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Toward precision phosphorus nutrition in broilers: insights from a meta-analytical model assessment

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ABSTRACT - This study used a systematic review and meta-analysis to evaluate a model for estimating the available phosphorus (aP) requirements of broilers. Databases (PubMed, Scopus, and Web of Science) were searched using the PICo methodology, including 90 studies from 1997–2023. The variables analyzed included performance (average daily gain (ADG) and feed efficiency (FE)) and bone traits (tibia P, ash, and shear force), expressed relative to the highest response in each study. The aP levels were compared to the Brazilian Tables for Poultry and Swine (BT), which were considered 100% aligned with the BT recommendations. Nonlinear regressions assessed the responses by phase (starter, grower, and finisher). In the starter phase, aP intake to maximize ADG and FE was 99% of the BT recommendations, with similar results for FE during the grower phase (99%), indicating slight overestimation. However, the ADG requirements in the grower and finisher phases were underestimated (102% of BT recommendations). The FE in the finisher phase matched BT recommendations (100%). Bone traits required a slightly higher aP intake (>100%) across all phases. The BT model reliably estimates aP needs, but may require additional supplementation to optimize bone mineralization.

Keywords: meta-analysis, minerals, modeling, nutrition, poultry, systematic review

1. Introduction

Phosphorus (P) is the second most abundant mineral in the animal body, and approximately 80% is present in bones (González and Silva, 2019), being essential for the formation of the organic bone matrix as well as the mineralization of the matrix. Adequate bone mineralization plays a fundamental role in poultry farming, as muscle development depends on solid bone support and is essential for the proper functioning of the locomotor system. Chickens with deficiencies in bone development are at risk of fractures during capture, transport, and slaughter operations, resulting in significant losses due to carcass condemnation at the slaughterhouse (Schoulten et al., 2003; Gomes et al., 2004).

The remaining 20% of body phosphorus is widely distributed in the fluids and soft tissues of the body and plays a range of essential roles, such as amino acid and protein synthesis, activity of the Na/K ion pump, participation as a component of phospholipids and nucleic acids, and mediators of energy metabolism through ATP (Suttle, 2010; Li et al., 2016a). The minimum P requirement has not yet been definitively established, as published results vary due to the use of different broiler genetics, age, use of exogenous enzymes (phytase), dietary calcium levels, and different sources of Ca and P that have been studied (Li et al., 2016b). P recommendations to meet the needs of chickens are provided in different nutritional requirements tables, such as the Brazilian Tables for Poultry and Swine (Rostagno et al., 2024), National Research Council (NRC, 1994), and specific nutrient requirement tables for certain commercial broiler breeds. Therefore, there are divergent P recommendations in the literature, making it difficult to determine which should be followed.

The P requirement is an important topic in animal research not only because of its economic relevance but also because of its environmental impact. Usually, guidelines like the Brazilian Tables for Poultry and Swine (Rostagno et al., 2024) prescribe the poultry requirements for these minerals, but nutritionists routinely include a margin of safety for phosphorus when they formulate diets. As a result, excess P eliminated in the environment can result in soil and water contamination, contributing to a growing concern about the accumulation of this mineral in the environment (Runho et al., 2001; Munir and Maqsood, 2013).

There is a range of information available in the literature reporting the responses of broilers to different levels of available P (Catalá-Gregori et al., 2007; Abudabos, 2012a; Li et al., 2016a). However, these experiments were conducted under different conditions, and it is difficult to draw general conclusions from the results. Meta-analysis is a relevant method for analyzing complex phenomena and quantifying relationships based on previous studies (Sauvant et al., 2005). Therefore, the aim of this study was to perform a meta-analysis using available literature data to assess the predictive model proposed by the Brazilian Tables for Poultry and Swine (BT) for estimating available phosphorus (aP) requirements in broilers, based on growth performance and bone mineralization outcomes.

2. Material and methods

2.1. Search strategy and eligibility criteria

In December 2023, a systematic review was conducted by performing an online search of scientific studies in indexing databases, such as PubMed, Scopus, and Web of Science. The search utilized the PICo methodology, which focuses on Population, Interest, and Context of the research (Schardt et al., 2007). Thus, the search key used a combination of keywords to define population (e.g., broiler, chick, chicken, poultry), interest (e.g., phosphorus, P level, phosphorus level), and context (e.g., performance, body weight, average daily gain, weight gain, average daily feed intake, feed intake, feed consumption, feed conversion, feed to gain, feed:gain, feed efficiency, gain to feed, bone quality, bone characteristics, tibia weight, tibia ash, and shear force).

All articles found in each database were exported to the EndNote X9 software, which allowed the organization of the bibliographic references obtained in the indexing databases. The PRISMA flow diagram (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) was applied to select the articles (Moher et al., 2009). The title and abstract of each study were reviewed and evaluated according to the following selection criteria: 1) articles in English with experiments carried out in broiler chickens; 2) the presence of at least three different levels (treatments) of aP in the diets; and 3) reported growth performance results (weight gain, average daily intake, conversion, and feed efficiency) according to the diet phase and/or bone characteristics (tibia P, tibia ash, and shear force). In addition, as a complement to the first search, bibliographic references listed in the selected articles were also reviewed to search for additional studies that could meet the selection criteria for inclusion in the databases. The full version of the selected studies was critically evaluated for their quality and relevance, considering the objective of this systematic review.

2.2. Database construction

Studies in the database were published between 1997 and 2023. Additionally, as a complement to the search, all reference lists of the selected studies were reviewed to search for additional studies that met the selection criteria for inclusion in the database. These scientific publications were evaluated according to the same selection criteria used in the previous step. After the final selection, data from the articles were transferred to a Microsoft Excel® spreadsheet, where each row of the spreadsheet represented a treatment and each column represented a variable. For each article/treatment, two moderator codes were applied: a) general code (study effect): each dose-response study received a sequential number; and (b) intra-code: composed of the general code plus a sequential number representing the treatment (e.g., article 1, treatment 01 – 1 + 01 = 101). Growth performance results, such as average daily weight gain (ADG), average daily feed intake (ADFI), feed conversion ratio (FCR), and feed efficiency (FE), were collected as raw data and later used as relative information.

To reduce heterogeneity among studies, performance responses from each treatment were expressed relative to the response observed in the treatment with the highest value within the same experiment. This standardization approach allowed comparisons across trials despite differences in experimental design and response magnitude. For instance, if in study A, the highest ADG was 55 g/day and in study B it was 52 g/day, these values were normalized to 100% within each study, and all other treatments were scaled proportionally (e.g., the treatment with the highest ADG in each study was considered 100%). Although this method may obscure absolute performance differences, it preserves within-study treatment effects and facilitates meta-analytical modeling.

The consumption of aP was also standardized relative to the BT recommendations (i.e., the values were considered 100% if they were totally following the recommendations in the tables). Models available in the most recent version of the BT (2024) were used, as follows:

Equation I - 1 to 21 days: $y = (0.026 \times BW^{0.75}) + (6.0 \times ADG)$

Equation II - 22 to 42 days: $y = (0.026 \times BW^{0.75}) + (5.0 \times ADG)$

in which y is the aP requirement, in g of aP per day; BW is the body weight, in kg; and ADG is the daily weight gain, in kg.

The BT was selected as a baseline due to its updated prediction models and relevance in the Brazilian market. This allowed a consistent comparison of relative aP intake across diverse studies, while recognizing that absolute values may vary depending on local practices.

The database was divided into three phases: starter (1 to 10 d), grower (11 to 21 d), and finisher (≥ 22 d). The studies were assigned to each phase, based on the initial and final ages of the experimental birds. Studies that included ages belonging to two of the phases described above were assigned to the one in which most of the study period belonged (i.e., if a study was conducted with broilers from 1 to 15 days, that study was considered to be in the starter phase (10 days) and not in the grower phase (only 5 days)).

2.3. Statistical analysis

Characteristics such as bibliographic information, genetics, and sex were used to perform a descriptive and graphical analysis of the studies present in the database to verify the coherence of the data. In the modeling stage, aP intake was considered the independent variable in a series of sequential analyses performed individually for each dependent variable (growth performance or bone mineralization characteristics). Only studies with at least one level lower and at least one level higher than the recommended aP estimated in BT were considered for modeling. In addition, treatments with aP content higher than 140% of the recommendations of the test model were also removed. This cutoff was applied because excessive dietary aP content can form insoluble complexes in the intestinal lumen, which reduce nutrient digestibility and impair performance. Therefore, data points with aP intake far above practical feeding levels were considered physiologically unrealistic and potentially confounding for model fitting.

Exponential regressions were first adjusted by the NLIN procedure using subgroups of data (one equation for each article). The data obtained were explored using descriptive statistics and were used as starting points in the following procedure. At this stage, new models were adjusted using the NLMIXED procedure to combine the models generated by each dose-response treatment present in the database, considering the random effect of the studies included. This method accounts for unmeasured inter-study variability and reduces the risk of confounding. Thus, a general model was obtained for each dependent variable that considered the variability among the studies. Finally, a new analysis was performed using the 'by' option to generate specific equations for each production phase (starter, grower, and finisher). The nonlinear common plateau asymptotic regression equation fitted was:

$$y = b0 + b1 \times (1 - exp\ (-b2\ (x - b3)))$$

Later, the optimal level of x was obtained by the following equation:

$$Optimal\ level = (\ln\ (0.05)\ /\ -b2) + b3$$

in which y is the dependent variable; x is the relation between intake and current requirement of aP; $b0$ is the response for the dependent variable estimated for the feed with the lowest level of x; $b1$ is the difference estimated between the minimum and maximum response obtained by increasing x; $b2$ is the slope of the exponential curve; $b3$ is the x at the lowest level. All analyses were performed using SAS statistical software (SAS Institute, v. 9.3).

3. Results

3.1. Literature search results

The PRISMA diagram illustrating the studies identified and selected at each stage of the literature search is presented in Figure 1. After searching the indexing databases, 1,934 references were identified and imported from the databases from which 748 duplicate references were removed. In the exclusion stage, based on the titles and abstracts of the studies, 1,002 studies were excluded because they did not fall within the established scope. Furthermore, 94 studies were excluded because they included fewer than three levels of aP, did not report performance responses, or reported responses inconsistent with the diet phase. After evaluating the full articles and their references, 90 studies were selected and included in this meta-analysis.

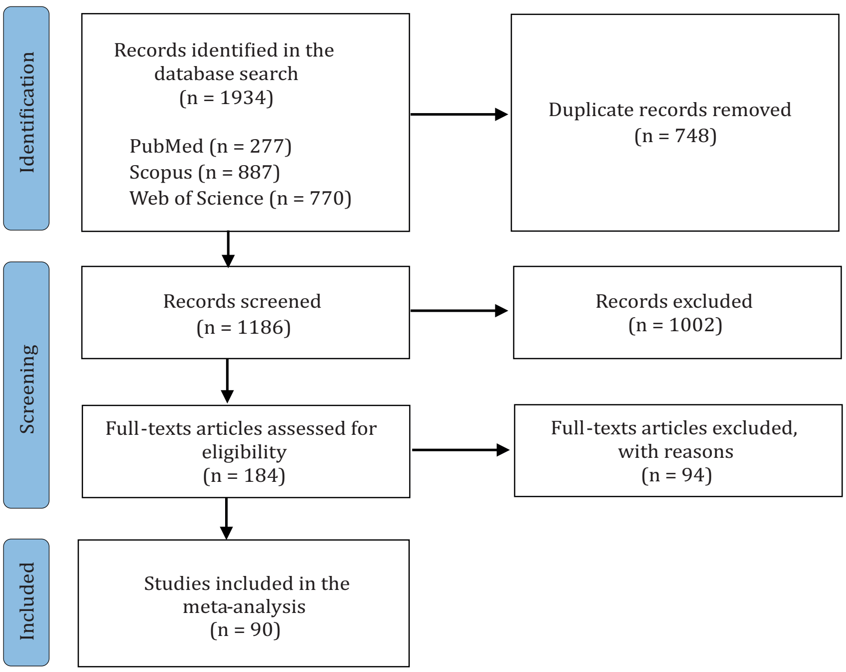


Figure 1 - PRISMA flow diagram describing the selection process of the studies.

3.2. Description of the database

The studies included in the database were published between 1997 and 2023 (Table 1). Only 3 studies did not report aP levels, and 43% of the studies reported phytase treatments. Most studies were conducted in the United States and Brazil, with 19 and 16 articles, respectively (Figure 2). The selected studies included 74,519 broilers, of which 6% were mixed groups (females and males), 71% were male, 8% were female, and 15% were not described. A wide diversity of genetic lineages has been described in the articles. Of these, the most cited were Ross and Cobb.

Table 1 - Description of the 90 studies in the database

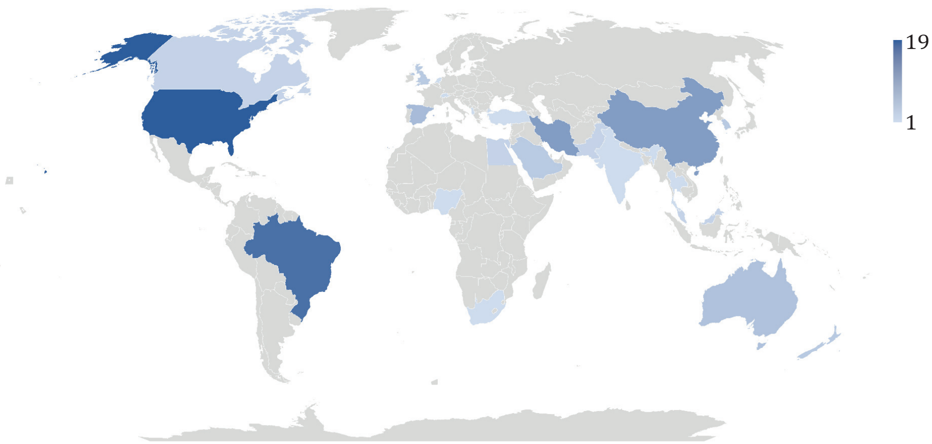
Code	Reference	aP[1] (%)	Variables analyzed[2]						
			ADG	ADFI	FCR	FE	TA	TP	SF
1	Abdulla et al. (2016)	0.35-0.68	+	+	+	+	-	-	-
2	Abdulla et al. (2017)	0.35-0.68	+	+	+	+	+	+	-
3	Abudabos (2012a)	0.14-0.29	+	+	+	+	+	+	-
4	Abudabos (2012b)	0.13-0.40	+	+	+	+	-	-	-
5	Abudabos (2012c)	0.13-0.40	+	+	+	+	+	-	-
6	Adeola and Sands (2004)	0.40-0.55	+	+	+	+	+	-	-
7	Adeola and Walk (2013)	0.12-0.34	+	+	+	+	+	-	-
8	Aderibigbe et al. (2022)	0.12-0.44	+	+	+	+	-	-	-
9	Ahmad et al. (2023)	0.25-0.45	+	+	+	+	-	-	-
10	Akter et al. (2016)	0.30-0.40	+	+	+	+	+	+	-
11	Baradaran et al. (2014)	0.15-0.40	+	+	+	+	-	-	-
12	Bertechini et al. (2022)	0.20-0.40	+	+	+	+	+	+	-
13	Beyranvand et al. (2018)	0.39-0.49	+	+	+	+	+	+	+
14	Cabahug et al. (1999)	0.23-0.45	+	+	+	+	-	-	-
15	Cardoso Júnior et al. (2010)	0.27-0.42	+	+	+	+	+	-	-
16	Catalá-Gregori et al. (2007)	0.16-0.50	+	+	+	+	-	-	-
17	Cavalcanti and Behnke (2004)	0.35-0.50	+	+	+	+	-	-	-
18	Coon et al. (2007)	0.14-0.85	+	+	+	+	-	-	-
19	Coto et al. (2008a)	0.35-0.50	+	+	+	+	-	-	-
20	Coto et al. (2008b)	0.35-0.50	+	+	+	+	-	-	-
21	Cowieson et al. (2020)	0.35-0.48	+	+	+	+	-	-	-
22	David et al. (2022)	-	+	+	+	+	+	+	-
23	David et al. (2023)	-	+	+	+	+	+	+	-
24	Dhandu and Angel (2003)	0.10-0.31	+	+	+	+	+	-	+
25	Driver et al. (2005)	0.20-0.50	+	+	+	+	+	-	-
26	El-Sherbiny et al. (2010)	0.13-0.40	+	+	+	+	+	+	-
27	Garcia et al. (2006)	0.22-0.40	+	+	+	+	+	-	-
28	Gautier et al. (2017)	0.20-0.80	+	+	+	+	+	-	+
29	Gautier et al. (2018)	0.29-0.50	+	+	+	+	-	+	-
30	Gomes et al. (2004)	0.15-0.60	+	+	+	+	+	+	+
31	Gürbüz et al. (2009)	0.13-0.49	+	+	+	+	+	-	-
32	Hamdi et al. (2015a)	0.25-0.45	+	+	+	+	+	-	-
33	Hamdi et al. (2015b)	0.30-0.45	+	+	+	+	+	-	-
34	Hamdi et al. (2017)	0.27-0.42	+	+	+	+	+	-	-
35	Han et al. (2015)	0.20-0.45	+	+	+	+	+	+	+
36	Han et al. (2016)	0.35	+	+	+	+	+	+	+
37	Han et al. (2018)	0.25-0.65	+	+	+	+	+	+	-
38	Hassan et al. (2016)	0.21-0.45	+	+	+	+	-	-	-
39	Hu et al. (2020)	0.32	+	+	+	+	-	-	-
40	Imari et al. (2020)	0.28-0.48	+	+	+	+	+	+	-
41	Iqbal et al. (2023)	0.20-0.50	+	+	+	+	-	-	-
42	Iyayi et al. (2013)	0.14-0.23	+	+	+	+	+	-	-

Continues...

Table 1 (Continued)

Code	Reference	aP[1] (%)	Variables analyzed[2]						
			ADG	ADFI	FCR	FE	TA	TP	SF
43	Jiang et al. (2013)	0.15-0.45	+	+	+	+	+	+	+
44	Kahindi et al. (2017)	0.25-0.45	+	+	+	+	+	-	-
45	Karimi (2005)	0.29-0.45	+	+	+	+	-	-	-
46	Karimi et al. (2013)	0.15-0.45	+	+	+	+	+	-	-
47	Kiani and Taheri (2022)	-	+	+	+	+	-	-	-
48	Kwon et al. (2022)	0.10-0.40	+	+	+	+	+	-	-
49	Laurentiz et al. (2009)	0.17-0.45	+	+	+	+	-	-	-
50	Lee et al. (2017)	0.22-0.60	+	+	+	+	+	+	+
51	Leytem et al. (2008)	0.26-0.51	+	+	+	+	-	-	-
52	Li et al. (2016a)	0.27-1.13	+	+	+	+	-	-	-
53	Li et al. (2000)	0.20-0.45	+	+	+	+	+	-	-
54	Lim et al. (2001)	0.15-0.45	+	+	+	+	-	-	-
55	Lima et al. (1997)	0.15-0.45	+	+	+	+	-	-	-
56	Liu et al. (2016)	0.18-0.57	+	+	+	+	+	+	+
57	Mello et al. (2012a)	0.17-0.55	+	+	+	+	+	+	-
58	Mello et al. (2012b)	0.17-0.55	+	+	+	+	+	+	-
59	Miao et al. (2017)	0.23-0.68	+	+	+	+	-	-	-
60	Moghadam (2006)	0.20-0.30	+	+	+	+	+	+	-
61	Moradi et al. (2023)	0.33-0.48	+	+	+	+	-	-	-
62	Namini et al. (2012)	0.14-0.33	+	+	+	+	-	-	-
63	Nardelli et al. (2018)	0.11-0.34	+	+	+	+	+	+	-
64	Onyango et al. (2003)	0.13-0.50	+	+	+	+	+	-	+
65	Panda et al. (2007)	0.30-0.45	+	+	+	+	+	-	+
66	Peng et al. (2003)	0.29-0.45	+	+	+	+	-	-	-
67	Pereira and Adeola (2016)	0.12-0.35	+	+	+	+	-	-	-
68	Persia and Saylor (2006)	0.13-0.53	+	+	+	+	+	-	-
69	Powell et al. (2011)	0.40	+	+	+	+	-	-	-
70	Ribeiro et al. (2003)	0.16-0.36	+	+	+	+	+	-	+
71	Ribeiro Jr. et al. (2016)	0.18-0.45	+	+	+	+	+	+	-
72	Runho et al. (2001)	0.15-0.65	+	+	+	+	+	+	+
73	Santos et al. (2011)	0.29-0.47	+	+	+	+	+	-	-
74	Santos et al. (2019)	0.18-0.45	+	+	+	+	+	-	-
75	Sharma et al. (2018)	0.30-0.50	+	+	+	+	-	-	-
76	Shaw et al. (2011)	0.22-0.38	+	+	+	+	+	-	+
77	Silva et al. (2006)	0.25-0.45	+	+	+	+	-	-	-
78	Solomon et al. (2022)	0.23-0.43	+	+	+	+	+	+	-
79	Sun et al. (2018)	0.28-0.36	+	+	+	+	-	-	-
80	Tay-Zar et al. (2019)	0.23-0.53	+	+	+	+	+	-	+
81	Um et al. (2000)	0.12-0.45	+	+	+	+	-	-	-
82	Valable et al. (2018)	0.26-0.40	+	+	+	+	-	-	-
83	Vieira et al. (2015)	0.14-0.42	+	+	+	+	+	+	-
84	Viveros et al. (2002)	0.14-0.45	+	+	+	+	-	-	-
85	Waldroup et al. (2000)	0.10-0.50	+	+	+	+	+	-	-
86	Wang and Kim (2021)	0.20-0.44	+	+	+	+	+	-	-
87	Wilkinson et al. (2014)	0.25-0.55	+	+	+	+	+	-	-
88	Wu et al. (2004)	0.20-0.48	+	+	+	+	-	-	-
89	Yan et al. (2001)	0.10-0.45	+	+	+	+	+	-	-
90	Yan et al. (2004)	0.20-0.50	+	+	+	+	+	-	-

ADG - average daily gain; ADFI - average daily feed intake; FCR - feed conversion ratio; TA - tibia ash; TP - tibia phosphorus; SF - shear force.
[1] Variation (minimum and maximum) of P available in each study.
[2] Presence (+) or absence (-) of the variable in each study.

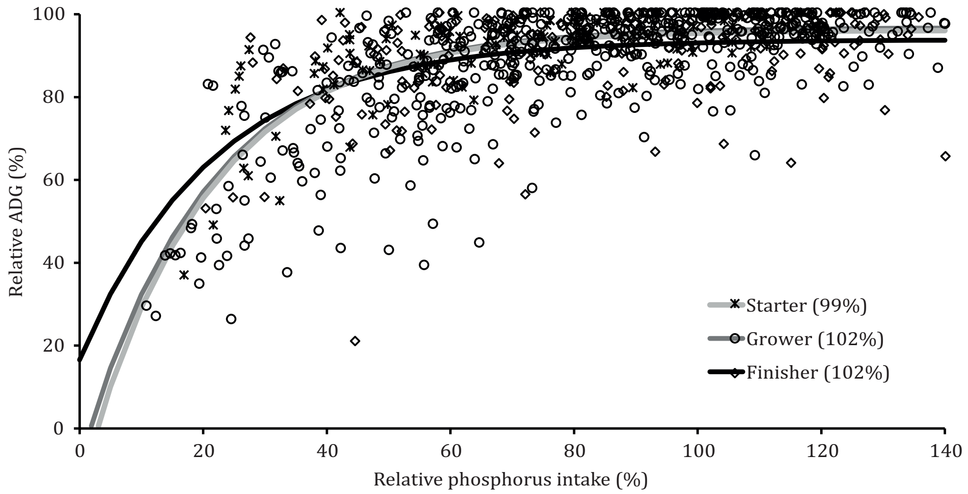


[1] In cases of international collaboration, the country where the experimental work was conducted was prioritized. When this information was not explicitly stated, the country of the first author's institutional affiliation was used.

Figure 2 - Origin[1] of the studies that were used to build the database.

3.3. Exploratory analysis

In addition to age, the aP level recommended to optimize broiler growth performance varied depending on the variables evaluated. Using the exponential model, the relative P intake required to maximize ADG was 99% of the baseline BT recommendations, suggesting a slight trend toward overestimation (Figure 3). On the other hand, the grower (102%) and finisher (102%) phases showed a higher estimate of relative P intake, indicating a marginal potential underestimation. A slight overestimation of BT was identified for FE because the relative intake of P was 99% of the

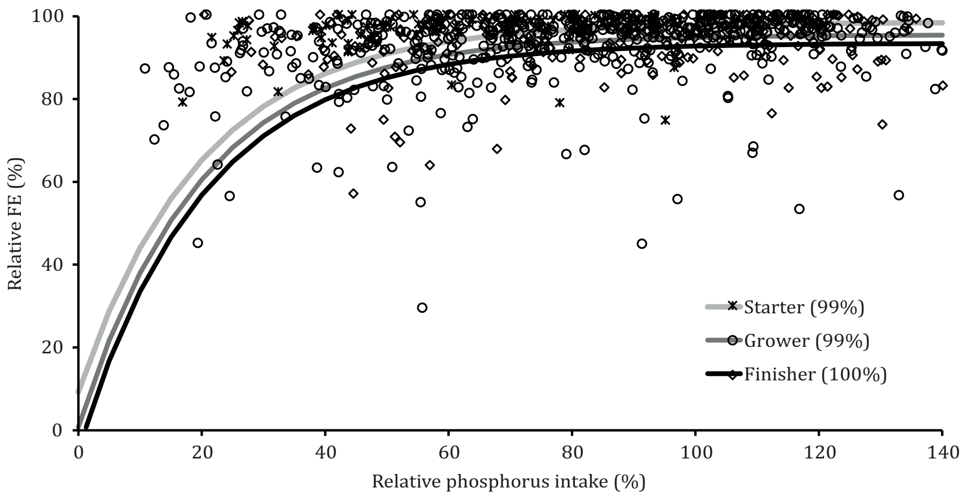


[1] Daily gain was expressed relative to the highest response in each study. Phosphorus intake was standardized to the Brazilian Tables for Poultry and Swine.

Figure 3 - Effect of relative available phosphorus intake on the average daily weight gain (ADG) of broilers[1].

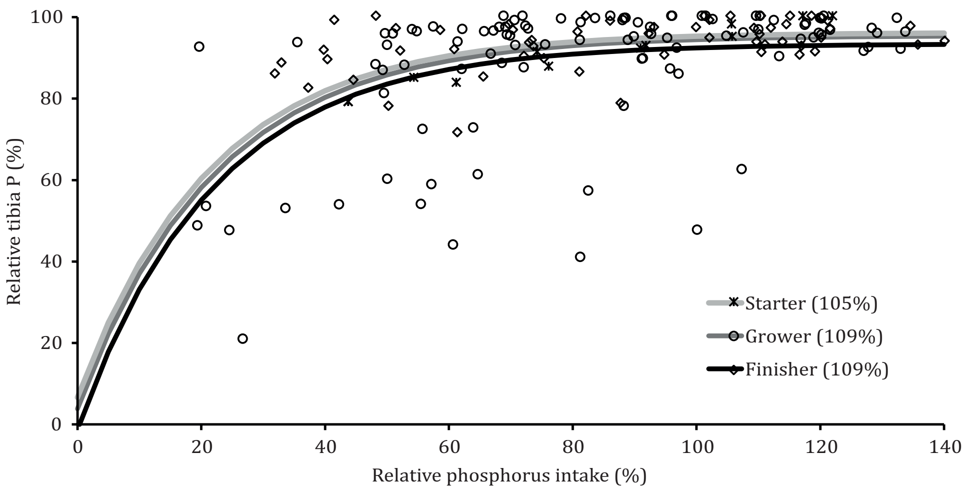
recommendations for the starter and grower phases (Figure 4). However, in the finisher phase, the estimate of relative P consumption reached exactly (100%) the recommendation suggested by the BT. Given the proximity of all these values to 100%, the model results should be interpreted as indicative of general alignment with BT values, rather than evidence for precise dietary adjustment.

The relative intake of P that maximized the bone mineralization characteristics of the broilers was higher than the recommendations established in the BT in all responses and in the three phases studied, suggesting an underestimation, especially in the final phase. The values obtained for maximum P deposition in the tibia ranged from 105% (starter) to 109% (grower and finisher) of the BT recommendations (Figure 5). A similar behavior was observed for the bone ash characteristics, with



[1] Feed efficiency was expressed relative to the highest response in each study. Phosphorus intake was standardized to the Brazilian Tables for Poultry and Swine.

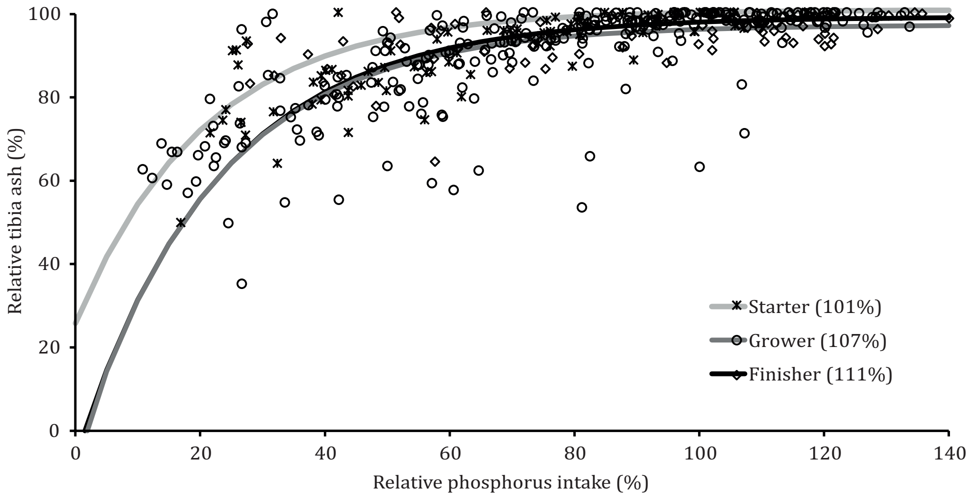
Figure 4 - Effect of relative available phosphorus intake on the feed efficiency (FE) of broilers[1].



[1] Tibia phosphorus was expressed relative to the highest response in each study. Phosphorus intake was standardized to the Brazilian Tables for Poultry and Swine.

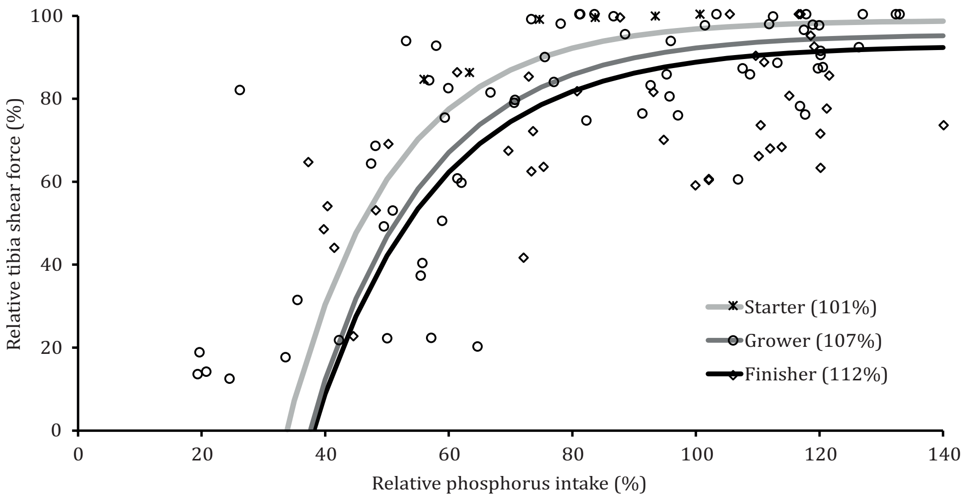
Figure 5 - Effect of relative available phosphorus intake on the tibia phosphorus of broilers[1].

adjustment values between 101 (starter) and 111% (finisher) of the recommendation of the proposed models in BT (Figure 6). Finally, the shear force was maximized at levels between 101 (starter) and 112% (finisher) of the current recommendations of the tested models (Figure 7).



[1] Tibia ash was expressed relative to the highest response in each study. Phosphorus intake was standardized to the Brazilian Tables for Poultry and Swine.

Figure 6 - Effect of relative available phosphorus intake on the tibia ash of broilers[1].



[1] Shear force was expressed relative to the highest response in each study. Phosphorus intake was standardized to the Brazilian Tables for Poultry and Swine.

Figure 7 - Effect of relative available phosphorus intake on the shear force measured in tibias of broilers[1].

4. Discussion

Assessing the predictive model proposed by the BT was a key objective of this study. The BT differ from fixed-value guidelines by providing mathematical equations that estimate daily aP intake based on metabolic weight and expected growth. This approach enhances flexibility and applicability across different production systems. Although the BT were developed using data from Brazil, their model structure allows for extrapolation to other contexts, provided that input variables are accurately adjusted to local conditions. Therefore, the alignment or deviation of published data from BT predictions offers valuable insight into the robustness and potential limitations of this modeling strategy.

The modeling results revealed an overestimation in the starter phase of ADG. This outcome is a relevant condition in the context of sustainability because excess supplemented minerals (beyond the physiological limit required for maximum retention) are excreted, generating both environmental and economic concerns (Manangi and Coon, 2007). In general, several factors can influence P absorption and, consequently, animal growth performance. For example, higher ratios of Ca and non-phytic P (NPP; these two elements have the propensity to form Ca phosphate, an insoluble complex in the intestines of chickens) can reduce nutrient absorption, which negatively affects the ADG and ADFI of animals (Underwood, 1981; Georgievskii et al., 1982; Rama Rao et al., 2006). Thus, only levels lower than 140% of the BT recommendations were used in this modeling stage.

Current results align with the literature showing that high dietary P concentrations can enhance growth performance (ADG and FCR) but reduce mineral ileal digestibility (Ca and P) and increase fecal excretion (Van Krimpen et al., 2013). On the other hand, the model showed that tibial ash and shear force values approached the table recommendations across all phases. However, achieving optimal bone mineralization and strength appears to require P levels slightly above those recommended by BT, especially in the grower and finisher phases. This is consistent with the findings of Létourneau-Montminy et al. (2010), who observed that for each NPP dietary level, Ca should be adjusted to the level that optimizes P utilization, so that there is an appropriate balance between growth performance and bone mineralization.

Although the values of the relative P intake for tibial ash and shear force were close to the current recommendations for all phases, it would be necessary to include higher amounts of P. This would allow an adequate intake of P, as well as ensure adequate mineral content in the tibia and maximize the shear force to obtain healthier bones and, therefore, better animal welfare. In general, changes in diet affect body weight gain and bone mineralization differently, possibly because approximately 80% of total P in the body is present in the skeleton of birds (Yi et al., 1996; Waldroup et al., 2000). Bone ash is a critical measure of bone mineralization, and chickens with bone disorders often have a lower percentage of bone ash than healthy chickens (Shim et al., 2012). Increases or decreases in this concentration may indicate an efficiency or deficiency in the use of P present in the diet of broilers, which is an important parameter for evaluating the nutritional quality and efficacy of feed formulations for broilers.

Increased intake of Ca and NPP is intended for the synthesis and deposition of hydroxyapatite in the bone, resulting in increased bone mineralization. This result, considering that body weight gain is not as sensitive as a measure of Ca and NPP requirements, suggests that the concentrations required to maximize bone mineralization are probably higher than the concentrations required to maximize growth performance (Waldroup et al., 2000; Dhandu and Angel, 2003; Gautier et al., 2017). In contrast, Persia and Saylor (2006) observed that, although the concentration of ash in the tibia provides consistent results and represents a direct measure of P status, ADG, and ADFI would be more applicable to verify P requirements. In contrast, Faridi et al. (2015) reported that the amount of ash in the tibia, specifically in broilers, is a sensitive indicator of P used by chickens. Similar results were reported by Van Krimpen (2013), who found that the ash content of the tibia was reduced when birds were fed a diet with low P content and low Ca:P ratio; however, the performance characteristics were not affected.

Mineralization affects bone strength, enables the skeleton to withstand gravity and additional loads, and is crucial to ensure that the bones are strong enough to support the weight of the body (Shim et al., 2012). Thus, rupture, density, mineral content, and bone ash are used as indicators of bone state in poultry mineral nutrition research (Watkins and Southern, 1992; Onyango et al., 2003; Shim et al., 2008). The amount of ash present in bone is proportional to its degree of hardness or compressive strength. The organic component of the bone is important for providing tensile strength and flexibility, and these two components contribute to the rupture strength (Rath et al., 1999; Velleman, 2000; Bonser and Casinos, 2003). A paradox occurs in relation to Ca and P levels in broilers, where it is sought to optimize bone performance and mineralization and, on the other hand, to minimize P excretion and reduce environmental pollution. This dilemma has been accentuated by the search for broiler chickens with high yield, selected to reduce the time needed to reach the desired body weight and FE, causing adverse effects on the skeletal system of these animals (Faridi et al., 2015). The observed mismatch between P levels for optimal growth and bone strength highlights a critical nutritional paradox: while the industry prioritizes performance, ensuring skeletal health may require higher P inclusion, potentially at the cost of greater environmental P output. Therefore, a higher incidence of musculoskeletal problems may occur in high-performance broilers (Bessi, 2006).

The fact that BT has a lower P requirement compared to other tables, together with the lack of articles conducted in the final phase of the present study, may explain the slight overestimation observed in the variables analyzed, especially in bone characteristics. This suggests the importance of conducting more specific studies in this phase to ensure accurate models of P requirement, since precision feeding allows adjusting the nutrient supply to the specific needs of each chicken for each phase. This will facilitate formulation, which will be more accurate, in addition to reducing costs, minimizing nutrient excretion, and increasing efficiency in the use of resources, thereby contributing to sustainable poultry production (Zuidhof, 2020).

5. Conclusions

This meta-analysis demonstrates that the estimated aP intake required to maximize broiler growth performance is generally aligned with the Brazilian Tables, with minor deviations depending on the production phase and evaluated variable. For ADG and FE, the predicted optimal aP intake was close to the recommendations of the Brazilian Tables, suggesting no need for major adjustments in practical feeding programs. However, maximizing bone mineralization traits required slightly higher aP intake values, particularly in the grower and finisher phases. These findings underscore the need to balance growth performance with bone quality, reinforcing the utility of predictive models to guide precise and sustainable nutrient formulation.

Data availability

The entire dataset supporting the results of this study is available upon request to the corresponding author.

Author contributions

Conceptualization: Miranda, A.; Franceschi, C. H.; Mariani, A. B.; Kipper, M. and Andretta, I. **Data curation:** Miranda, A.; Franceschi, C. H.; Mariani, A. B.; Nogueira, D. V. and Andretta, I. **Formal analysis:** Miranda, A. and Andretta, I. **Investigation:** Miranda, A. **Methodology:** Franceschi, C. H.; Mariani, A. B. and Andretta, I. **Supervision:** Andretta, I. **Visualization:** Franceschi, C. H.; Mariani, A. B.; Silva, J. P.; Galli, G. M. and Kipper, M. **Writing – original draft:** Miranda, A. **Writing – review & editing:** Miranda, A.; Franceschi, C. H.; Mariani, A. B.; Silva, J. P.; Nogueira, D. V.; Galli, G. M.; Kipper, M. and Andretta, I.

Conflict of interest

The authors declare no conflict of interest.

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