



Ideal Protein Concept in broiler chicken nutrition: Advances in essential amino acid profiling, modeling approaches, and sustainable feed formulation

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Abstract

A crucial precondition for creating nutritionally optimal diets for fast-growing animals, especially broiler chickens, is the precise determination of amino acid requirements. An imbalance of amino acids in the diet impairs the efficiency of protein deposition and increases nitrogen excretion, which raises nitrogen emissions in the environment. Poultry have dynamic amino acid requirements that are influenced by environmental factors, dietary composition, sex, and genetic potential. Logistically and financially, it is not feasible to systematically evaluate the entire range of these interacting parameters using traditional dose-response experiments. The ideal protein notion has become a strong and comprehensive foundation for predicting amino acid requirements in this setting. By defining the necessary amounts of essential amino acids as fixed ratios relative to a reference amino acid, this method allows for accurate dietary amino acid profile modification. Since lysine plays a crucial part in muscle protein accretion and its requirement is well-defined throughout growth phases and has been extensively validated by experiments, it is frequently used as the reference amino acid. To ensure maximum protein utilization and minimize nitrogen losses, this paper critically analyzes the ideal protein concept, paying particular attention to amino acid profiling in broiler chickens.

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1. Introduction

Feed costs, especially in intensive farming systems, can account for 70–80% of production costs, making them the largest expense in livestock farming (Anggriawan et al. 2024a). Farmers, particularly those operating on a large commercial scale, have used various approaches to optimize feed costs while maintaining good nutritional quality (Anderson et al. 2025). The use of more efficient feed formulations, ingredient substitutions based on price changes, and the use of appropriate feed technology to reduce waste are some examples of these approaches (Atzori et al. 2021; Anggriawan et al. 2024b). Improved feed efficiency has been shown to significantly increase business profitability, as even ordinary improvements in feed conversion efficiency significantly reduces feed costs, which reflects in enhanced profitability of broiler production systems. Even modest improvements in feed conversion ratio (FCR) can significantly reduce feed costs, which account for the largest proportion of total production expenses, thereby increasing economic returns. Recent studies have demonstrated that optimizing feed efficiency through precise nutrient

formulation, including amino acid balancing, can substantially improve growth performance and production efficiency in broiler chickens (Martinez and valdivie 2021). Therefore, obtaining efficient and high-quality feed ingredients is essential for improving profit margins and ensuring the economic sustainability of poultry production systems (Alabi and Adedokun 2025).

Efforts to achieve a balance of essential amino acids that meets the requirements of livestock and minimizes protein excretion have become a primary concern for nutritionists, especially in the formulation of poultry feed in recent years. A meta-analysis indicates that amino acid supplementation can increase nitrogen efficiency by 7% and reduce nitrogen excretion by up to 29% in broiler chickens aged 0–21 days, as well as lower ammonia concentrations by up to 48% on day 33 of rearing (Niyonsaba et al. 2023). The amino acid content of feed is closely related to environmental sustainability and economic aspects (Ullrich et al. 2018; Kamil et al. 2024). It has been reported that optimizing the amino acid pattern in commercial rations can result in a 4.2% increase in feed conversion, a 3.5% increase in breast meat yield,

and a 6.7% reduction in feed costs per kilogram of weight gain. In addition, nitrogen excretion can be reduced by up to 25% (Kamil et al. 2024). Pollution caused by poultry production, particularly nitrogen and phosphorus emissions, has received considerable attention in developed countries because of its impact on air and water quality (Ullrich et al. 2018; Attia et al. 2022). Reduced dietary crude protein levels along with supplementation of limiting amino acid in appropriate quantities can cause a decrease in litter nitrogen content from 51.2 g/kg dry matter to 46.2 g/kg DM (a 9.8% decrease) at a level of -2% crude protein, and up to 36.2 g/kg DM (a 29.3% decrease) at a level of -3% crude protein (Ullrich et al. 2018).

Using biomarkers such as serum uric acid nitrogen and dynamic prediction models, a precision amino acid requirement-based formulation approach enables more accurate ration adjustments to prevent both nitrogen excess and deficiency, thereby supporting sustainable and environmentally friendly productivity (Cambra-Lopez et al. 2022; Wang et al. 2024). However, strategies for reducing crude protein are highly dependent on the complete supplementation of all limiting amino acids. Deficiencies in essential amino acids other than methionine and lysine can lead to poorer production performance in broiler chickens (Attia et al. 2022). Broiler chicken growth rates have increased more than 2.5 times over the last 50 years due to genetic advancements compared to the 1950s (Zuidhof et al. 2014). Because of this rapid development, nutritionists are constantly evaluating the exact energy and protein requirements to reduce feed expenses and environmental pollution. Since essential amino acid requirements are prioritized over crude protein in monogastric animals like chickens, precise amino acid profiling enables protein reduction, which lowers feed costs and nitrogen excretion (Woyengo 2023).

In response to rapid genetic advancement, recent studies have investigated the essential amino acid (EAA) requirements for broiler chickens using advanced factorial, regression, and modeling techniques to perfect nutritional specifications (Adhikari et al. 2025; Alabi and Adedokun 2025). Recent studies have applied a range of approaches to estimate essential amino acid (EAA) requirements, including dynamic modeling to predict standardized ileal digestible amino acids across different growth phases, as well as linear-logistic models for more precise calculations (Ramirez-Camba and Levesque 2023; Wang et al. 2024). Alongside these developments, the ideal protein concept remains a widely used framework in which the requirements of other EAAs are expressed relative to lysine to optimize amino acid balance, reduce excess dietary protein, improve feed efficiency, and minimize nitrogen excretion. Despite its well-established theoretical basis, the practical application of the ideal protein concept in ration formulation, particularly in Indonesia, is still relatively limited (Woyengo 2023). Therefore, this review focuses on broiler chickens as a case study to further explain the ideal protein framework and highlight key calculation approaches used in determining amino acid requirements.

2. Review methodology

This review employed a structured literature approach to ensure transparency, reproducibility, and rigor. Relevant studies were identified through systematic searches in major scientific databases, including Scopus, Web of Science, and Google Scholar. The search strategy combined keywords such as “ideal protein concept,” “amino acid requirements,” “broiler nutrition,” “digestible amino acids,” and “low protein diets in poultry.” Boolean operators (AND, OR) refined the search and

increased the relevance of retrieved articles (Snyder 2019; Page et al. 2021). The inclusion criteria focused on peer-reviewed journal articles about amino acid nutrition, ideal protein formulation, and broiler chicken performance. Studies on other livestock, non-peer-reviewed sources, conference abstracts, and publications lacking sufficient methodological detail were excluded. Priority went to studies using experimental, modeling, or meta-analytical approaches to ensure scientific robustness (Tranfield et al. 2020; Paul et al. 2021).

The timeframe of the literature included in this review primarily covers publications from 2015 to 2025, with particular emphasis on recent advances within the last five years to capture current developments in amino acid nutrition and precision feeding strategies. A total of approximately 70–90 relevant articles were screened, of which around 45–60 studies were selected for in-depth analysis based on their relevance, methodological quality, and contribution to the topic (Page et al. 2021). Overall, this structured approach allowed for a comprehensive and critical synthesis of the existing literature, ensuring that the review reflects both established knowledge and recent advancements in the field of broiler amino acid nutrition.

3. The Ideal protein concept

Currently, livestock feed ration formulation can be done quickly, efficiently, and accurately due to the availability of various software tools equipped with comprehensive databases on the nutritional requirements of livestock species and the nutrient composition of feed ingredients (Belkhanchi et al. 2023). However, many nutritionists still rely on the NRC (1994) publication as the primary reference for broiler chicken nutritional requirements. The balance of essential amino acids (EAAs) must be considered when formulating rations because imbalances, whether deficiencies or excesses, can cause antagonism between EAAs, disrupt metabolism, and even become toxic, thereby inhibiting growth and feed efficiency (Alabi and Adedokun 2025). For example, amino acid antagonism can occur among essential amino acids, such as between lysine and arginine. In addition, antagonistic interactions are well documented among branched-chain amino acids (BCAAs), including leucine, isoleucine, and valine. On the other hand, excess threonine may inhibit growth, while excess methionine can increase vitamin B6 requirements (Adhikari et al. 2025). Liebig's law of the minimum states that a deficiency in one essential amino acid inhibits the utilization of other amino acids, even if they are available in sufficient quantities, thereby inhibiting protein synthesis and livestock growth (Alabi and Adedokun 2025). Factors such as sex, genetics, age, and environmental conditions affect an individual's nutritional requirements, and all these factors must be considered when formulating rations. The ideal protein concept remains relevant for formulating livestock rations taking into consideration their genetic variation, gender, and body weight. This is because it is based on consistent relative ratios of essential amino acids for maintenance and growth, even though the absolute requirements of livestock vary (Barua et al. 2020).

In the ideal protein concept, lysine is chosen as the reference amino acid for determining the ratio of other essential amino acids in broiler chickens. The selection of lysine as a reference is based on several main reasons: (1) lysine is often the second limiting amino acid after methionine + cystine in corn-soybean meal-based feed; (2) lysine can be easily analyzed directly using standard methods; (3) lysine is utilized directly for maintenance and growth protein synthesis without

functioning as a precursor; and (4) comprehensive lysine requirement data is available for various genetic, environmental, and growth phase conditions, facilitating the calculation of other amino acid requirements (Baker 2009). Thus, lysine serves as the practical basis for developing an ideal protein profile. Table 1 and Table 2 present the relative ratios of essential amino acids to lysine in broiler diets at different growth stages. A strategic approach to formulating broiler chicken rations is the ideal protein concept, which focuses on the proportional balance of essential amino acids, with lysine as the reference amino acid (100%). This method makes ration formulation easier under various production conditions, such as variations in sex, dietary metabolic energy and protein levels, poultry genetic potential, and environmental conditions. By adjusting the ratios of essential amino acids relative to lysine, feed formulation can be done more precisely, thereby increasing nutrient utilization efficiency and reducing nitrogen excretion into the environment (Kidd et al. 2021; Selle et al. 2023). Table 1 and Table 2 show highly similar patterns between the experimental and conceptual approaches in terms of the relative ratios of essential amino acids to lysine across both the starter phase (1–21 days) and the grower–finisher phase (21–42 days), indicating a strong consistency between empirical observations and theoretical predictions of amino acid requirements. Chrystal et al. (2020) demonstrated that using a low crude protein diet supplemented with digestible amino acids can maintain broiler chicken growth performance, provided the balance of amino acid-to-lysine ratios are maintained. These results support the ideal protein framework summarized by Kidd et al. (2021), which uses lysine as the basis for determining the requirements of other essential amino acids at different growth stages.

The role of lysine in muscle protein deposition and broiler chicken growth efficiency reflects its importance as a reference amino acid. Since the biological availability of amino acids is greatly influenced by the type and quality of feed ingredients, all contemporary protein concepts rely on ileal digestible amino acids (SID). The digestibility of amino acids in conventional feed ingredients such as corn and soybean meal varies, but crystalline amino acids are typically 100% digestible. Therefore, crystalline amino acids can be effectively used in low-protein diets to achieve an ideal nutrient balance (Wu 2018; Chrystal et al. 2020). Therefore, the concept of lysine-based ideal protein not only improves feed protein utilization efficiency but also helps maintain poultry production systems by reducing excess or deficiency of essential amino acids in rations. A comparison of amino acid ratios in Table 1 and Table 2, taken from recent studies, shows that this method is still relevant and useful in the formulation of contemporary broiler

chicken feed (Kidd et al. 2021; Selle et al. 2023).

The findings synthesized in this review indicate that, although the ideal protein concept provides a robust framework for improving amino acid efficiency in broiler nutrition, inconsistencies remain across studies due to variations in experimental design, genetic strain, and response criteria. Several studies have reported that the optimal amino acid-to-lysine ratios differ depending on whether growth performance, feed efficiency, or carcass traits are used as response variables (Chrystal et al. 2020; Kidd et al. 2021). Moreover, the increasing use of low-protein diets supplemented with crystalline amino acids has revealed potential limitations, particularly in maintaining nitrogen retention efficiency under different environmental and management conditions (Selle et al. 2023). In addition, while modeling approaches such as factorial and exponential nitrogen utilization models provide more precise estimations of amino acid requirements, their application may still be constrained by assumptions related to protein deposition efficiency and metabolic variability among birds (Wang et al. 2024; Oviedo et al. 2025). This suggests that no single method can universally predict amino acid requirements across all production systems. Therefore, integrating multiple approaches, including empirical supplementation trials and mechanistic modeling, is necessary to achieve more reliable and adaptable nutritional recommendations. Taken together, these findings highlight that the ideal protein concept should not be applied as a static formulation strategy but rather as a dynamic framework that requires continuous adjustment based on genetic progress, environmental conditions, and production goals. This perspective reinforces the importance of adopting a more critical and integrative approach in future research on amino acid nutrition in broiler chickens.

4. Limitations of the Ideal protein concept

The ideal protein concept has been widely applied as a practical framework for balancing essential amino acids in broiler diets; however, several limitations have been reported in recent studies. One major limitation is that the concept primarily focuses on essential amino acids while often overlooking the physiological roles of non-essential or conditionally essential amino acids such as glycine and glutamine. These amino acids are increasingly recognized for their roles in gut health, immune function, and metabolic regulation, and their deficiency may limit optimal performance even when essential amino acid requirements are met (Ramirez-Camba and Levesque 2023; Alabi and Adedokun 2025). This indicates that the classical ideal protein framework may not fully capture the complexity of amino acid nutrition in modern broiler systems. In addition, the ideal protein

Table 1. Comparison of essential amino acid ratios relative to lysine (100%) in broiler chickens aged 1–21 days			
Amino acid	Chrystal et al. (2020)	Kidd et al. (2021)	Description
Lysine (Lys)	100	100	Comparative amino acids
Methionine (Met)	36	37	Free methionine adjusted in low PK rations
Histidine (His)	34	35	Generally not a limiting factor
Methionine + Cysteine (Met + Cys)	72	74	Critical for growth and feed efficiency
Tryptophan (Trp)	16	17	Minor limiting amino acids
Threonine (Thr)	67	68	Important for intestinal health
Leucine (Leu)	108	109	Generally excessive in corn-based rations
Valine (Val)	78	80	Critical in low protein rations
Isoleucine (Ile)	68	70	Often a limiting factor along with Val
Phenylalanine + Tyrosine (Phe + Tyr)	105	108	Rarely a limiting factor
Arginine (Arg)	108	110	Important for performance and immunity

Table 2. Comparison of essential amino acid ratios relative to lysine (100%) in broiler chickens aged 21–42 days

Amino acid	Chrystal et al. (2020)	Kidd et al. (2021)	Description
Lysine (Lys)	100	100	Comparative amino acids
Methionine (Met)	37	38	Increase with age
Histidine (His)	35	36	Generally not a limiting factor
Methionine + Cystine (Met + Cys)	75	76	Supports continued growth efficiency
Tryptophan (Trp)	18	18	Minor limiting amino acids
Threonine (Thr)	70	72	Play a role in intestinal function
Leucine (Leu)	108	110	Generally not a limiting factor
Valine (Val)	80	82	Critical in low-protein diets
Isoleucine (Ile)	70	72	Critical together with Val
Phenylalanine + Tyrosine (Phe + Tyr)	105	108	Rarely a limiting factor
Arginine (Arg)	110	112	Important for performance and immunity

concept assumes relatively fixed amino acid ratios relative to lysine, which may not reflect dynamic physiological conditions. Recent studies have demonstrated that amino acid requirements vary depending on environmental stress, dietary protein levels, and genetic improvements in broiler strains (Selle et al. 2023; Wang et al. 2024). Therefore, although the ideal protein concept remains a valuable guideline, its application should be complemented with flexible and adaptive nutritional strategies to improve accuracy and efficiency.

5. Contradictions in amino acid requirement estimates

Despite extensive research, significant inconsistencies remain in reported amino acid requirements for broiler chickens. These discrepancies are largely attributed to differences in experimental design, dietary composition, and response criteria used across studies. For instance, requirement estimates based on growth performance often differ from those based on carcass yield or breast muscle deposition, indicating that the selected biological response strongly influences the outcomes (Chrystal et al. 2020; Kidd et al. 2021). Such variation complicates the establishment of standardized amino acid recommendations applicable across different production systems. Furthermore, the increasing use of low-protein diets supplemented with crystalline amino acids has introduced additional variability in requirement estimations. While some studies report that reduced crude protein diets can maintain performance when amino acid balance is optimized, others highlight limitations due to amino acid interactions and the presence of unidentified limiting amino acids (Hilliar et al. 2020; Selle et al. 2023). These contradictions suggest that amino acid requirements are highly context-dependent and require integrative approaches combining experimental data and predictive modeling.

6. Challenges in commercial application

Although the ideal protein concept has shown promising results under experimental conditions, its practical implementation in commercial broiler production remains challenging. One of the primary limitations is the variability in feed ingredient quality and amino acid digestibility, which can significantly affect formulation accuracy. Variations in raw material composition, processing conditions, and storage practices may lead to variations in nutrient availability, thereby reducing the effectiveness of ideal protein-based formulations (Selle et al. 2023; Chrystal et al. 2020). In addition, the application of precision amino acid nutrition requires access to high-quality feed additives, accurate feed evaluation systems, and technical expertise, which may not always

be available in commercial settings, particularly in developing countries. Economic constraints and limited adoption of advanced formulation technologies can further restrict the practical implementation of the ideal protein concept (Kidd et al. 2021; Wang et al. 2024). Therefore, bridging the gap between theoretical models and field application remains a critical challenge in modern poultry nutrition.

7. Variables impacting the optimal amino acids

The amino acid requirements of broiler chickens depend not only on growth and production but also on tissue maintenance. Ideal amino acid requirements are influenced by the age and body weight of the birds. The proportion of maintenance requirements increases with the age of the chickens (Kidd et al. 2021; Selle et al. 2023). Therefore, the ratio of essential amino acids relative to lysine changes accordingly during the growth phase. According to the modern approaches to poultry nutrition, lysine remains the primary amino acid, but its requirement for tissue maintenance is relatively lower than that of some other essential amino acids. This is because the rate of body protein turnover slows with age in poultry, especially in tissues containing high lysine content. As a result, the lysine requirement for tissue maintenance does not increase proportionally (Liu et al. 2021). Instead, after the starter phase, the requirements for amino acids such as methionine, cysteine, threonine, and tryptophan tend to increase in proportion to the maintenance requirements. Studies on low-protein diet formulations indicate that the grower–finisher phase requires higher dietary ratios of essential amino acids relative to lysine compared with the starter phase, primarily due to increased maintenance demands and shifts in metabolic priorities with advancing age. For example, it has been found that the threonine to lysine ratio increases with age in chickens when requirements are calculated based on growth performance and feed conversion efficiency. This indicates a greater role for threonine in maintaining tissue integrity and digestive tract function (Chrystal et al. 2020; Kidd et al. 2021). Similar results were reported when the response criteria shifted from weight gain to breast meat deposition and the threonine:lysine ratio was higher in the late growth phase than in the early phase (Barkley et al. 2001).

Therefore, recent research suggests that estimates of amino acid requirements, especially lysine, should be based on the concept of ileal digestible amino acids (SID). This concept should be linked to maintenance requirements and production goals used as response variables. This method allows for more accurate adjustment of the ideal amino acid ratio at each growth stage of broiler chickens and supports

the efficiency and sustainability of feed protein utilization (Kidd et al. 2021; Selle et al. 2023). Despite the recognized influence of age and body weight on amino acid requirements, considerable variability has been reported across studies due to differences in genetic strain, environmental conditions, and production systems. For instance, modern fast-growing broiler strains exhibit higher amino acid demands compared to older genotypes, particularly in phases of rapid muscle deposition (Kidd et al. 2021; Selle et al. 2023). In addition, environmental stressors such as heat stress can alter amino acid metabolism and nutrient utilization efficiency, thereby shifting the optimal amino acid ratios required to maintain performance (Alabi and Adedokun 2025). These findings suggest that amino acid requirements are not static and must be continuously adjusted according to both biological and environmental factors. Furthermore, discrepancies in determining optimal amino acid ratios are also influenced by the response criteria used in different studies, such as growth rate, feed efficiency, or carcass yield. Studies have shown that amino acid requirements based on breast meat yield are often higher than those based solely on body weight gain, indicating differences in nutrient partitioning (Chrystal et al. 2020; Wang et al. 2024). This highlights the limitation of applying a single standard ratio across diverse production goals. Therefore, a more integrative approach that combines biological modeling, performance-based evaluation, and environmental considerations is essential to accurately define amino acid requirements and optimize feed formulation in modern broiler production systems.

8. Exponential methods of assessing amino acid requirements

The amino acid requirements of broiler chickens are currently based on the amounts needed for tissue production and maintenance. Contemporary amino acid nutrition methods recognize that the amino acid requirements of chickens increase with age and growth stage, with maintenance requirements tending to increase with age of chickens (Kidd et al. 2021; Wang et al. 2024). For this reason, it is crucial to use a diet formulation approach that optimizes the use of protein and amino acids separately for growth and maintenance of birds. In practice, by limiting one of the amino acids evaluated in the ration and combining it with other amino acids, the amount required can be calculated. In the factorial approach, total amino acid requirements are divided into maintenance and growth components based on the physiological development in poultry (Wang et al. 2024). According to this model, the amount of amino acids required by the body is not constant, but depends on the rate of body protein deposition and the specific metabolic efficiency of each amino acid. To improve the accuracy of ration formulation, this approach is often combined with the use of ileal digestible amino acid (SID) values. The use of SID allows for more accurate calculations of the amount of amino acids available for body metabolism after accounting for endogenous losses in the small intestine. Thus, the calculation method using SID is regarded as superior to traditional approaches that rely on total protein (Alabi and Adedokun 2025). Thus, the calculation methods that account for the biological efficiency of amino acid utilization provide a stronger basis for formulating balanced and efficient rations for broiler chickens at various growth stages, as outlines below:

8.1. Nitrogen balance calculation

The N-balance calculation is performed by subtracting the total nitrogen lost through feces and urine from total nitrogen intake, while

nitrogen losses through skin and feathers are often ignored due to their small contribution. Mathematically:

$$N_{\text{balance}} = N_{\text{intake}} - (N_{\text{faecal}} + N_{\text{urinary}}) \text{ (mg/BWkg}^{0.67}\text{)}$$

The exponential model is often used to describe the relationship between nitrogen intake and nitrogen retention. The commonly used form is:

$$y = A(1 - e^{-bx})$$

Description:

$$y = \text{Daily N balance} + \text{NMR (mg/BWkg}^{0.67}\text{)}$$

$$A = \text{Maximum theoretical N deposition capacity (PDmax Theor) (mg/BWkg}^{0.67}\text{)}$$

$$x = \text{Daily N intake (mg/BWkg}^{0.67}\text{)}$$

$$b = \text{N retention slope (protein quality indicator)}$$

$$e = \text{base of the natural logarithm}$$

This type of exponential model has been used widely to understand the relationship between nitrogen intake and nitrogen retention in modern poultry nutrition (He et al. 2021; Rehman et al. 2018).

8.2. Calculation of protein quality and amino acid efficiency

The exponential nitrogen utilization model is widely used to describe the relationship between nitrogen intake and nitrogen retention in animals. This model assumes that nitrogen retention increases with nitrogen intake but approaches a biological maximum as intake continues to rise, reflecting physiological limitations in protein deposition. Within this model, parameter **b** represents the quality of the available protein, specifically describing the efficiency of nitrogen utilization, or the extent to which nitrogen retention increases relative to nitrogen intake. Mathematically, this parameter is derived as:

$$b = \ln A - \ln(A - y) / x$$

This efficiency model can be extended further to calculate the efficiency of limiting amino acid utilization. The efficiency of amino acid utilization can be written as:

$$bc^{-1} = \ln A - \ln(A - y) / 16 \times \text{LAA}$$

Description:

$$A = \text{maximum theoretical nitrogen retention (mg/BWkg}^{0.67}\text{)}$$

$$y = \text{daily nitrogen retention (mg/BWkg}^{0.67}\text{)}$$

$$x = \text{daily nitrogen intake (mg/BWkg}^{0.67}\text{)}$$

$$\ln = \text{natural logarithm (logarithm to the base } e\text{)}$$

$$bc^{-1} = \text{limiting amino acid efficiency}$$

$$x_{\text{LAA}} = \text{daily consumption of limiting amino acids (mg/BWkg}^{0.67}\text{)}$$

This mathematical approach has been applied in studies of poultry and other monogastrics to compare protein and amino acid utilization efficiency among different feed sources (Waldroup et al 2002; Adeola and Cowieson 2011).

8.3. Calculation of amino acid requirements

In the efficiency-based model, amino acid requirements are determined by the efficiency of limiting amino acid utilization and the level of consumption of that amino acid. Therefore, the requirement for limiting amino acids can be calculated using the following equation:

$$xLAA = \ln A - \ln (A - y) / (16 \times bc^{-1})$$

Description:

$$xLAA \text{ (mg/BWkg}^{0.67}\text{)} = \text{daily intake of the limiting amino acid}$$

Other components of equation are as previously defined.

This approach has been widely applied in recent poultry nutrition studies to estimate amino acid requirements, particularly in the development of low-protein diets for broiler chickens (Alabi and Adedokun 2025; Wang et al. 2024). By incorporating the efficiency of amino acid utilization, this method provides more precise estimates compared to conventional single-variable approaches (Alabi and Adedokun 2025). Fig. 1 illustrates the non-linear relationship between daily nitrogen intake (mg/BWkg^{0.67}) and daily nitrogen deposition in broiler chickens, where increasing nitrogen consumption results in increased nitrogen deposition up to a theoretical maximum limit (NDmaxT). This asymptotic exponential curve pattern indicates the biological limitations of chickens in converting nitrogen into protein as they age and gain weight (Alabi and Adedokun 2025).

According to contemporary modeling-based research, the NDmaxT value decreases gradually as chickens age. This indicates that nitrogen allocation shifts from new tissue growth toward maintenance needs. Given the increased nitrogen requirements for key metabolic functions and tissue protein turnover during the grower-finisher phase compared to the starter phase, this phenomenon is consistent (Sakomura et al. 2015). It is very common to use nitrogen deposition models to calculate amino acid requirements based on biological efficiency. These models calculate the amount of amino acids required based on the relationship between nitrogen intake, retention efficiency, and maximum protein deposition potential (PDmax) and constant efficiency of nitrogen utilization, which may not fully capture the variability observed in modern broiler strains under different environmental and management conditions (Wang et al. 2024; Oviedo et al. 2025). Additionally, differences in experimental methodologies, such as variations in diet composition, bird genotype,

and measurement techniques, can lead to inconsistencies in parameter estimation and model outputs. Therefore, while the exponential approach offers a robust quantitative framework, its practical application should be complemented with empirical validation and adjusted according to specific production contexts to ensure more accurate and reliable amino acid requirement predictions.

9. Supplementation approaches and biological responses in determining amino acid requirements

The amino acid requirements of broiler chickens can be assessed using supplementation and nitrogen balance techniques or biological modeling. These methods involve gradual supplementation of essential amino acids to a deficient basal diet, while other amino acids are maintained at adequate levels. As a result, the biological response of the livestock can be specifically attributed to the amino acid being tested (Fig. 2). Using response parameters such as weight gain and feed conversion efficiency, the broken-line regression method is mostly used to calculate the lysine requirements of broiler chicken in the starter phase. This method identifies the minimum lysine requirement point, which is indicated by the break point on the response curve. Beyond this point, increasing lysine supplementation results in no significant improvement in performance (Sarsour et al. 2022; Zarghi et al. 2020). In addition, supplementation-based studies indicate that the response to lysine is influenced by the crude protein level of the diet; however, when measured in relation to standard digestible lysine, lysine requirements are relatively constant. Therefore, the supplementation-based broken-line method is considered practical and biologically reliable for calculating the essential amino acid requirements of modern broiler chickens (Kidd et al. 2021).

Recent research shows that the breakpoint on the broken-line curve indicates the minimum level of lysine required for optimal performance (Sarsour and Persia 2022). In other words, increasing lysine intake beyond this breakpoint does not result in significant weight gain. The authors revealed that in starter phase broiler chickens, although the crude protein content of the feed varied, the lysine requirements based on body weight were relatively the same. These observations suggest that the biological growth potential of chickens has a greater influence on lysine requirements than the crude protein content of the diet. As a result, broken-line techniques based on supplementation are widely used to determine the essential amino acid requirements of

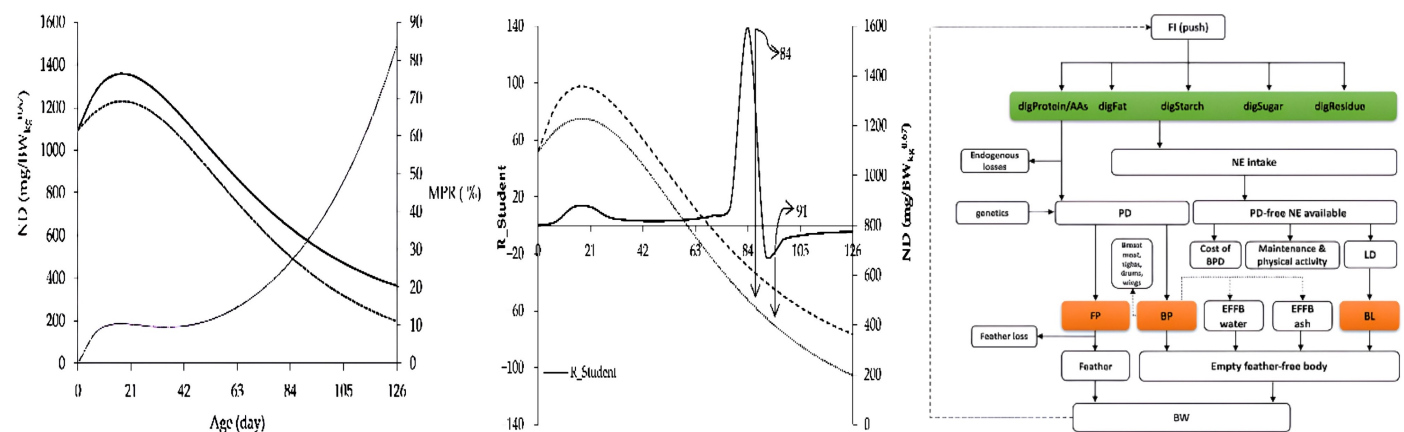


Fig. 1. Relationship between daily nitrogen intake and theoretical maximum nitrogen deposition (NDmaxT) in broiler chickens based on growth phase (Alabi and Adedokun 2025)

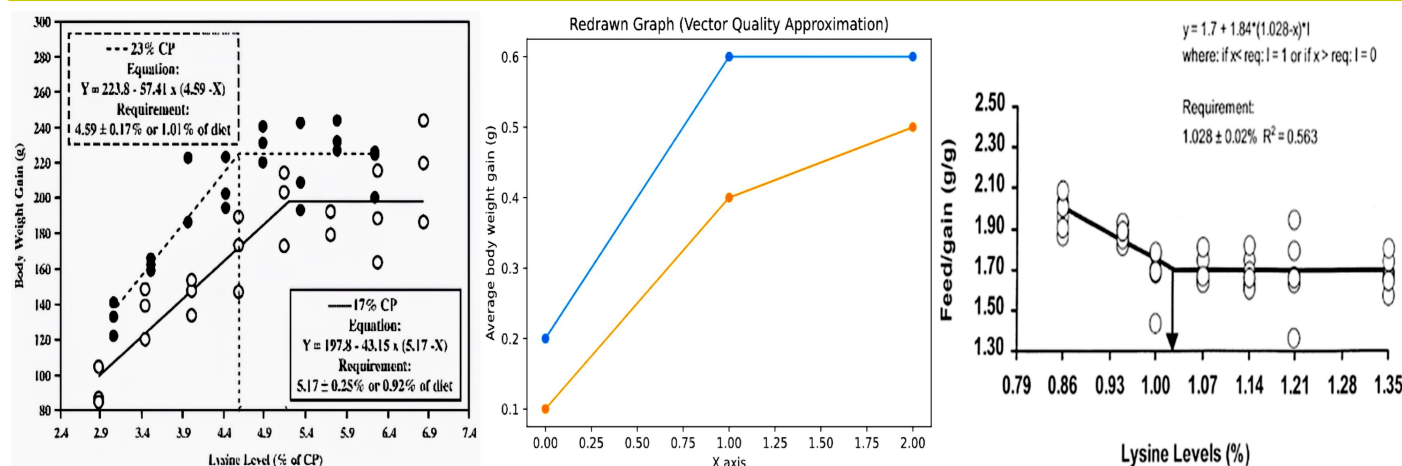


Fig. 2. Shows the supplementation process to determine the amount of lysine required for broiler chickens. The biological response observed was an increase in body weight, as shown by the broken-line linear regression approach. This method allows for the gradual addition of lysine to a deficient basal diet, while other amino acids are maintained at sufficient levels. As a result, the growth response shows a specific requirement for lysine (Taghinejad-Roudbaneh et al. 2011)

contemporary broiler chickens (Sarsour and Persia 2022). Although supplementation-based approaches, particularly the broken-line regression model, are widely used due to their practical simplicity and biological relevance, several limitations must be considered. The breakpoint identified in these models may vary depending on the selected response criteria, experimental conditions, and statistical assumptions, potentially leading to underestimation or overestimation of true amino acid requirements (Kidd et al. 2021; Sarsour and Persia 2022). Moreover, these approaches typically evaluate one limiting amino acid at a time under controlled conditions, which may not fully reflect the complex interactions among multiple amino acids in practical feeding systems. In addition, responses observed under experimental settings may differ from commercial production environments, where factors such as stress, health status, and feed variability play significant roles. Therefore, while supplementation-based methods remain valuable, their application should be interpreted cautiously and ideally integrated with modeling approaches and field validation to improve the accuracy and applicability of amino acid requirement estimations in modern broiler production systems.

10. Conclusions

The ideal protein concept provides a robust and flexible framework for optimizing amino acid utilization in broiler nutrition by ensuring a balanced profile of essential amino acids relative to lysine. The findings of this review indicate that precise amino acid formulation, adjusted for growth stage, genetic potential, and environmental conditions, can improve feed efficiency, enhance growth performance, and reduce nitrogen excretion. However, the findings also demonstrate that amino acid requirements are dynamic and influenced by multiple interacting factors, including response criteria, dietary protein levels, and production systems, leading to variability across studies. Therefore, no single approach can universally define optimal amino acid ratios, highlighting the need for integrative strategies that combine supplementation trials, dose-response modeling, and mechanistic approaches. Future research should focus on refining dynamic models under varying production conditions, standardizing response criteria, and evaluating the practical application of the ideal protein concept in commercial systems, particularly in developing countries. These efforts

are essential to improve the precision, applicability, and sustainability of broiler feed formulation in modern poultry production.

Declarations

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