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Phytase supplementation effects on performance and tibia ash content in male broilers (22-42 days of age): A systematic review and meta-analysis

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ABSTRACT - The finisher phase (22 to 42 days post-hatching) is a critical period in broiler production due to its high feed consumption and growth rate. This study performed a systematic review and meta-analysis of 21 peer-reviewed articles, comprising data from 10,706 male broilers aged 22 to 42 days, to quantify the effects of phytase (PHY) supplementation during this critical phase. A mixed-effects model was used to assess the impacts of PHY, dietary non-phytate phosphorus (NPP), and the calcium to non-phytate phosphorus (Ca:NPP) ratio, including their interactions, on average daily gain (ADG), average daily feed intake (ADFI), feed conversion ratio (FCR), and tibia ash content. PHY supplementation improved growth performance and tibia ash content ($P<0.05$), with more pronounced effects observed in low-NPP diets. Additionally, increasing dietary NPP levels also enhanced growth performance and tibia ash content. However, higher Ca:NPP ratios negatively affected ADG, ADFI, FCR, and tibia ash content, particularly in diets without PHY supplementation. These findings highlight the positive effects of PHY supplementation, reinforcing its benefits for improving growth performance, FCR, and tibia ash content in male broilers during the finisher phase.

Keywords: finisher phase, non-phytate phosphorus, poultry

1. Introduction

Calcium (Ca) and phosphorus (P) are essential minerals for broilers, playing key roles in metabolic processes, bone development, and skeletal strength (Létourneau-Montminy et al., 2010; Bougouin et al., 2014; Valente Junior et al., 2024). However, most dietary P in plant-based ingredients is bound to phytic acid ($InsP_6$), which is poorly utilized by poultry due to their limited endogenous phytase (PHY) activity (Sommerfeld et al., 2018; Selle et al., 2023; Sobotik et al., 2023).

In addition, phytate (PP) can bind minerals and nutrients, reducing their bioavailability, and high dietary Ca may aggravate this effect by forming insoluble complexes (Singh and Satyanarayana, 2015; Selle et al., 2023). In this context, inorganic P sources are commonly included in diets, increasing feed costs and contributing to environmental P excretion (Bougouin et al., 2014).

Supplementation with microbial PHY improves P utilization by hydrolyzing $InsP_6$ and releasing non-phytate phosphorus (NPP), thereby enhancing the availability of P, Ca, amino acids, and energy (Cowieson et al., 2006; Walk et al., 2018). However, PHY efficacy and NPP requirements may vary according to age and physiological stage.

Nutrient recommendations indicate reduced Ca and NPP requirements during the finisher phase (22–42 days) compared with the starter phase (NRC, 1994; Rostagno et al., 2024). Despite this reduction, the finisher phase accounts for approximately two-thirds of total feed intake and body weight gain in male broilers (Valable et al., 2018; Aviagen, 2022; Cobb-Vantress, 2022; Hubbard, 2023), making the precise optimization of Ca, NPP, and PHY particularly relevant from economic and environmental perspectives.

Although several studies have evaluated the effects of PHY supplementation, NPP levels, and Ca:NPP ratios, the results remain inconsistent. Meta-analysis provides a robust approach for evaluating complex interactions by quantitatively synthesizing data from multiple studies (Sauvant et al., 2020). To date, only one meta-analysis has specifically addressed male broilers from 22 to 42 days of age, focusing mainly on P- and Ca-deficient conditions (Nuamah et al., 2024). The interactive effects of different PHY inclusion levels, NPP concentrations, and Ca:NPP ratios during the finisher phase remain unclear.

Therefore, this study aimed to conduct a systematic review and meta-analysis to quantify the effects of PHY supplementation, dietary NPP levels, and Ca:NPP ratios on growth performance and tibia ash content in male broilers during the finisher phase.

2. Material and methods

This study exclusively used data from the published literature and did not involve the use of animals, eliminating the need for approval from the Institutional Animal Care and Use Committee.

2.1. Systematic review

A systematic literature search was conducted to identify indexed publications assessing the impact of PHY supplementation on performance and tibia ash content in male broiler chickens aged 22 to 42 days post-hatching. The search was finalized in January 2025 and performed using the databases PubMed, Web of Science, and Scopus. The research strategy was developed using the PICo framework (Andretta et al., 2021), in which the population was defined as broilers, the interest as PHY supplementation, and the context as growth performance or tibia ash content.

Based on this framework, the search strategy used combinations of keywords structured as follows: (“Broiler” OR “Broilers” OR “poultry” OR “poultries” OR “chicken” OR “chickens”) AND (“phytase”) AND (“performance” OR “body weight” OR “average daily gain” OR “feed intake” OR “average daily feed intake” OR “feed conversion ratio” OR “feed efficiency” OR “tibia ash”). Minor adaptations were applied according to the syntax requirements of each database.

Only studies published in English, Portuguese, or Spanish were included, and only peer-reviewed journal articles were considered. To ensure completeness, the reference lists of the selected articles were manually screened for additional relevant publications. All retrieved records were exported to reference management software (EndNote X9, Clarivate Analytics, Philadelphia, PA, USA) for duplicate removal. The relevance of the selected studies was evaluated through a two-stage screening process, beginning with the review of titles and abstracts, followed by a full-text assessment. A flow diagram summarizing the study selection process is presented in Figure 1.

The criteria for selecting publications were as follows: (1) *in vivo* experiments conducted with commercial broiler chicken breeds; (2) experiments including both non-supplemented control diets (negative control) and diets supplemented with commercial PHY; (3) studies reporting performance

parameters, including average daily gain (ADG), average daily feed intake (ADFI), and feed conversion ratio (FCR), or evaluating the effects of PHY on tibia ash content; and (4) studies published from 2000 onward. Publications were excluded if they met any of the following criteria: (1) did not use male broiler chickens or did not specify the sex of the birds; (2) involved sanitary challenges; (3) included treatments combining PHY with other exogenous enzymes; (4) did not include a control treatment; or (5) presented significant inconsistencies in the experimental design, methodology, or reported outcomes.

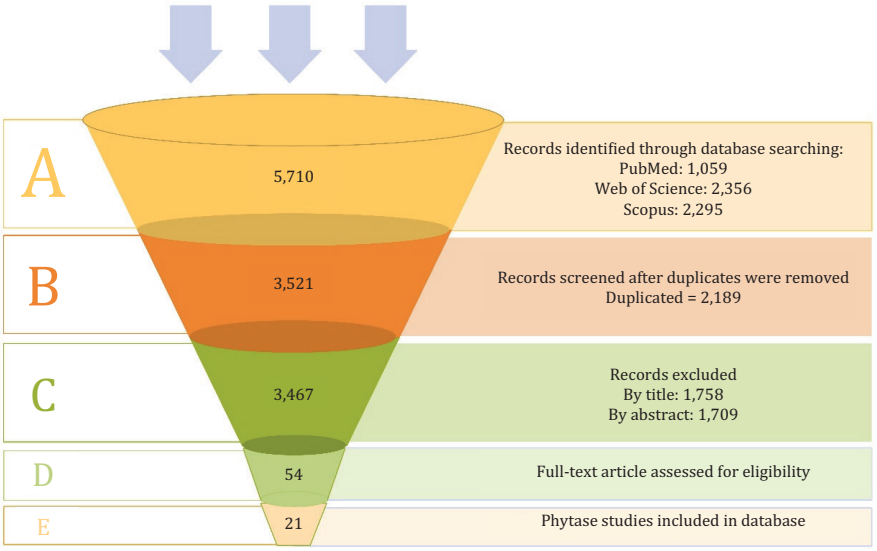


Figure 1 - Study selection diagram illustrating the process used to identify and include studies in the meta-analysis investigating the effects of phytase supplementation in male broilers from 22 to 42 days of age.

Studies were retained in the meta-analysis when treatments included PHY as the sole enzyme and when neither the PHY-supplemented nor the control groups were subjected to sanitary challenges. When other treatments within the same study did not meet these criteria, only the eligible treatments were retained for analysis. Studies or treatments using superdosing of PHY (>2,500 FTU/kg) were excluded due to insufficient available data.

Only studies evaluating broilers aged 22 to 42 days post-hatching, or experiments partially conducted within this period, were considered. When studies reported multiple growth phases (e.g., 1-21 and 22-42 days), only the treatment means corresponding to the finisher phase (22-42 days) were extracted. In studies where the experimental period covered the entire growth cycle (e.g., 1-42 days), only the values reported for the finisher phase were retained when available. Studies in which finisher-phase data could not be clearly isolated were excluded from the dataset. Two studies (Dilger et al., 2004; Ceylan et al., 2012) reported experimental periods slightly different from the target window (22-42 days), specifically 22-40 and 22-43 days. These minor deviations were considered biologically comparable to the defined age window and were therefore retained in the meta-analysis. To ensure a precise evaluation of PHY effects, only non-supplemented diets (negative control) with NPP levels matching those used in the PHY-supplemented treatments were included in the meta-analysis.

Initially, 5,710 studies were identified and screened based on titles and abstracts. A total of 54 studies were assessed for eligibility through full-text review for eligibility. After applying the predefined inclusion and exclusion criteria, 33 publications were excluded. Consequently, 21 publications were included in the final meta-analysis. The complete list of selected studies is presented in Table 1.

Table 1 - Summary of phytase supplementation studies in male broilers (22-42 days of age) included in the meta-analysis, categorized by location, journal, and year of publication

Code	Study	Location	Journal
1	Viveros et al. (2002)	Spain	Poultry Science
2	Dilger et al. (2004)	United States	Poultry Science
3	Wu et al. (2004)	New Zealand	Journal of Applied Poultry Research
4	Zobač et al. (2004)	Czech Republic	Czech Journal of Animal Science
5	Han et al. (2009)	China	Journal of Applied Poultry Research
6	Manangi et al. (2009)	United States	International Journal of Poultry Science
7	Nourmohammadi et al. (2010)	Iran	American Journal of Animal and Veterinary Sciences
8	Junqueira et al. (2011)	Brazil	Acta Scientiarum. Animal Sciences
9	Ceylan et al. (2012)	Turkey	Journal of Animal and Feed Sciences
10	Nourmohammadi et al. (2012)	Iran	Italian Journal of Animal Science
11	Jiang et al. (2013)	China	Italian Journal of Animal Science
12	Midilli et al. (2014)	Turkey	Kafkas Üniversitesi Veteriner Fakültesi Dergisi
13	Taheri et al. (2015a)	Iran	British Poultry Science
14	Taheri et al. (2015b)	Iran	Poultry Science Journal
15	Taheri et al. (2015c)	Iran	British Poultry Science
16	Tizziani et al. (2016)	Brazil	Revista Brasileira de Zootecnia
17	Islam et al. (2017)	Malaysia	Cogent Food & Agriculture
18	Nafea et al. (2019)	Iran	Biochemical and Cellular Archives
19	Mohiti-Asli et al. (2020)	Iran	Italian Journal of Animal Science
20	Javadi et al. (2022)	Spain	Animals
21	França et al. (2023)	Brazil	Livestock Science

2.2. Meta-analysis database construction

The methodology used to build the database, encode the data, and define the variables was based on the approach described by Sauvant et al. (2020). To maintain consistency and comprehensiveness in dietary composition across studies, experiments lacking complete nutrient composition were recalculated using the Practical Program for Formulation of Rations (Garcia-Neto, 2008), considering the Brazilian Tables for Poultry and Swine (Rostagno et al., 2024). When nutritional values were fully reported in the original studies, the published values were used directly; otherwise, missing values were recalculated based on the ingredient composition and the corresponding reference nutrient values. The variability in diet composition within the dataset is summarized in Table 2.

2.3. Statistical analysis

A meta-analytical approach was employed to model the dependent variables following the methodology described by Andretta et al. (2012). The analysis was conducted through a sequential process including graphical exploration, correlation, and variance-covariance analyses. To account for the hierarchical structure of the data and variability among studies, mixed-effects models were fitted with study included as a random effect, allowing the partitioning of variability attributable to differences among studies while estimating the overall relationships between explanatory variables and responses (St-Pierre, 2001). Because the objective of this study was to evaluate quantitative relationships using meta-regression rather than to estimate pooled treatment effect sizes, traditional publication bias diagnostics (e.g., funnel plots or Egger's test) were not applied.

Table 2 - Diet composition variability across studies with male broilers (22-42 days old) included in the dataset

	N[1]	Mean	Minimum	Maximum	SD
Total phosphorus (% of diet)	21	0.53	0.35	1.06	0.17
Phytate phosphorus (% of diet)	21	0.29	0.22	0.70	0.12
Calcium (% of diet)	21	0.81	0.51	1.19	0.14
Metabolizable energy (kcal/kg)	21	3,085	2,914	3,227	96.0
Crude protein (% of diet)	21	19.3	17.0	22.3	0.95
Total lysine (% of diet)	21	1.07	0.90	1.42	0.12
Digestible lysine (% of diet)	21	0.99	0.80	1.30	0.12
Total methionine (% of diet)	21	0.45	0.32	0.60	0.08
Digestible methionine (% of diet)	21	0.41	0.24	0.58	0.09
Total methionine + cysteine (% of diet)	21	0.75	0.34	0.98	0.13
Digestible methionine + cysteine (% of diet)	21	0.69	0.48	0.86	0.10
Total threonine (% of diet)	21	0.75	0.53	0.84	0.07
Digestible threonine (% of diet)	21	0.67	0.53	0.74	0.05
Vitamin D3 (IU/kg of diet)	21	2,670	360	8,800	1,928
Copper (mg/kg of diet)	21	7	2	13	2.8
Zinc (mg/kg of diet)	21	70	17	107	22
Iron (mg/kg of diet)	21	57	14	80	21
Manganese (mg/kg of diet)	21	80	24	125	24
Iodine (mg/kg of diet)	21	0.9	0.2	2.0	0.5
Selenium (mg/kg of diet)	21	0.19	0.03	0.33	0.07
Sodium (% of diet)	21	0.16	0.09	0.21	0.03

[1] Number of studies that reported poultry diet composition.

Each observation corresponded to a treatment mean extracted from the original publications. Because multiple treatments were often reported within the same experiment, the random study effect accounted for the non-independence and clustering of observations within studies. Fixed effects included PHY level, dietary NPP, Ca:NPP ratio, and their interactions, and quadratic terms were evaluated when biologically relevant. The relationships between PHY and NPP, as well as PHY and the Ca:NPP ratio, were analyzed using separate models to avoid collinearity among dietary P variables. Independent variables were tested, and only those that demonstrated statistical significance ($P<0.05$) or a tendency ($P<0.10$) were retained in the final models. Following the approach described by Létourneau-Montminy et al. (2010), the responses of ADG, ADFI, FCR, and tibia ash content were evaluated using quadratic meta-regression models:

$$Y_{ijk} = \alpha + \alpha_i + \beta_1 \text{NPP}_{ij} + \beta_2 \text{PHY}_{ik} + \beta_3 [\text{NPP}_{ij}]^2 + \beta_4 [\text{PHY}_{ik}]^2 + \beta_5 [\text{NPP}_{ij} \times \text{PHY}_{ik}] + e_{ijk} \quad (1)$$

and

$$Y_{ijk} = \alpha + \alpha_i + \beta_1 \text{CaNPP}_{ij} + \beta_2 \text{PHY}_{ik} + \beta_3 [\text{CaNPP}_{ij}]^2 + \beta_4 [\text{PHY}_{ik}]^2 + \beta_5 [\text{CaNPP}_{ij} \times \text{PHY}_{ik}] + e_{ijk} \quad (2)$$

in which Y_{ijk} denotes the dependent variable Y in experiment i, at level j of NPP (for equation 1) or Ca:NPP (for equation 2), and level k of PHY. Parameter α represents the overall fixed-effect intercept, while α_i accounts for the random effect of experiment i. Coefficients β_1 and β_2 correspond to linear effects, β_3 and β_4 capture quadratic effects, and β_5 represents the interaction effect. The term e_{ijk} represents the residual error.

Random effects and residual errors were examined to ensure that they followed a normal distribution. To identify potential outliers, internally studentized residuals (ISR) were investigated, with values exceeding three ($|ISR| > 3$) flagged and excluded from further analysis (Faridi et al., 2015; Kermani et al., 2023). Across all models, over 95% of the ISR values fell within the range of −2 to 2, confirming a good model fit. Model accuracy was assessed using multiple criteria, including the significance of the estimated parameters, standard error (SE), coefficient of determination (R^2), and root mean square error (RMSE). Model adequacy was further assessed by plotting the residuals (observed minus

predicted values) against the predicted values of Y to check for linear prediction bias (St-Pierre, 2001). For optimization, the partial derivatives of the models for each dependent variable were calculated following the methodology described by Létourneau-Montminy et al. (2010).

Statistical analyses were performed using mixed-model procedures in Minitab software (Minitab Inc., State College, PA, USA). Graphs were generated using the ggplot2 package in R (version 4.4.2; R Foundation for Statistical Computing, Vienna, Austria).

3. Results

3.1. Database characterization

The meta-analysis included 21 studies evaluating male broiler chickens 22 to 42 days post-hatching, encompassing a total population of 10,706 male broilers. A total of 86 treatment groups, including the respective control groups, were analyzed. Among the commercial breeds represented, Ross 308 was the most frequently studied (n = 49), followed by Cobb 500 (n = 22) and Arbor Acres (n = 15).

The PHY supplementation varied across studies. Among the 59 treatments that used PHY, 40.7% used 3-phytase (EC 3.1.3.8), whereas 37.3% utilized 6-phytase (EC 3.1.3.26). The remaining 22.0% of the treatments did not specify the PHY type. PHY enzymes were derived from various organisms, including *Aspergillus niger* (44.1%), *Escherichia coli* (28.7%), *Trichoderma reesei* (8.50%), *Enterobacter sakazakii* (5.1%), *Serratia odorifera* (5.1%), *Buttiauxella* sp. (3.4%), and *Peniophora lycii* (3.4%). In addition, 1.7% of the treatments did not specify the donor organism for the exogenous PHY. Furthermore, the final dataset for the meta-analysis included studies conducted in Iran (n = 7), Brazil (n = 3), China, Spain, Turkey, and the United States of America (USA) (n = 2); and the Czech Republic, Malaysia, and New Zealand (n = 1). Most treatments used corn-soybean meal-based diets (77.9%), with a smaller proportion using corn-wheat-soybean meal-based diets (16.3%) or wheat-soybean meal-based diets (5.8%). Only grain-based feedstuffs were included in 82.6% of the diets, while the remaining 17.4% also included animal-based feedstuffs. The feed was presented in various forms: mash (36.0%), cold-pelleted (5.8%), pelleted (4.7%), or unspecified (53.5%). Diets were classified as cold-pelleted diets when the maximum temperature during the pelleting process did not exceed 70 °C (Ravindran et al., 2008). Mineral P supplementation was primarily provided through dicalcium phosphate (89.0%), followed by monocalcium phosphate (6.1%), and tricalcium phosphate (4.9%). Additionally, the dataset revealed that 15.2% of the diets had a Ca:NPP ratio lower than 2:1, while 26.7% had ratios between 2:1 and 3:1. Diets with Ca:NPP ratios between 3:1 and 4:1 accounted for 17.4%, those between 4:1 and 5:1 represented 9.3%, and diets with a ratio greater than 5:1 comprised 31.4% of the dataset.

3.2. Phytase supplementation effects

Summary statistics for the dependent and independent variables included in the meta-analysis of male broilers aged from 22 to 42 days are presented in Table 3.

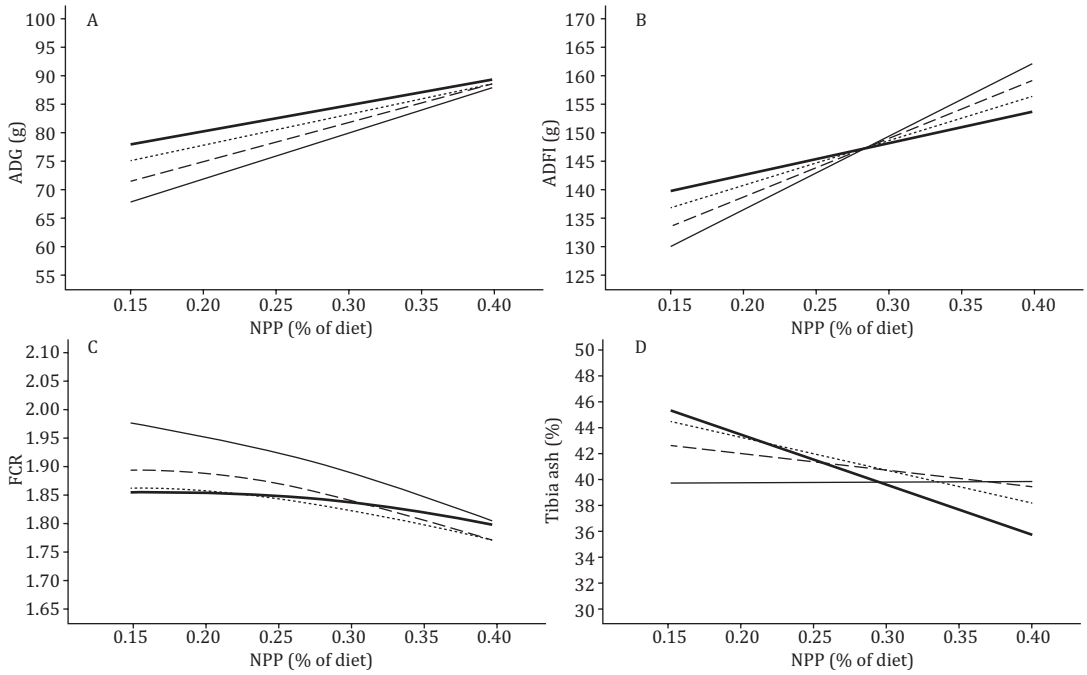
Table 3 - Summary statistics of the data used in the meta-analyses of male broilers aged 22 to 42 days post-hatching

Variable	n	N	Mean	SD	Min.	Max.
Phytase (FTU/kg)	86	21	531	578	0.00	2,500
Non-phytate phosphorus (%)	86	21	0.24	0.09	0.13	0.43
Calcium to non-phytate phosphorus ratio	86	21	3.8	1.8	1.2	6.9
Average daily gain (g/day)	86	21	77.4	14.7	52.1	118.5
Average daily feed intake (g/day)	79	19	146.0	33.6	91.8	231.6
Feed conversion ratio	79	19	1.90	0.27	1.17	2.69
Tibia ash content (%)	21	5	44.7	6.3	32.7	52.7

n - number of observations; N - number of studies; SD - standard deviation; Min. - minimum value of the parameter; Max. - maximum value of the parameter.

Dietary PHY supplementation increased the intercept for ADG and ADFI in male broilers from 22 to 42 days post-hatching, while reducing the intercept for FCR, depending on the dietary NPP and PHY levels (Table 4; Figure 2). The interaction between exogenous PHY supplementation and dietary NPP levels showed a tendency to increase ADG (PHY × NPP; P = 0.092) and significantly increased ADFI (PHY × NPP; P = 0.012), with the strongest effects observed at lower dietary NPP levels exhibited on both ADG and ADFI (P = 0.001; Table 4; Figure 2). The interaction between PHY supplementation and the dietary Ca:NPP ratio on ADG was not significant (P>0.10), and as a result, ADG was excluded from subsequent model development. However, ADFI was significantly affected by PHY supplementation and the dietary Ca:NPP ratio, with greater PHY effects observed at higher Ca:NPP ratios, showing a significant linear effect (P = 0.01).

Diets supplemented with PHY improved FCR in male broilers aged 22 to 42 days post-hatching (Table 4; Figure 2). PHY exerted a significant linear effect (P<0.001), while dietary NPP influenced FCR through significant quadratic effect (P = 0.001), with a tendency for a greater impact in low-NPP diets (PHY × NPP; P = 0.066; Table 4; Figure 2). Additionally, PHY supplementation displayed significant quadratic effects (P = 0.007) on FCR, whereas the dietary Ca:NPP ratio had a significant positive linear effect (P = 0.011) in male broilers (Table 5; Figure 3). Tibia ash content in male broilers aged 22 to 42 days was influenced by PHY supplementation and dietary NPP levels, showing a tendency for a quadratic effect (P = 0.062) for PHY supplementation and a linear effect (P<0.001) of increasing dietary NPP levels (Table 4; Figure 2). The impact of PHY supplementation on tibia ash content was more pronounced at lower dietary NPP levels (PHY × NPP; P = 0.096; Table 4; Figure 2). Furthermore, the



Description of curve types and regression equations for ADG, ADFI, FCR, and tibia ash content. Panels (A)-(D) illustrate model-predicted responses of male broilers (22-42 days of age) to different dietary phytase levels: solid thin line – 0 FTU/kg; dashed thick line – 500 FTU/kg; dotted line – 1,000 FTU/kg; and solid thick line – 1,500 FTU/kg. The regression equations for each performance parameter are as follows: (A) ADG (g) = $56.08 + 1.0 \times 10^{-2} \times$ Phytase + $79.59 \times$ NPP − $2.3 \times 10^{-2} \times$ Phytase × NPP (RMSE = 12.09, $R^2 = 0.94$). (B) ADFI (g) = $111.56 + 1.4 \times 10^{-2} \times$ Phytase + $126.71 \times$ NPP − $4.9 \times 10^{-2} \times$ Phytase × NPP (RMSE = 25.74, $R^2 = 0.98$). (C) FCR = $2.001 - 2.2 \times 10^{-4} \times$ Phytase + $6.4 \times 10^{-8} \times$ Phytase^2 − $1.249 \times$ NPP^2 + $3.2 \times 10^{-4} \times$ Phytase × NPP (RMSE = 0.21, $R^2 = 0.98$). (D) Tibia ash (%) = $39.74 + 1.1 \times 10^{-2} \times$ Phytase − $2.3 \times 10^{-6} \times$ Phytase^2 − $2.6 \times 10^{-2} \times$ Phytase × NPP (RMSE = 4.98, $R^2 = 0.94$).

Figure 2 - Effects of phytase supplementation and non-phytate phosphorus (NPP) levels on average daily gain (ADG, g), average daily feed intake (ADFI, g), feed conversion ratio (FCR), and tibia ash content (%) in male broilers from 22 to 42 days of age.

Table 4 - Effects of phytase supplementation and dietary non-phytate phosphorus (NPP), along with their parameter estimates from the mixed model applied to male broilers from 22 to 42 days of age, on performance and tibia ash content

Male broiler growth performance and tibia ash content models												
	Average daily gain (g/day)			Average daily feed intake (g/day)			Feed conversion ratio			Tibia ash content (%)		
	Coefficient	SE	P	Coefficient	SE	P	Coefficient	SE	P	Coefficient	SE	P
Intercept	56.08	5.28	<0.001	111.56	11.44	<0.001	2.001	8.0×10^{-2}	<0.001	39.74	3.10	<0.001
Phytase	1.0×10^{-2}	2.8×10^{-3}	0.001	1.4×10^{-2}	4.0×10^{-3}	0.001	-2.2×10^{-4}	5.5×10^{-7}	<0.001	1.1×10^{-2}	3.2×10^{-3}	0.009
NPP	79.59	15.05	<0.001	126.71	21.71	<0.001	-	-	NS	-	-	
Phytase^2	-	-	NS	-	-	NS	6.4×10^{-8}	1.9×10^{-10}	0.001	-2.3×10^{-6}	1.0×10^{-6}	0.062
NPP^2	-	-	NS	-	-	NS	−1.249	3.6×10^{-1}	0.001	-	-	NS
Phytase × NPP	-2.3×10^{-2}	1.4×10^{-2}	0.092	-4.9×10^{-2}	1.9×10^{-2}	0.012	3.2×10^{-4}	1.7×10^{-6}	0.066	-2.6×10^{-2}	1.4×10^{-2}	0.096
R^2		0.94			0.98			0.98			0.94	
RMSE		12.09			25.74			0.21			4.98	

RMSE - root mean square error; SE - standard error; NS - not significant (P>0.10).

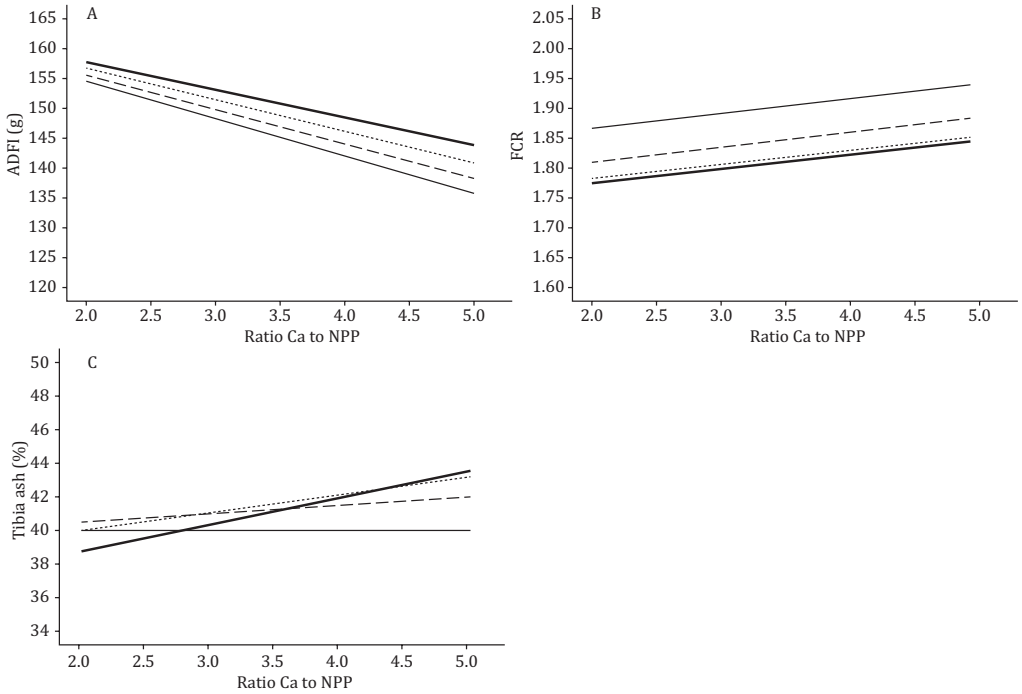
interaction between PHY supplementation and the Ca:NPP ratio had a significant effect on tibia ash content, with a stronger PHY response observed in diets with higher Ca:NPP ratios (PHY × Ca:NPP; P = 0.005; Table 5; Figure 3). Additionally, PHY supplementation influenced tibia ash content in a quadratic pattern (P = 0.049; Table 5; Figure 3).

Table 5 - Effects of phytase supplementation and calcium to non-phytate phosphorus (NPP) (Ca:NPP) ratio on performance and tibia ash content in male broilers from 22 to 42 days of age, along with the parameter estimates from the applied mixed model

Male broiler growth performance and tibia ash content models

	Average daily feed intake (g/day)			Feed conversion ratio			Tibia ash content (%)		
	Coefficient	SE	P	Coefficient	SE	P	Coefficient	SE	P
Intercept	166.69	10.39	<0.001	1.816	0.081	<0.001	39.93	3.00	<0.001
Phytase	-	-	NS	-1.4×10^{-4}	3.2×10^{-5}	<0.001	-	-	NS
Ca:NPP ratio	−6.211	1.104	<0.001	2.4×10^{-2}	9.1×10^{-3}	0.011	-	-	NS
Phytase^2	-	-	NS	4.9×10^{-8}	1.8×10^{-8}	0.007	-1.9×10^{-6}	8.5×10^{-7}	0.049
(Ca:NPP)^2	-	-	NS	-	-	NS	-	-	NS
Phytase × Ca:NPP	1.0×10^{-3}	3.0×10^{-4}	0.001	-	-	NS	1.1×10^{-3}	2.9×10^{-4}	0.005
R^2		0.97			0.98			0.94	
RMSE		24.84			0.21			4.75	

RMSE - root mean square error; SE - standard error; NS - not significant (P>0.10).

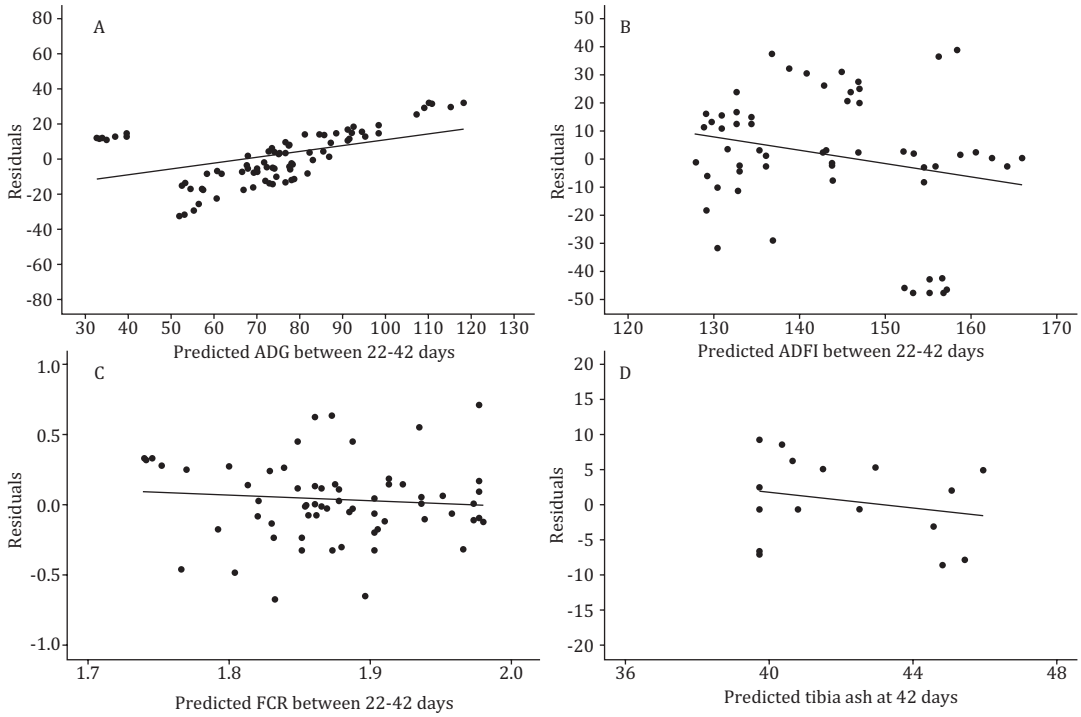


Description of curve types and regression equations for ADFI, FCR, and tibia ash content. Panels (A)-(C) illustrate the predicted responses of male broilers (22-42 days of age) to different dietary phytase inclusion levels: solid thin line – 0 FTU/kg; dashed thick line – 500 FTU/kg; dotted line – 1,000 FTU/kg; and solid thick line – 1,500 FTU/kg. Curves represent the effects of the dietary calcium-to-non-phytate phosphorus (Ca:NPP) ratio on the following parameters: (A) ADFI (g) = $166.69 - 6.211 \times$ Ca:NPP + $1.0 \times 10^{-3} \times$ Phytase × Ca:NPP (RMSE = 24.84, R^2 = 0.97). (B) FCR = $1.816 - 1.4 \times 10^{-4} \times$ Phytase + $2.4 \times 10^{-2} \times$ Ca:NPP + $4.9 \times 10^{-8} \times$ Phytase^2 (RMSE = 0.21, R^2 = 0.98). (C) Tibia ash (%) = $39.93 - 1.9 \times 10^{-6} \times$ Phytase^2 + $1.1 \times 10^{-3} \times$ Phytase × Ca:NPP (RMSE = 4.75, R^2 = 0.94).

Figure 3 - Response of average daily feed intake (ADFI, g), feed conversion ratio (FCR), and tibia ash content (%) to the dietary calcium to non-phytate phosphorus (NPP) ratio in male broilers from 22 to 42 days of age, fed diets with different dietary phytase levels.

3.3. Model adequacy

The residual plots against the predicted values shown in Figures 4 and 5 indicate the adequacy of the model for assessing the effects of various dietary NPP levels and Ca:NPP ratios in broilers fed different PHY levels. Residuals displayed a good distribution around zero across the different models, indicating a good fit. The residuals differed from the predicted values by 15.9%, 17.8%, 11.2%, and 11.8% for ADG, ADFI, FCR, and tibia ash content, respectively, in the models that included various dietary NPP levels. The residuals differed from the predicted values by 17.1%, 11.1%, and 9.1% for ADFI, FCR, and tibia ash content, respectively, in the models evaluating the effects of different Ca:NPP ratios in broiler diets with varying PHY supplementation.

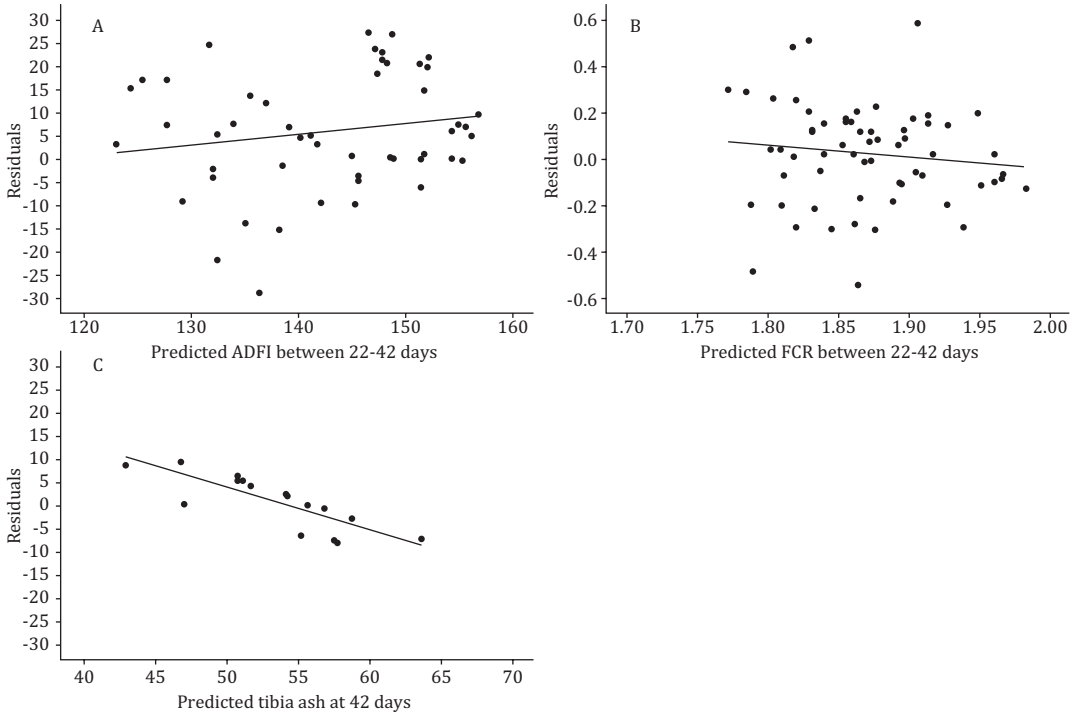


The lines represent the regression of residuals on predicted values for each response variable: (A) ADG [Y = −22.74 + 0.331 × predicted ADG; R^2 = 0.18]; (B) ADFI [Y = 162.1 − 1.095 × predicted ADFI; R^2 = 0.09]; (C) FCR [Y = 0.70 − 0.351 × predicted FCR; R^2<0.001]; and (D) Tibia ash content [Y = 24.1 − 0.560 × predicted tibia ash; R^2<0.001].

Figure 4 - Residuals (observed – predicted) plotted against predicted ADG, ADFI, FCR, and tibia ash content in male broilers (22–42 days of age) fed diets with different levels of phytase and non-phytate phosphorus.

4. Discussion

Microbial PHY is widely used in poultry nutrition to improve P and nutrient digestibility, thereby enhancing broiler performance while reducing production costs and environmental pollution. Various studies have investigated the interactions among PHY supplementation, NPP, and the Ca:NPP ratio; however, results remain variable. Previous meta-analyses have primarily focused on the starter phase (Létourneau-Montminy et al., 2010; Bougouin et al., 2014; Faridi et al., 2015; Cowieson et al., 2017; Kermani et al., 2023; Nuamah et al., 2024). To our knowledge, only one meta-analysis has evaluated these effects during the finisher phase, and it was restricted to P- and Ca-deficient diets (Nuamah et al., 2024). In addition, fewer studies evaluating the interactions among PHY, dietary NPP, and Ca have been identified for this phase than for the starter period, highlighting the need for further research.



The lines represent the regression of residuals on predicted values for each response variable: (A) ADFI [Y = 117.3 − 0.785 × predicted ADFI; R^2 = 0.003]; (B) FCR [Y = −0.23 + 0.148 × predicted FCR; R^2<0.001]; and (C) tibia ash [Y = 48.76 − 0.902 × predicted tibia ash; R^2 = 0.63].

Figure 5 - Residuals (observed − predicted) plotted against predicted values of ADFI, FCR, and tibia ash (%) in male broilers (22–42 days of age) fed diets with different levels of phytase and calcium to non-phytate phosphorus (Ca:NPP) ratio.

Exogenous PHY supplementation in broiler diets can improve performance, as tibia ash content is often associated with enhanced nutrient digestibility (Olukosi et al., 2008; Woyengo et al., 2010). PHY hydrolyzes phytate (InsP6) complexes, releasing P and other nutrients, which improve performance in broilers fed diets with low NPP or deficient in both Ca and NPP (Nuamah et al., 2024). In the present meta-analysis, PHY supplementation improved ADG, ADFI, tibia ash content, and FCR in male broilers from 22 to 42 days post-hatching. These results agree with those reported by Nuamah et al. (2024), who also reported improved growth performance and bone mineralization in male broilers supplemented with PHY during the finisher phase. Although NPP and Ca requirements decrease during this stage compared with the starter phase, the finisher phase accounts for almost two-thirds of the total feed intake and growth of male broilers (Valable et al., 2018).

The fitted models indicated that PHY supplementation positively affected ADFI, with stronger responses observed at lower dietary NPP levels. Low-NPP diets may reduce feed intake; however, this adverse effect can be mitigated by either directly increasing dietary NPP levels or by supplementing with PHY (Rousseau et al., 2016). Diets supplemented with 1,000 FTU/kg of PHY increased ADFI by 6.45 g/day in male broilers fed diets containing 1.50 g/kg NPP. However, no significant improvement was observed at NPP levels above 2.90 g/kg, suggesting that this concentration meets the dietary NPP requirements. These findings are consistent with the recommendations of Rostagno et al. (2024) and Han et al. (2009), who reported optimal dietary NPP levels of approximately 3.15 g/kg and 2.90 g/kg, respectively. Similarly, Han et al. (2009) reported that PHY supplementation at 500, 1,000, and 1,500 FTU/kg of diet was equivalent to increasing dietary NPP by 0.49, 0.68, and 0.86 g/kg, respectively, in broilers fed low-NPP diets (1.30 g/kg).

Higher dietary Ca:NPP ratios negatively affected growth performance in male broilers during the finisher phase, although PHY responses tended to be greater under these conditions. Elevated Ca:NPP

levels can reduce P availability in the gut lumen by promoting the formation of insoluble calcium phosphate complexes (Kermani et al., 2023). Additionally, excess Ca binds to PP molecules, reducing $InsP_6$ solubility and limiting its accessibility to phosphatases in the digestive tract (Selle and Ravindran, 2007). Calcium may also compete with exogenous PHY for binding sites, reducing its efficacy (Selle and Ravindran, 2007).

Supplementation with PHY also improved ADG, with stronger responses observed at lower dietary NPP levels. Supplementation with 1,000 FTU/kg increased ADG by 3.16 g/day at 3.00 g/kg NPP, whereas a greater improvement (6.63 g/day) was observed when NPP was reduced to 1.50 g/kg. Similarly, Han et al. (2009) reported that PHY supplementation at levels of 500, 1,000, and 1,500 FTU/kg was equivalent to increasing dietary NPP levels by 0.60, 0.78, and 0.96 g/kg, respectively, for ADG in male broilers from 22 to 42 days. Nuamah et al. (2024) reported an even greater improvement, with an increase of 7.78 g/day in broilers fed diets containing an average dietary NPP level of 3.00 g/kg and supplemented with an average dose of 875 FTU/kg during the same period. Although the Ca:NPP ratio influenced ADFI in interaction with PHY supplementation, no significant effect on ADG was observed.

In the present meta-analysis, PHY supplementation significantly improved FCR, particularly in diets with lower NPP concentrations, consistent with the findings of Nuamah et al. (2024). Based on the fitted models, similar FCR performance could be achieved with diets containing 2.25 g/kg NPP when supplemented with 500 FTU/kg of PHY, compared with diets formulated with the recommended NPP level of 3.15 g/kg (Rostagno et al., 2024). This suggests that PHY supplementation at this dosage may release approximately 0.90 g/kg of NPP. However, the dataset included studies using different PHY generations, which may have resulted in a lower estimated NPP release than that achievable using more recent enzyme technologies. The improvement in FCR is likely related to the ability of PHY to release P and mitigate the anti-nutritional effects of phytate ($InsP_6$), thereby increasing the availability of Ca, minerals, amino acids, and energy, and improving feed efficiency (Selle and Ravindran, 2007). Furthermore, higher dietary Ca:NPP ratios negatively affected FCR in male broilers during the finisher phase, suggesting that excessive dietary Ca reduces P availability and impairs feed efficiency (Kermani et al., 2023).

Supplementation with PHY also increased tibia ash content, with stronger responses observed in diets containing lower NPP levels. Diets supplemented with 1,000 FTU/kg PHY increased tibia ash by 4.85 percentage points in male broilers fed diets containing 1.50 g/kg NPP, whereas only a 0.99 percentage points increase was observed at 3.00 g/kg NPP. Similarly, Han et al. (2009) reported that PHY supplementation at levels of 500, 1,000, and 1,500 FTU/kg was equivalent to increasing dietary NPP levels by 0.77, 0.95, and 1.14 g/kg, respectively, for tibia ash in male broilers from 22 to 42 days. These responses are likely related to the ability of PHY to release minerals from PP complexes, increasing mineral availability (Sobotik et al., 2023). The effects of PHY were more pronounced in diets with higher Ca:NPP ratios, whereas increasing the Ca:NPP ratio negatively affected tibia ash in male broilers during the finisher phase. Diets with high Ca levels, particularly when combined with low dietary NPP concentrations, increase the pH in the upper gastrointestinal tract, especially in the gizzard, promoting the formation of insoluble PP-Ca complexes and further reducing Ca and P availability (Selle et al., 2009; Bedford and Rousseau, 2017).

Several meta-analyses have reported stronger effects of PHY on tibia ash during the starter phase (Faridi et al., 2015; Kermani et al., 2023) compared with those reported in the present meta-analysis, which focused on the finisher phase. Supplementation with PHY appears to be more effective during early growth because birds in the starter phase require greater Ca and P deposition in bones to support rapid body weight gain (Talaty et al., 2009; Babatunde et al., 2020). Bone mineralization peaks at approximately four weeks of age. After this stage, although tibia growth continues, bone density increases only slightly due to the expansion of the bone surface area (Talaty et al., 2009; Nuamah et al., 2024). Furthermore, Scholey and Burton (2017) suggested that the femur may be a more appropriate bone for estimating ash content in broilers at six weeks of age, as mineralization still actively occurs in the femur compared with the tibia.

The results observed in this meta-analysis reflect the complex biochemical interactions among PP, P, and Ca in broiler diets. As previously stated, PP binds P in a chemically stable form and can also interact with Ca and other nutrients, reducing their solubility and intestinal availability (Cowieson et al., 2006; Selle and Ravindran, 2007). When dietary Ca is present in excess relative to available P, the formation of insoluble Ca–PP and Ca–phosphate complexes may further limit P availability and restrict the accessibility of PP to enzymatic hydrolysis (Selle et al., 2009; Bedford and Rousseau, 2017). Under these conditions, PHY supplementation promotes PP degradation and releases P that would otherwise remain unavailable, partially restoring mineral availability and supporting metabolic processes associated with growth and skeletal development (Cowieson et al., 2006). However, the magnitude of these responses may differ between performance traits and skeletal indicators because bone tissue is highly responsive to changes in Ca and P availability.

Bone mineralization traits, particularly tibia ash, often respond rapidly to variations in dietary P supply and are therefore widely used as sensitive indicators of mineral utilization in broilers (Faridi et al., 2015). This sensitivity is especially relevant when compared with growth performance, as broilers can partially maintain weight gain through physiological regulation of nutrient use even when mineral supply is suboptimal, whereas skeletal tissues respond more directly to changes in Ca and P availability. Age-related changes in bone development may also contribute to differences in response across growth phases. During the starter phase, rapid skeletal growth and high rates of Ca and P deposition increase the requirement for available P, which partly explains the greater responses to PHY often observed in young broilers. In contrast, during the finisher phase, broilers continue to deposit minerals in the skeleton, but patterns of bone development and mineralization change as birds age, with relatively slower mineral accretion compared with early growth (Talaty et al., 2009). Consequently, moderate improvements in mineral utilization may be detected more clearly in tibia ash than in growth performance, helping to explain why skeletal responses can remain evident even when performance responses are comparatively modest. Taken together, these findings highlight the importance of considering the interactive effects of PHY supplementation, dietary NPP supply, and the Ca:NPP balance when evaluating mineral utilization in broiler diets during the finisher phase. By integrating data from multiple experiments conducted under diverse nutritional conditions, this meta-analysis provides quantitative evidence that helps clarify how these nutritional factors interact to influence both performance and bone mineralization. Such integrative approaches are particularly valuable in the context of modern poultry nutrition, where greater precision in nutrient supply is required to improve feed efficiency, reduce reliance on inorganic P sources, and minimize environmental P excretion (Bougouin et al., 2014; Valente Junior et al., 2024). Meta-analytical methodologies allow the synthesis of a large body of experimental data to identify consistent biological patterns and strengthen the interpretation of complex nutritional interactions across studies (Sauvant et al., 2020). The insights generated by this meta-analysis contribute to a better understanding of mineral nutrition in finishing broilers and support the development of more precise and sustainable feeding strategies.

5. Conclusions

Exogenous PHY supplementation improved growth performance and tibia ash content, with more pronounced responses observed in diets with lower dietary NPP levels. Increasing dietary NPP levels also enhanced these parameters. In contrast, high dietary Ca:NPP ratios impaired performance and bone mineralization, particularly in diets without PHY supplementation. Given the complex interactions among Ca, NPP, and exogenous PHY, as well as the limited number of studies evaluating broilers during the finisher period, further research is required to better understand their combined effects on P utilization in broiler chickens.

Data availability

The dataset used is available from the corresponding author upon reasonable request.

Author contributions

Conceptualization: Yamawaki, R. A. and Maiorka, A. **Data curation:** Yamawaki, R. A. **Formal analysis:** Yamawaki, R. A. **Funding acquisition:** Yamawaki, R. A. **Investigation:** Yamawaki, R. A. **Methodology:** Yamawaki, R. A. **Project administration:** Yamawaki, R. A. **Resources:** Yamawaki, R. A. **Software:** Yamawaki, R. A. **Supervision:** Andretta, I. and Maiorka, A. **Validation:** Yamawaki, R. A. **Visualization:** Yamawaki, R. A. **Writing – original draft:** Yamawaki, R. A. **Writing – review & editing:** Hickmann, F. M. W.; Andretta, I.; Vieira, B. S. and Maiorka, A.

Conflict of interest

The authors declare no conflict of interest.

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Declaration of generative AI in scientific writing

During the preparation of this manuscript, the authors exclusively used AI tools to enhance grammar and language clarity. All the content was reviewed and edited by the authors.

References

Andretta, I.; Kipper, M.; Lehnen, C. R. and Lovatto, P. A. 2012. Meta-analysis of the relationship of mycotoxins with biochemical and hematological parameters in broilers. Poultry Science 91:376-382. https://doi.org/10.3382/ps.2011-01813

Andretta, I.; Hickmann, F. M. W.; Remus, A.; Franceschi, C. H.; Mariani, A. B.; Orso, C.; Kipper, M.; Létourneau-Montminy, M-P. and Pomar, C. 2021. Environmental impacts of pig and poultry production: insights from a systematic review. Frontiers in Veterinary Science 8:750733. https://doi.org/10.3389/fvets.2021.750733

Aviagen. 2022. Ross 308 and Ross 308 FF Broiler: performance objectives. Aviagen, Huntsville, AL.

Babatunde, O. O.; Jendza, J. A.; Ader, P.; Xue, P.; Adedokun, S. A. and Adeola, O. 2020. Response of broiler chickens in the starter and finisher phases to three sources of microbial phytase. Poultry Science 99:3997-4008. https://doi.org/10.1016/j.psj.2020.05.008

Bedford, M. and Rousseau, X. 2017. Recent findings regarding calcium and phytase in poultry nutrition. Animal Production Science 57:2311-2316. https://doi.org/10.1071/AN17349

Bougouin, A.; Appuhamy, J. A. D. R. N.; Kebreab, E.; Dijkstra, J.; Kwakkel, R. P. and France, J. 2014. Effects of phytase supplementation on phosphorus retention in broilers and layers: A meta-analysis. Poultry Science 93:1981-1992. https://doi.org/10.3382/ps.2013-03820

Ceylan, N.; Cangir, S.; Corduk, M.; Grigorov, A. and Golzar Abadi, S. H. 2012. The effects of phytase supplementation and dietary phosphorus level on performance and on tibia ash and phosphorus contents in broilers fed maize-soya-based diets. Journal of Animal and Feed Sciences 21:696-704. https://doi.org/10.22358/jafs/66142/2012

Cobb-Vantress. 2022. Cobb500 broiler performance and nutrition supplement. Cobb-Vantress Inc., Siloam Springs, AR.

Cowieson, A. J.; Acamovic, T. and Bedford, M. R. 2006. Phytic acid and phytase: implications for protein utilization by poultry. Poultry Science 85:878-885. https://doi.org/10.1093/ps/85.5.878

Cowieson, A. J.; Ruckebusch, J. P.; Sorbara, J. O. B.; Wilson, J. W.; Guggenbuhl, P. and Roos, F. F. 2017. A systematic view on the effect of phytase on ileal amino acid digestibility in broilers. Animal Feed Science and Technology 225:182-194. https://doi.org/10.1016/j.anifeedsci.2017.01.008

Dilger, R. N.; Onyango, E. M.; Sands, J. S. and Adeola, O. 2004. Evaluation of microbial phytase in broiler diets. Poultry Science 83:962-970. https://doi.org/10.1093/ps/83.6.962

Faridi, A.; Gitoee, A. and France, J. 2015. A meta-analysis of the effects of nonphytate phosphorus on broiler performance and tibia ash concentration. Poultry Science 94:2753-2762. https://doi.org/10.3382/ps/pev280

França, T. P.; Ferreira, R. S.; Leo, R. A. R.; Oliveira, C. H.; Dias, K. M. M.; Gomes, K. M.; Costa, L. S. and Albino, L. F. T. 2023. Effects of carbohydrase and phytase enzymes supplementation within low energy diets on performance and energy utilization of broiler chickens. Livestock Science 274:105271. https://doi.org/10.1016/j.livsci.2023.105271

Garcia-Neto, M. 2008. Programa prático para formulação de rações/frangos de corte PPFR. Available at: <https://sites.google.com/site/ppfrparaexcel2007ousuperior/monogastricos/planilhas/frango-de-corte>. Accessed on: Oct. 02, 2025.

Han, J. C.; Yang, X. D.; Qu, H. X.; Xu, M.; Zhang, T.; Li, W. L.; Yao, J. H.; Liu, Y. R.; Shi, B. J.; Zhou, Z. F. and Feng, X. Y. 2009. Evaluation of equivalency values of microbial phytase to inorganic phosphorus in 22-to 42-day-old broilers. Journal of Applied Poultry Research 18:707-715. https://doi.org/10.3382/japr.2009-00029

Hubbard. 2023. Hubbard efficiency plus broiler performance objective. Hubbard Breeders S.A.S., Mauguérand.

Islam, R.; Ideris, A.; Kasim, A.; Omar, A. R.; Hussin, A. S. M.; Yasmin, F. and González-Redondo, P. 2017. Evaluation of humoral immune response, body weight and blood constituents of broilers supplemented with phytase on infectious bursal disease vaccination. Cogent Food & Agriculture 3:1306933. https://doi.org/10.1080/23311932.2017.1306933

Javadi, M.; Cerisuelo, A.; Cambra-López, M.; Macías-Vidal, J.; Donadeu, A.; Dupuy, J.; Carpintero, L.; Ferrer, P. and Pascual, J. J. 2022. The duration of the trial influences the effects of mineral deficiency and the effective phytase dose in broilers' diets. Animals 12:1418. https://doi.org/10.3390/ani12111418

Jiang, X. R.; Luo, F. H.; Qu, M. R.; Bontempo, V.; Wu, S. G.; Zhang, H. J.; Yue, H. Y. and Qi, G. H. 2013. Effects of non-phytate phosphorus levels and phytase sources on growth performance, serum biochemical and tibia parameters of broiler chickens. Italian Journal of Animal Science 12:e60. https://doi.org/10.4081/ijas.2013.e60

Junqueira, O. M.; Duarte, K. F.; Assuena, V.; Filardi, R. S.; Laurentiz, A. C. and Praes, M. F. F. M. 2011. Effect of phytase supplementation on performance, bone densitometry and carcass yield in broilers chicks. Acta Scientiarum. Animal Sciences 33:301-307. https://doi.org/10.4025/actascianimsci.v33i3.10702

Kermani, Z. A.; Taheri, H. R.; Faridi, A.; Shahir, M. H. and Baradaran, N. 2023. Interactive effects of calcium, vitamin D3, and exogenous phytase on phosphorus utilization in male broiler chickens from 1 to 21 days post-hatch: A meta-analysis approach. Animal Feed Science and Technology 295:115525. https://doi.org/10.1016/j.anifeedsci.2022.115525

Létourneau-Montminy, M. P.; Narcy, A.; Lescoat, P.; Bernier, J. F.; Magnin, M.; Nys, Y. ; Sauvant, D. and Jondreville, C. 2010. Meta-analysis of phosphorus utilization by broilers receiving corn-soyabean meal diets: influence of dietary calcium and microbial phytase. Animal 4:1844-1853. https://doi.org/10.1017/S1751731110001060

Manangi, M. K.; Sands, J. S. and Coon, C. N. 2009. Effect of adding phytase to broiler diets containing low and high phytate phosphorus: 1. Performance, phytate P hydrolysis, tibia ash, litter phosphorus and Ca and P digestion and retention. International Journal of Poultry Science 8:919-928. https://doi.org/10.3923/ijps.2009.919.928

Midilli, M.; Salman, M.; Muğlali, Ö. H.; Öğretmen, T.; Çenesiz, S. and Ormanci, N. 2014. The effects of organic or inorganic zinc and microbial phytase, alone or in combination, on the performance, biochemical parameters and nutrient utilization of broilers fed a diet low in available phosphorus. Kafkas Üniversitesi Veteriner Fakültesi Dergisi 20:99-106.

Mohiti-Asli, M.; Ghanaatparast-Rashti, M.; Akbarian, P. and Mousavi, S. N. 2020. Effects of a combination of phytase and multi-carbohydrase enzymes in low-density corn–soybean meal based diets on growth performance and ileal nutrients digestibility of male broilers. Italian Journal of Animal Science 19:1533-1541. https://doi.org/10.1080/1828051X.2020.1857311

Nafea, H. H.; Alkhilan, F. M. H. and Hamid, B. I. 2019. Effect of adding high levels of phytase enzyme to corn-soybeans based diets in the production and physiological performance of broilers. Biochemical & Cellular Archives 19:1621-1628.

Nourmohammadi, R.; Hosseini, S. M.; Farhangfar, H. and Bashtani, M. 2012. Effect of citric acid and microbial phytase enzyme on ileal digestibility of some nutrients in broiler chicks fed corn-soybean meal diets. Italian Journal of Animal Science 11:e7.

Nourmohammadi, R.; Hosseini, S. M. and Farhangfar, H. 2010. Influence of citric acid and microbial phytase on growth performance and carcass characteristics of broiler chickens. American Journal of Animal and Veterinary Sciences 5:282-288. https://doi.org/10.3844/ajavsp.2010.282.288

NRC - National Research Council. 1994. Nutrient requirements of poultry. 9th ed. National Academy Press, Washington, D.C.

Nuamah, E.; Okon, U. M.; Jeong, E.; Mun, Y.; Cheon, I.; Chae, B.; Odoi, F. N. A.; Kim, D. W. and Choi, N. J. 2024. Unlocking phytate with phytase: A meta-analytic view of meat-type chicken muscle growth and bone mineralization potential. Animals 14:2090. https://doi.org/10.3390/ani14142090

Olukosi, O. A.; Cowieson, A. J. and Adeola, O. 2008. Energy utilization and growth performance of broilers receiving diets supplemented with enzymes containing carbohydrase or phytase activity individually or in combination. British Journal of Nutrition 99:682-690. https://doi.org/10.1017/S0007114507815807

Ravindran, V.; Cowieson, A. J. and Selle, P. H. 2008. Influence of dietary electrolyte balance and microbial phytase on growth performance, nutrient utilization, and excreta quality of broiler chickens. Poultry Science 87:677-688. https://doi.org/10.3382/ps.2007-00247

Rostagno, H. S.; Albino, L. F. T.; Calderano, A. A.; Hannas, M. I.; Sakomura, N. K.; Perazzo, F. G.; Rocha, G. C.; Saraiva, A.; Abreu, M. L. T., Genova, J. L. and Tavernari, F. C. 2024. Tabelas brasileiras para aves e suínos: composição de alimentos e exigências nutricionais. 5.ed. UFV, Departamento de Zootecnia, Viçosa, MG.

Rousseau, X.; Valable, A. S.; Létourneau-Montminy, M. P.; Même, N.; Godet, E.; Magnin, M.; Nys, Y.; Duclos, M. J. and Narcy, A. 2016. Adaptive response of broilers to dietary phosphorus and calcium restrictions. Poultry Science 95:2849-2860. https://doi.org/10.3382/ps/pew172

Sauvant, D.; Letourneau-Montminy, M. P.; Schmidely, P.; Boval, M.; Loncke, C. and Daniel, J. B. 2020. Review: use and misuse of meta-analysis in animal science. Animal 14:s207-s222. https://doi.org/10.1017/S1751731120001688

Scholey, D. V. and Burton, E. J. 2017. The effect of bone choice on quantification of mineralization in broiler chickens up to 6 weeks of age. Journal of Applied Poultry Research 26:485-490. https://doi.org/10.3382/japr/pfx020

Selle, P. H. and Ravindran, V. 2007. Microbial phytase in poultry nutrition. Animal Feed Science and Technology 135:1-41. https://doi.org/10.1016/j.anifeedsci.2006.06.010

Selle, P. H.; Cowieson, A. J. and Ravindran, V. 2009. Consequences of calcium interactions with phytate and phytase for poultry and pigs. Livestock Science 124:126-141. https://doi.org/10.1016/j.livsci.2009.01.006

Selle, P. H.; Macelline, S. P.; Chrystal, P. V. and Liu, S. Y. 2023. The contribution of phytate-degrading enzymes to chicken-meat production. Animals 13:603. https://doi.org/10.3390/ani13040603

Singh, B. and Satyanarayana, T. 2015. Fungal phytases: characteristics and amelioration of nutritional quality and growth of non-ruminants. Journal of Animal Physiology and Animal Nutrition 99:646-660. https://doi.org/10.1111/jpn.12236

Sobotik, E. B.; House, G. M.; Stiewert, A. M.; Bello, A.; Dersjant-Li, Y.; Shoesmith, E.; Remus, J. and Archer, G. S. 2023. Evaluating a novel consensus bacterial 6-phytase variant on growth performance of broilers fed U.S. commercial diets deficient in nutrients and energy through 63 days of age. Journal of Animal Science 101:skac407. https://doi.org/10.1093/jas/skac407

Sommerfeld, V.; Künzel, S.; Schollenberger, M.; Kühn, I. and Rodehutscord, M. 2018. Influence of phytase or myo-inositol supplements on performance and phytate degradation products in the crop, ileum, and blood of broiler chickens. Poultry Science 97:920-929. https://doi.org/10.3382/ps/pex390

St-Pierre, N. R. 2001. Invited review: Integrating quantitative findings from multiple studies using mixed model methodology. Journal of Dairy Science 84:741-755. https://doi.org/10.3168/jds.S0022-0302(01)74530-4

Taheri, H. R.; Jabbari, Z.; Adibnia, S.; Shahir, M. H. and Hosseini, S. A. 2015a. Effect of high-dose phytase and citric acid, alone or in combination, on growth performance of broilers given diets severely limited in available phosphorus. British Poultry Science 56:708-715. https://doi.org/10.1080/00071668.2015.1093094

Taheri, H. R. and Taherkhani, S. 2015b. Effect of phytase superdoses and citric acid on growth performance, plasma phosphorus and tibia ash in broilers fed canola meal-based diets severely limited in available phosphorus. Poultry Science Journal 3:27-36. https://doi.org/10.22069/psj.2015.2325

Taheri, H. R.; Heidari, A. and Shahir, M. H. 2015c. Effect of high-dose phytase supplementation in broilers from 22 to 42 days post-hatch given diets severely limited in available phosphorus. British Poultry Science 56:330-336. https://doi.org/10.1080/00071668.2015.1020480

Talaty, P. N.; Katanbaf, M. N. and Hester, P. Y. 2009. Life cycle changes in bone mineralization and bone size traits of commercial broilers. Poultry Science 88:1070-1077. https://doi.org/10.3382/ps.2008-00418

Tizziani, T.; Donzele, R. F. M. O.; Donzele, J. L.; Balbino, E. M.; Silva, A. D.; Figueiredo, E. M.; Muniz, J. C. L. and Jacob, R. F. 2016. Available phosphorus levels in diets supplemented with phytase for male broilers aged 22 to 42 days kept in a high-temperature environment. Revista Brasileira de Zootecnia 45:48-55. https://doi.org/10.1590/S1806-92902016000200002

Valable, A. S.; Narcy, A.; Duclos, M. J.; Pomar, C.; Page, G.; Nasir, Z.; Magnin, M. and Létourneau-Montminy, M. P. 2018. Effects of dietary calcium and phosphorus deficiency and subsequent recovery on broiler chicken growth performance and bone characteristics. Animal 12:1555-1563. https://doi.org/10.1017/S1751731117003093

Valente Junior, D. T.; Genova, J. L.; Kim, S. W.; Saraiva, A. and Rocha, G. C. 2024. Carbohydrases and phytase in poultry and pig nutrition: A review beyond the nutrients and energy matrix. Animals 14:226. https://doi.org/10.3390/ani14020226

Viveros, A.; Brenes, A.; Arija, I. and Centeno, C. 2002. Effects of microbial phytase supplementation on mineral utilization and serum enzyme activities in broiler chicks fed different levels of phosphorus. Poultry Science 81:1172-1183. https://doi.org/10.1093/ps/81.8.1172

Walk, C. L.; Bedford, M. R. and Olukosi, O. A. 2018. Effect of phytase on growth performance, phytate degradation and gene expression of myo-inositol transporters in the small intestine, liver and kidney of 21-day old broilers. Poultry Science 97:1155-1162. https://doi.org/10.3382/ps/pex392

Woyengo, T. A.; Slominski, B. A. and Jones, R. O. 2010. Growth performance and nutrient utilization of broiler chickens fed diets supplemented with phytase alone or in combination with citric acid and multicarbohydrase. Poultry Science 89:2221-2229. https://doi.org/10.3382/ps.2010-00832

Wu, Y. B.; Ravindran, V.; Morel, P. C. H.; Hendriks, W. H. and Pierce, J. 2004. Evaluation of a microbial phytase, produced by solid-state fermentation, in broiler diets. 1. Influence on performance, toe ash contents, and phosphorus equivalency estimates. Journal of Applied Poultry Research 13:373-383. https://doi.org/10.1093/japr/13.3.373

Zobač, P.; Kumprecht, I.; Suchý, P.; Straková, E.; Brož, J. and Heger, J. 2004. Influence of L-lactic acid on the efficacy of microbial phytase in broiler chickens. Czech Journal of Animal Science 49:436-443. https://doi.org/10.17221/4329-CJAS