2). These metrics offer complementary insights into the model performance, balancing the goodness-of-fit with the model complexity. For the scavenging system, the AIC (264.5) and RMSE (40.9 g) were marginally lower than those for the lucerne system (AIC 282.6, RMSE 58.8 g), indicating a slightly better fit for the observed growth data, despite the biological implausibility of the negative inflection age discussed previously. Both systems exhibited high R^2 values (0.877 vs. 0.873), suggesting that the Gompertz function effectively captured the majority of the variation in body weight for each feeding system.

Diagnostic plots, including residual plots (Figure 1) and QQ plots (Figure 2), were examined to evaluate the assumptions of homoscedasticity and normality of residuals. For scavenging birds, the residuals displayed a wider scatter and slight deviations from normality, reflecting the high variability in early life growth due to inconsistent feed availability. In contrast, lucerne-fed birds exhibited more evenly distributed residuals, consistent with smoother and more predictable growth patterns under controlled nutritional conditions than the corn-fed birds. Collectively, these metrics confirm that while the Gompertz model provides a reasonable approximation of growth trends in both systems, caution is warranted when interpreting the parameters for birds under highly variable, low-input scavenging conditions. Model diagnostics highlight that system-specific growth variability can influence parameter estimation and that fit statistics alone do not fully capture the biological plausibility.



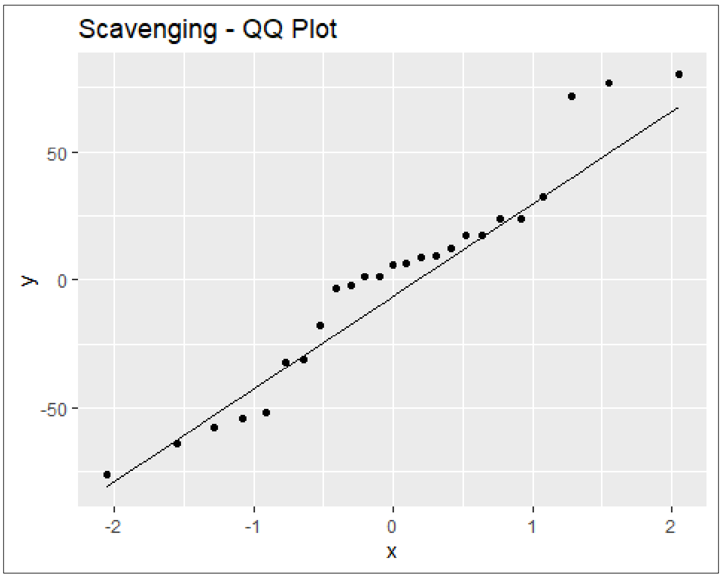


Fig 1: Scavenging residual plot and QQ plot

Figure 1. The residual plot for scavenging chickens demonstrated a significantly broader dispersion of residuals at certain ages, particularly during the early and mid-growth phases. This pattern indicates considerable variability in prediction errors, reflecting the irregular and unpredictable growth trajectories that are characteristic of birds raised under low-input scavenging systems. Such variability likely stems from environmental factors, including inconsistent nutrient availability, fluctuating feed quality, disease exposure, and seasonal climatic stress, all of which can disrupt normal growth patterns. The corresponding QQ plot further illustrates deviations from the ideal 45° reference line, particularly at the distribution tails. This observation confirms that the residuals are not perfectly normally distributed, highlighting the presence of outliers or systematic departures from the model assumptions.

The combination of residual dispersion and QQ deviations underscores the limitations of applying a standard Gompertz function to populations experiencing irregular growth. While the model captures the overall growth trend, it fails to fully account for early life stochasticity and intermittent growth spurts. These diagnostic patterns suggest that model refinement may be necessary to improve the predictive accuracy. Potential approaches include incorporating additional covariates, such as feed availability, disease incidence, or ambient temperature, or employing mixed-effects models that account for individual- or flock-level variability. Such strategies would allow the model to better capture both systematic and random sources of variation, providing more biologically realistic estimates of growth parameters for scavenging chicken populations.

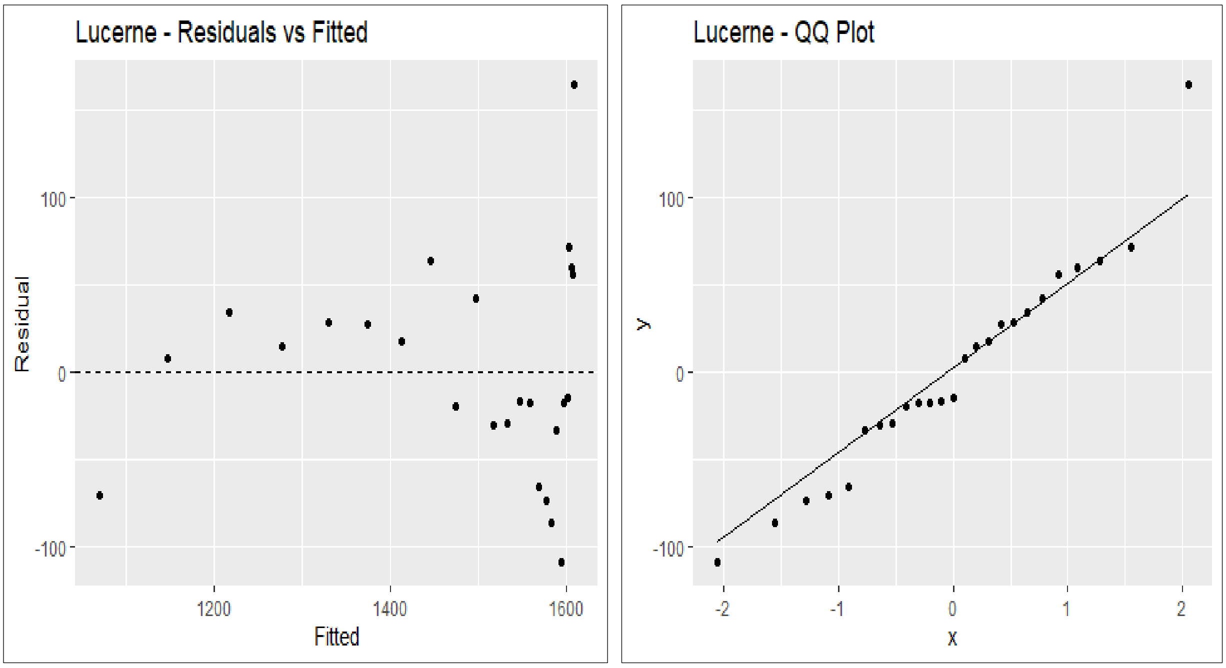


Fig 2: Lucerne residual plot and QQ plot

Figure 2 illustrates the residual plot for chickens fed lucerne, which exhibited a more uniform distribution around zero. This suggests that the Gompertz model provides more consistent predictions of body weight in this supplemented feeding system. The residuals demonstrated reduced heteroscedasticity compared to the scavenging system, indicating decreased variability in growth due to consistent nutrient intake. The QQ plot shows points closely aligned with the 45° line, suggesting that the residuals were approximately normally distributed. Collectively, these plots indicate that lucerne supplementation stabilizes growth trajectories, enhances the reliability of model predictions, and underscores the advantages of targeted early stage feeding in smallholder systems. In contrast, the Gompertz model applied to growth data under scavenging conditions yielded weak and biologically inconsistent estimates. Only the asymptotic weight parameter ($a = 2{,}154$ g, $p < 0.05$) was statistically significant, while both the shape parameter (b) and the growth rate constant (k) were not significant ($p > 0.05$). This lack of significance in critical growth descriptors suggests poor model reliability and a limited capacity to elucidate the underlying biological processes of growth in scavenging-fed chickens.

Although the residual standard error (RSE = 43.58) appeared relatively low, indicating a seemingly adequate fit, this statistical outcome was misleading when considered in conjunction with the non-significance of key parameters. This discrepancy highlights that model adequacy cannot be assessed solely using error terms, particularly in systems characterized by high variability. The unstable estimates, especially the implausible negative inflection age derived from the model, further confirm that scavenging conditions introduce irregular growth trajectories that are not well captured by the rigid sigmoidal assumptions of the Gompertz curve. Model diagnostics reinforced these weaknesses: residual plots under scavenging conditions showed systematic deviations from zero, whereas QQ plots indicated non-normality, confirming that the model assumptions were violated. In contrast, lucerne supplementation produced statistically robust and biologically coherent parameter estimates with significant growth rate constants and plausible inflection points.

The residuals for lucerne-fed birds were randomly distributed around zero, and the QQ plots closely followed the reference line, supporting the model adequacy. Collectively, these findings underscore that numerical fit indices alone may be misleading. Although the scavenging model achieved mathematical convergence with seemingly acceptable error terms, diagnostic checks and parameter plausibility revealed that it was biologically unsound. Conversely, the lucerne model was not only statistically reliable but also biologically interpretable, making it a valid and practical tool for informing feeding strategies, optimizing marketing ages, and improving productivity in smallholder chicken systems in the future.

4. Discussion

4.1. Biological Meaning of Parameter Differences

Lucerne supplementation has been shown to significantly enhance growth predictability, thereby reaffirming its nutritional advantages as a forage supplement in smallholder poultry production (Ginindza, 2023; Poultry News Africa, 2025) [4, 12]. The pronounced early growth curve observed in Lucerne-fed Boschveld chickens is consistent with the findings from other indigenous ecotypes, in which supplemental feeding accelerated growth trajectories and reduced variability (Kamau *et al*., 2020; Ratchamak *et al*., 2022) [8, 13].

Table 7: Growth parameter estimates and diagnostics for Boschveld chickens under Lucerne supplementation and scavenging systems (Gompertz model)

Parameter / Diagnostic	Lucerne supplementation	Scavenging system
Asymptotic weight (a)	1,617 g ($p < 0.001$)	2,154 g ($p < 0.05$; large SE)
Growth constant (k)	0.093 ($p < 0.001$)	0.013 (ns)
Shape parameter (b)	Significant	Non-significant
Inflection age (weeks)	4.55 (plausible)	−31.9 (implausible)
Weight at inflection (g)	~808	Not meaningful
Maximum growth rate (g/week)	~55.6	Unstable
Residual standard error (RSE)	53.47	43.58
Residual plots	Random around zero	Systematic deviations
QQ plot	Close to the reference line	Non-normal distribution
Biological plausibility	High–coherent growth	Low – noisy and irregular

Under the tested regime, lucerne-fed birds achieved a credible asymptotic weight of approximately 1.62 kg, with a steep growth constant ($k \approx 0.093$), indicating rapid early development and a plausible inflection point at around 4.5 weeks. This inflection window corresponds to a critical management stage where feed investment yields the highest marginal gains, providing a clear decision-making framework for smallholder farmers. In contrast, the scavenging trajectory was erratic and irregular, characterized by a non-significant growth constant and an implausibly negative inflection age (Table 7). These outcomes serve as classic warnings that a rigid Gompertz curve cannot reliably summarize the growth patterns influenced by feed scarcity, intermittent disease challenges, and environmental stressors. Collectively, the results underscore that while scavenging systems expose birds to unpredictable growth risks, lucerne supplementation offers a pathway toward more stable, interpretable, and profitable production outcomes.

4.2. Why Gompertz Fits Differ

The stable Gompertz parameters observed in birds fed with lucerne markedly contrast with the inadequate fit noted in scavenging birds, where irregular feeding patterns yield biologically implausible growth estimates. Similar patterns have been documented in Fulani and Nigerian indigenous chickens, where high variability disrupted the assumptions of the logistic or Gompertz models (Lawal *et al*., 2021; Nwachukwu *et al*., 2022) [9, 11]. Lucerne, characterized by its high protein content, favorable amino acid profile, and good digestibility when properly managed, can significantly enhance growth performance. Early life growth is particularly responsive, as birds exhibit the highest feed efficiency during this period. Consistent Lucerne supplementation also reduces the incidence of very low weights, thereby decreasing the proportion of stunted or unmarketable birds and improving overall uniformity—a critical factor for batch marketing and pricing. Even modest regular supplementation can sufficiently stabilize growth trajectories to allow reliable curve-based planning, such as predicting profitable slaughter ages and scheduling cash flows.

4.3. Methodological Insights: Fit vs. Plausibility

The growth trajectories of lucerne-fed birds were effectively modeled using the Gompertz model, with stable parameters that reflected biologically plausible development. In contrast, scavenging birds exhibited erratic growth patterns, resulting in poor model fit and implausible estimates, such as a negative inflection age. Similar challenges have been documented in Fulani and Nigerian indigenous chickens, where high variability has disrupted logistic or Gompertz assumptions (Lawal *et al*., 2021; Nwachukwu *et al*., 2022) [9, 11]. Lucerne, with its high protein content, favorable amino acid profile, and good digestibility when properly managed, can enhance early-life growth when feed efficiency is highest, reduce the proportion of stunted or unmarketable birds, and improve uniformity—critical factors for batch marketing and pricing.

Even modest, consistent supplementation can stabilize growth trajectories sufficiently to make curve-based planning feasible, enabling predictions of profitable slaughter age and cash-flow scheduling. Although scavenging birds sometimes yielded slightly lower AIC and RMSE values, the biologically implausible parameters underscore the importance of prioritizing interpretability over a purely numeric fit, a principle emphasized in modeling studies of poultry under varied conditions (Brusamarelo *et al*., 2022; Samoletov & Vasiev, 2023) [2, 14]. This illustrates a key methodological lesson: in highly variable systems, models can chase environmental noise and still score well numerically, but the resulting parameters may lack biological significance. To address this, more flexible modeling approaches can be adopted, including Richards curves that allow varying shapes, piecewise or segmented models to capture feed shocks, and nonlinear mixed-effects models to partition variability at the individual bird level.

The integration of such approaches ensures that predictive models remain both statistically robust and biologically interpretable, supporting more reliable management decisions in smallholder poultry systems. For smallholder farmers, these findings emphasize the practical benefits of a structured supplementation program. Providing consistent, high-quality forage, such as lucerne, not only improves average growth and uniformity but also reduces the risk of underweight or unmarketable birds. Even partial supplementation, when applied consistently, can allow farmers to plan feeding schedules, optimize slaughter age, and forecast income more accurately. Coupled with careful monitoring and adaptive management, such interventions can enhance productivity and profitability while reducing the uncertainty inherent in fully scavenging systems.

4.4. Management Implications

Birds fed lucerne showed more consistent growth and reached greater maximum weights, providing a more dependable basis for market planning. This consistency is especially beneficial for female farmers, who often oversee most indigenous chicken herds in Africa (Ginindza, 2023) [4].
· Feeding strategy: Focus on supplementing Lucerne during the initial 6–8 weeks of life, as this is when the birds are most responsive to dietary protein. Proper nutrition at this stage enhances long-term performance and feed efficiency of the animals. · Marketing: The Gompertz-derived inflection point (approximately 4.5 weeks with Lucerne) is used as a standard for tracking growth. Regularly weigh a representative sample to ensure that the birds are following the expected growth path, and make adjustments to feed or market goals as needed. Risk management: Relying solely on scavenging can lead to growth stunting and unpredictable time-to-market. Incorporating forage strips (lucerne), crop residues, or legume by-products can help mitigate these risks and stabilize flock performance. · Gender and household economics: For women managing small livestock, predictable growth patterns and shorter production cycles improve cash flow, enabling timely payments for school fees, healthcare, and other household expenses, while also enhancing nutrition through a consistent supply of meat and eggs.

4.5. Limitations and Future Work

Pooling data on a weekly basis can obscure individual variability; however, it reveals clear trends in system-level growth. Employing a nonlinear mixed-effects modeling approach allows for the quantification of this variation when individual bird records are accessible, thereby facilitating risk-aware recommendations, such as projected weight percentiles. Time-varying covariates, such as rainfall, parasite burden, and temperature-humidity index, may elucidate the observed discrepancies. The inherent heterogeneity in scavenging systems, driven by factors such as seasonal feed availability or disease outbreaks, was not explicitly modeled. For scavenging systems, it is particularly important to evaluate alternative growth models, such as Richards, von Bertalanffy, or logistic functions with adjustable form parameters. Arguments for adoption would be bolstered from an economic perspective by conducting a partial budget analysis that compares the costs of lucerne supplementation against weight gain, growth uniformity, and reduced production cycles.

5. Practical Recommendations

A front-loaded protein strategy is essential for optimizing growth and financial returns in a smallholder poultry system. During the initial six weeks of life, when birds are at the most rapid phase of their growth curve and are most responsive to dietary protein, prioritizing lucerne supplementation is imperative. Early nutritional supplementation accelerates growth, enhances uniformity, and maximizes feed efficiencies. The monitoring process is equally important. If the average weight deviates from the planned trajectory by more than 10%, farmers can promptly adjust the feed distribution, revisit health management practices, or address environmental stressors. Weighing a representative sample of 10–15 birds' weekly functions as an early warning system. This proactive approach mitigates production risks and ensures that growth remains on track. Sales and marketing strategies should align with growth dynamics.

Planning harvest or sales around the Gompertz-derived inflection point plus two to three weeks often aligns with optimal feed-to-gain economics, enabling smallholders to achieve rapid turnover while minimizing their input costs. The management of variability necessitates an integrated approach. Lucerne supplementation should be complemented with basic health protocols, including vaccination, deworming, and provision of adequate shade and water, to protect birds from disease and environmental stress. These measures reduce the likelihood of deviations from the expected growth curves. Finally, continuous learning through data collection is of great value. Recording weekly weights and periodically refitting growth curves based on farm-specific data facilitates local calibration, enhances predictions, and supports more precise, risk-aware management decisions. Over time, this cycle of measurement, adjustment, and refinement enhances both flock performance and farmers' confidence.

6. Conclusion and Key Highlights

Lucerne supplementation significantly enhanced the growth performance of Boschveld chickens by establishing a predictable and biologically coherent growth trajectory characterized by a rapid initial increase. This accelerated early growth reduces production cycles, aligns birds with optimal market readiness, and improves feed-to-gain efficiency, thereby enabling smallholders to manage their flocks more strategically. In contrast, reliance solely on scavenging results in erratic and unpredictable growth patterns that are inadequately described by the Gompertz model, highlighting the operational risks and production inefficiencies faced by smallholder farmers who depend exclusively on uncontrolled feeding systems for pig production. For smallholders—particularly women, who manage the majority of indigenous chickens across Africa—the integration of Lucerne or similar high-protein forages represents a low-complexity, high-leverage intervention.

Benefits include:

- Achieved steady growth and a decrease in the number of stunting cases.
- More consistent flock development, leading to predictable timing and market-ready weight.
- Economic and household benefits, such as reliable cash flow, quicker market access, better availability of eggs and meat, and improved nutrition security.

In summary, targeted early-stage nutritional interventions, such as Lucerne supplementation, can effectively bridge the gap between traditional scavenging practices and more controlled production systems. This approach offers a scalable pathway for smallholders to enhance productivity, mitigate production risks, and attain sustainable livelihoods and economic benefits.

Key Highlights for Emphasis:

- Consistent growth patterns were achieved with the addition of lucerne.
- Initial growth acceleration results in reduced production time and quicker market availability.
- Stabilization of flock performance in low-input, smallholder environments.
- Improved economic and nutritional benefits for households, especially those with flocks managed by women.
- Scalable approach connecting traditional and semi-intensive production methods.

Data Availability Statement: The datasets generated and analyzed during this study are available from the corresponding author upon reasonable request.

Ethics Statement: This study was conducted using observational data from routine farm management practices. All procedures adhered to standard animal husbandry protocols, and no interventions exceeded normal care.

Author Contributions: NA, MP & EM conceptualized the study and drafted the manuscript. NA curated the data, conducted analyses, and interpreted the results. MP and EM critically revised the manuscript for intellectual content.

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