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Research Article

Effect of Dietary Calcium to Phosphorus Ratios on Productivity and Egg Quality in Early-Phase Laying Quails

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Abstract | High-quality eggs are vital in poultry farming, particularly in quail production, where nutrition is critical during the early laying phase. This study aimed to evaluate the impact of varying dietary calcium-to-phosphorus (Ca:P) ratios on the productivity and egg quality of laying quails at the onset of their production phase. A total of 160 six-week-old female quails were randomly assigned to four dietary treatments with Ca:P ratios of 2.7:1, 3.0:1, 3.3:1, and 3.6:1, maintaining a constant phosphorus level of 0.6%. The diets were iso-protein (20%) and iso-caloric (2,900 Kcal/kg), and birds were raised over four weeks with ad libitum access to feed and water. Key parameters such as feed intake, egg production, feed conversion ratio, digestibility, and both internal and external egg quality were assessed weekly. Data were analyzed using ANOVA followed by Duncan's test where appropriate. Results indicated no statistically significant differences in feed intake, egg production, or feed conversion ratio across treatments ($P > 0.05$); however, a dietary Ca:P ratio of 2.7:1 showed a substantial increase in nutrient digestibility (67.19%; $P = 0.2$) and mineral absorption (77.06%; $P = 0.09$), with the lowest calcium excretion ($P = 0.04$). Egg weight ($P < 0.05$) and shell thickness ($P > 0.05$) were highest at moderate calcium levels (2.7–3.3%). Excess calcium (3.6%) led to a significant increase in mineral excretion and lower digestibility, suggesting diminishing returns. In conclusion, a dietary Ca:P ratio of 2.7:1 to 3.0:1 optimizes performance and egg quality in early-phase laying quails. Moderation in calcium supplementation enhances productivity while reducing environmental waste from mineral excretion.

Keywords | Calcium, Phosphorus, Laying quails, Egg production

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INTRODUCTION

The production of high-quality eggs remains a fundamental goal in the poultry industry, particularly within the niche sector of quail farming. In recent years, quail egg production has garnered increasing attention due to the high nutritional value, unique sensory properties, and market demand for quail eggs. However, one of the persistent challenges in quail production is ensuring optimal nutritional management to maximize egg production, enhance egg quality, and improve feed efficiency, especially during the early laying phase when nutrient requirements are heightened (Kadam *et al*., 2006; Sultana *et al*., 2007).

Among the critical dietary components affecting poultry productivity, calcium (Ca) and phosphorus (P) are essential minerals with closely interrelated physiological roles. Calcium is fundamental for eggshell formation and influences the external quality of eggs. Its dietary requirement increases with the genetic advancement and maturing age of poultry, as evidenced by ongoing updates in nutritional recommendations for laying hens (Zhang *et* al., 2017). However, an excess of calcium, although initially beneficial for eggshell quality, can lead to overly thick shells, hindering hatchability (Shinde *et al.*, 2024), and cause nutritional imbalances that may suppress overall egg production (Wilkinson *et al.*, 2011).

Similarly, phosphorus is indispensable for bone development, metabolic processes, and plays a significant role in the utilization of calcium (Rama Rao *et al.*, 2006). The interactive effects between these two macrominerals require careful dietary balancing, as an improper Ca:P ratio can impair mineral absorption and consequently affect egg production and quality (Ribeiro *et al.*, 2016; Vellasco *et al.*, 2016). Several studies have demonstrated that a well-calibrated Ca:P ratio can improve phosphorus retention and optimize growth performance, feed conversion ratio, and egg quality in poultry, including quails (Sheikhlar *et al.*, 2009; Ribeiro *et al.*, 2016).

Nevertheless, a comprehensive review of existing literature reveals significant research gaps in this field. Most studies have focused on commercial laying hens or aged quails, while research specific to the initial production laying quails phase, characterized by rapid reproductive and metabolic changes, remains limited (De Souza *et al.*, 2016; Salajegheh *et al.*, 2020). Some studies on laying hens suggest that even wide variations in Ca:P ratios may not significantly affect performance or eggshell quality (Hassan and Al-Aqil, 2015). Still, these findings cannot be directly extrapolated to quail species due to their distinct physiological and production characteristics.

Notably, limited research has investigated the specific effects of Ca:P ratios on key production parameters such as feed consumption, egg production rate, feed conversion, nutrient digestibility, and mineral retention in quails. Studies like those by Aguda *et al.* (2015) and Gayirbegov and Engurazov (2023) highlight the importance of dietary optimization for improving both productivity and economic efficiency in quail farming, yet they stop short of providing definitive Ca:P ratio guidelines for young laying quails. In light of these gaps, this study aims to investigate the effects of varying dietary Ca:P ratios on the production performance and egg quality of initial production laying quails. By focusing on the early-laying phase, this research seeks to: Identify the optimal Ca:P ratio that supports peak egg production and quality; Evaluate its effects on feed intake, feed conversion, nutrient digestibility, and mineral retention; and provide actionable recommendations for improving quail nutrition strategies tailored to the early-laying phase.

MATERIALS AND METHODS

The experiment was conducted at the Poultry Production Laboratory, Department of Animal Science, Djuanda University, Bogor, Indonesia. All procedures involving animal care and use in this study were performed in accordance with applicable international, national, and institutional ethical guidelines and standards, including SNI 01-3907-2006, Regulation No. 54/Permentan/OT.140/9/2019, and Minister of Agriculture Decree No. 13/OT.140/1/2010.

The study involved 160 laying quails, aged six weeks (early laying period), which were raised for four weeks in battery cages under 16 hours of daily lighting. The quails were provided with feed and water ad libitum, formulated to meet iso-protein and iso-energy requirements (containing 20% crude protein and 2,900 Kcal/kg metabolizable energy) as shown in Table 1. Eggs were collected daily, and measurements of experimental variables were conducted weekly.

Table 1: Composition and nutrition of experimental diets.

Feed Ingredients (%)	D1	D2	D3	D4
Corn Meal	60.4	60	59.4	58.9
Corn Gluten Meal	7	6.8	6.6	7.8
Soybean Meal	13.05	13.05	12.95	12.00
Fish Meal	8.8	8.5	8.5	8
Premix	1.65	1.65	1.65	1.65
$CaCO_3$	5.6	6.5	7.2	8
CPO (Crude Palm Oil)	1.5	1.5	1.7	1.7
DCP (Dicalcium Phosphate)	2	2	2	2
Nutrients				
Crude Protein (%)	20.4	20.4	20.3	20.2
Metabolizable Energy (Kcal/kg)	2932	2935	2911	2905
Calcium (%)	2.72	3.10	3.31	3.61
Phosphorus (%)	0.60	0.61	0.60	0.60
Ratio Ca:P	2.7:1	3.0:1	3.3:1	3.6:1

Note: The experimental diet formulation was calculated based on the nutrient composition of the feed.

The basal diet was formulated as iso-protein (20% protein) and iso-calorie (2900 kcal/kg energy metabolizable) (NRC, 1994). They were composed of soybean meal, fish meal, yellow corn, corn gluten meal (CGM), and premix. In addition, the sources of calcium and phosphorus added to the diets come from calcium carbonate ($CaCO_3$) and dicalcium phosphate ($CaHPO_4$) (Table 1).

The research design used a completely randomized design (CRD) consisting of 4 treatments and five replications; eight quails were placed in 20 cages in each replication. The treatment feeds contained 0.6% P and Ca levels with different Ca:P ratios of D1 4.5 (2.7% Ca):1, D2 5.0 (3% Ca):1, D3 5.5 (3.3% Ca), and D4 6.0 (3.6%):1, respectively.

Table 2: The effect of dietary calcium levels on early egg production performance in laying quails.

Variables	D1	D2	D3	D4	Probability
Feed Consumption (g/day)	18.37±1.72	17.36±3.17	18.32±1.33	18.67±1.90	>0.05
Egg Production (%)	31.32±7.97	32.05±8.84	29.92±4.89	36.84±6.31	>0.05
Egg Mass (g/head)	19.76±5.31	19.25±5.53	18.83±2.28	22.02±3.24	>0.05
Feed Conversion Ratio	4.87±0.15	4.92±0.64	5.92±0.76	5.11±0.53	>0.05

Notes: D1: Ca 2.7%, D2: Ca 3.0%, D3: Ca 3.3%, D4: Ca 3.6%, while the total phosphorus content for all treatments is 0.6%.

The quails were raised according to the management of laying quail, fed and watered ad libitum. All measured parameters were analyzed by dividing them into performance, egg quality, and digestibility variables. Performance data were recorded weekly, including feed intake, body weight, egg production, egg weight, egg mass, and feed conversion ratio. Hen-day egg production was expressed as a percentage of total hen-days, and feed conversion was calculated based on feed intake per unit of egg mass. Egg quality parameters, such as shell thickness, yolk colour, albumen height, and Haugh unit, were assessed periodically and analyzed using linear models to compare treatment effects. Digestibility data were collected using the total collection method during the last four days of the trial. Excreta samples were taken and freeze-dried for analysis. Results were reported as means with standard error, and differences among treatments were considered significant at $P < 0.05$. Data were analyzed using analysis of variance. If the treatment means differed significantly, a Duncan test was performed.

RESULTS AND DISCUSSION

Effect of dietary calcium levels on early egg production performance in laying quails

Feed intake across calcium treatments varied slightly, with the highest value recorded at 3.6% Ca (18.67 ± 1.90 g/day) and the lowest at 3.0% Ca (17.36 ± 3.17 g/day). Although the differences were not statistically significant ($P > 0.05$), the trend suggests a slight increase in feed consumption with higher calcium levels (Table 2). This pattern is consistent with De Souza *et al.* (2016) findings, who reported that higher calcium intake (up to 3.85%) could lead to increased feed consumption due to enhanced shell formation demands. However, this did not always translate to better efficiency. Additionally, Sarmiento-García *et al.* (2022) found that feed intake remained stable across varying calcium pidolate levels, further supporting that moderate fluctuations in calcium do not drastically influence feed consumption.

Egg production (%) was numerically highest in the 3.6% Ca group (36.84 ± 6.31%) and lowest at 3.3% Ca (29.92 ± 4.89%), with intermediate values at 2.7% and 3.0% calcium. Again, these differences were not statistically significant ($P > 0.05$; Table 2). Despite the lack of statistical difference, the observed improvement at 3.6% calcium agrees with Sarmiento-García *et al.* (2022), who showed that calcium levels positively impact egg production up to a certain point, particularly in aged laying quail. However, Kadam *et al.* (2006) identified 3.0% calcium as optimal during the initial laying phase, improving production while maintaining efficiency. Thus, while 3.6% Ca showed the highest value here, 3.0–3.5% calcium is typically considered ideal for sustained egg output without compromising health.

Egg mass per head was greatest at 3.6% Ca (22.02 ± 3.24 g/head), followed by 2.7% (19.76 ± 5.31 g), with the lowest recorded at 3.3% Ca (18.83 ± 2.28 g). Again, no significant differences were found ($P > 0.05$), but the results indicate a positive response to increased calcium particularly at the upper limit (Table 2). Amoah *et al.* (2012) and Kadam *et al.* (2006) both emphasized the importance of balancing calcium with phosphorus, reporting that diets containing 3.0–3.5% Ca paired with 0.25% phosphorus significantly improved egg mass and overall productivity. Sultana *et al.* (2007) also found improved egg weight and shell deposition at 2.5–3.0% Ca, indicating that while higher levels (e.g., 3.6%) may boost output temporarily, moderate levels support sustainable performance.

Feed conversion ratio (FCR) values ranged from 4.87 ± 0.15 at 2.7% Ca to 5.92 ± 0.76 at 3.3% Ca, with the most efficient conversion at 2.7% Ca and the least efficient at 3.3% Ca. FCR at 3.6% Ca (5.11 ± 0.53) improved relative to 3.3% but was still higher than 2.7% (Table 2). These findings strongly correlate with Kadam *et al.* (2006) who reported improved feed efficiency at 3.0% Ca, especially when matched with appropriate energy levels (2700 kcal ME/kg). Aguda *et al.* (2015) also highlighted the importance of a balanced calcium-to-phosphorus ratio, recommending 2.5% Ca and 0.35% P as optimal for minimizing feed costs and maximizing egg output. The current results suggest that excessive Ca (e.g., 3.3%) may impair feed efficiency due to metabolic inefficiencies and reduced nutrient absorption.

The effect of dietary calcium on absorption efficiency

The dry matter digestibility (DMD) showed notable variation across dietary calcium levels, ranging from 57.27% at 3.0% Ca to 67.19% at 2.7% Ca, with a standard error of

1.74 and p < 0.2, indicating a non-significant trend (Table 3). The highest digestibility at 2.7% Ca suggests that excess calcium may impair DMD. This observation aligns with findings by (El-Katcha *et al*., 2015) who demonstrated that higher calcium levels (25% or 50% above NRC (1994) recommendations) improve dry matter digestibility only up to a point. Beyond this, excessive calcium may form insoluble complexes that reduce overall nutrient availability. Furthermore, Adedokun and Adeola (2013) emphasized that an imbalanced calcium-phosphorus ratio can increase digesta pH, interfering with phytase activity and nutrient absorption. Thus, while calcium is essential for quail nutrition, the results suggest that a moderate level (around 2.7%) is more effective for optimizing dry matter digestibility than higher

Table 3: Dry matter digestibility, mineral absorption, and Ca content of excreta (%).

Ca diets (%)	Dry matter digestibility	Absorption of Ash	Ca content of excreta
2.7	67.19	77.06	8.30
3	57.27	71.00	8.43
3.3	61.48	72.13	9.73
3.6	59.45	65.74	9.82
Standard Error	1.74	1.64	0.26
Probability	0.2	0.09	0.04

Mineral absorption percentages decreased progressively from 77.06% at 2.7% Ca to 65.74% at 3.6% Ca, with a standard error of 1.64 and P < 0.09, approaching statistical significance (Table 3). These results suggest that higher dietary calcium levels reduce mineral absorption efficiency. This trend is consistent with the findings of Adedokun and Adeola (2013), who highlighted the antagonistic effects of high dietary calcium on mineral absorption, particularly when it interferes with phosphorus availability and phytase efficacy. As calcium levels increase, more minerals may precipitate in the gut, reducing their bioavailability. Additionally, El-Katcha *et al*. (2015) reported that although calcium supports structural development and egg quality, excess amounts may impair absorption of ash due to complex formation with other nutrients. This supports the observation that lower calcium diets (2.7%) favor better ash absorption, underscoring the importance of balancing mineral inputs for optimal bioavailability.

The calcium content in excreta rose from 8.30% at 2.7% Ca to 9.82% at 3.6% Ca, with a standard error of 0.26 and p < 0.04, indicating a statistically significant increase in calcium excretion with higher dietary calcium (Table 3). This result is strongly supported by De Souza *et al*. (2016), who found that increased dietary calcium leads to proportional increases in calcium excretion, as excess calcium is not efficiently retained and is instead eliminated through feces. Furthermore, El-Katcha *et al*. (2015) reported similar findings, emphasizing that high dietary calcium does not correspond to improved absorption, but rather to greater excretion, which can also contribute to environmental nutrient loading.

Table 3 shows that excessive dietary calcium (3.3–3.6%) impairs mineral absorption in quails by forming insoluble complexes with phosphorus, fatty acids, and trace elements, reducing their bioavailability and digestibility (Adedokun and Adeola, 2013; El-Katcha *et al*., 2015). High Ca also elevates gut pH, inhibiting phytase activity and worsening phosphorus utilization, leading to greater mineral excretion (Korver and Stewart-Brown, 2024). Physiological feedback further downregulates Ca and P uptake, stressing renal function and lowering feed efficiency (Adedokun and Adeola, 2013). In contrast, moderate Ca levels (2.7%) optimize nutrient digestibility and mineral retention, maintaining a balanced Ca:P ratio that supports enzyme activity and shell quality (Kadam *et al*., 2006; Ribeiro *et al*., 2016). Thus, moderation in calcium supply enhances performance and minimizes nutrient waste, whereas oversupply is counterproductive for bird health and environmental sustainability.

The effect of dietary calcium on physical quality of eggs

Dietary calcium levels significantly affected egg weight (P < 0.05) (Table 4). The highest egg weight was observed at 2.7% Ca (10.3 ± 0.30 g), followed closely by 3.3% Ca (10.18 ± 0.20 g) and 3.0% Ca (10.12 ± 0.18 g), while the lowest was at 3.6% Ca (9.95 ± 0.16 g). This result is consistent with Sultana *et al*. (2007), who found that a 2.5% calcium level enhanced egg weight in Japanese quail. Additionally, De Souza *et al*. (2016) observed that increasing dietary calcium improved egg weight up to a point (around 3.85%), after which performance deteriorated. Therefore, moderate calcium levels (2.7%–3.3%) appear optimal for supporting egg mass without negatively impacting internal quality.

Table 4: The effect of dietary calcium diets on physical quality of eggs.

Ca diets (%)	Egg weight (g)	Egg shell weight (g)	Egg shell thickness (mm)	Egg index (Width/ length)%
2.7	$10.3{\pm}0.30^{b}$	1.01±0.04	0.25±0.01	74.13±6.34
3.0	$10.12{\pm}0.18^{ab}$	0.95±0.40	0.24±0.01	74.64±7.11
3.3	$10.18{\pm}0.20^{ab}$	0.97±0.06	0.25±0.02	71.92±6.53
3.6	$9.95{\pm}0.16^{a}$	0.99±0.03	0.24±0.01	67.94±8.92
Probability	<0.05	>0.05	>0.05	>0.05

Notes: Means with different letters in the same column indicate a significant difference, P < 0.05

Kadam *et al.* (2006) and Sultana *et al.* (2007) both found that moderate Ca levels (2.5–3.0%) optimized egg mass and shell quality. However, too much calcium may trigger a regulatory shift toward shell mineralization, with no added benefit to egg weight and a decline in overall egg mass. Amoah *et al.* (2012) found that quails maintained optimal egg weight and production when fed 3.0% calcium and 0.25% phosphorus. This suggests that imbalanced high-Ca diets without matched phosphorus can lead to inefficient nutrient utilization, resulting in lower egg output and weight.

The variation in eggshell weight across treatments was not statistically significant, though the highest value was recorded numerically at 2.7% Ca (1.01 ± 0.04 g) and the lowest at 3.0% Ca (0.95 ± 0.40 g; Table 4). The differences may be biologically relevant, even if not statistically conclusive. These findings align with those by Sultana *et al.* (2007), who emphasized that calcium source and age of the quail might influence shell weight more than the calcium level alone. Likewise, Ribeiro *et al.* (2016) noted that optimal shell weight is achieved when calcium levels are appropriately balanced with available phosphorus. Therefore, although no strong significance is seen, Ca levels below 3.3% are more favorable for eggshell mass.

Eggshell thickness remained fairly constant across treatments (0.24–0.25 mm), showing no statistically significant differences. However, the thicker shells at 2.7% and 3.3% Ca (0.25 mm) compared to other groups are notable (Table 4). Studies by Sarmiento-García *et al.* (2022) and De Souza *et al.* (2016) have shown that calcium levels between 2.5–3.85% enhance shell thickness, with excessive supplementation potentially diminishing results. Sultana *et al.* (2007) also found that a 2.5% Ca level was optimal for shell strength and thickness. Therefore, the observed pattern confirms that shell quality benefits from moderate calcium intake, particularly at 2.7% and 3.3%.

Egg shape index (width:length) showed a downward trend with increasing dietary calcium, from 74.64% at 3.0% Ca to 67.94% at 3.6% Ca, although P > 0.05, indicating non-significant differences (Table 4). Sarmiento-García *et al.* (2022) reported that high calcium pidolate levels negatively affect yolk and albumen structure, leading to shape irregularities. Meanwhile, De Souza *et al.* (2016) confirmed that higher calcium intake can deform eggs if not carefully balanced. The better shape indices at 2.7% and 3.0% Ca imply improved albumen integrity and symmetry, making these levels preferable for maintaining commercial egg appearance.

The effect of dietary calcium on internal egg quality

The proportion of egg white (albumen) showed no statistically significant differences across dietary treatments (P > 0.05), though values ranged slightly from 60.14% (3.3% Ca) to 61.4% (2.7% Ca). This mild fluctuation indicates that calcium inclusion within the 2.7–3.6% range does not substantially alter albumen deposition in quail eggs (Table 5). However, Ribeiro *et al.* (2016) reported that increasing dietary calcium to 38 g/kg reduced albumen proportion, suggesting that excess calcium could potentially suppress albumen yield if not appropriately balanced. Additionally, De Souza *et al.* (2016) observed similar trends. Still, they did not provide exact values for white percentage, while Prelipcean *et al.* (2012) detailed that quail egg white naturally contains high water and protein (87.48% water, 9.91% protein), which are largely preserved across reasonable Ca levels. Therefore, moderate calcium levels (around 2.7–3.0%) appear adequate for maintaining albumen composition, while excess may risk slight reductions without significant advantage.

Table 5: Effect dietary calcium on internal egg quail quality.

Ca diets (%)	Egg white weight (%)	Yolk egg weight (%)	Hugh unit (%)	Egg yolk color score
2.7	61.4±1.68	37.1±2.49	85.0±1.08	5.59±0.19
3	60.99±3.64	38.85±3.47	84.90±0.86	5.53±0.43
3.3	60.14±2.69	38.35±3.03	85.53±1.47	5.40±0.26
3.6	61.36±2.32	38.82±1.39	85.73±1.45	5.51±0.30
P value	>0.05	>0.05	>0.05	>0.05

Yolk percentage varied between 37.1% (2.7% Ca) and 38.85% (3.0% Ca), with no statistically significant difference (P > 0.05; Table 5). Nonetheless, the slightly higher yolk proportions at 3.0% and 3.6% Ca suggest better nutrient partitioning under moderate to high Ca intake. Calcium (Ca) levels had a limited impact on yolk percentage (Chang *et al.*, 2019). In contrast, Attia *et al.* (2020), working on laying hens, reported that increasing calcium up to 4% improved yolk percentage and yolk:albumen ratio, but effects plateaued beyond this point. Additionally, genetic and nutritional factors, such as age and carotenoid-rich diets, also play critical roles in yolk proportion (Sujatha and Narahari, 2011). In conclusion, while Ca levels from 2.7% to 3.6% do not statistically influence yolk proportion in quails, marginal numerical increases at 3.0–3.6% may suggest better yolk development, likely supported by age, breed, and nutrient availability.

The results regarding Haugh Unit, a key indicator of egg freshness and albumen quality was presented in Table 5. The results showed that there was a non-significant difference across treatments (P > 0.05), but values ranged from 84.90% (3.0% Ca) to 85.73% (3.6% Ca) all within the "AA" grade threshold (>72). Akinola and Iyomo (2020) and Attia *et al.* (2020) both highlighted that optimal

Ca intake, especially in combination with vitamin D_3, positively influences HU scores in laying birds. The slight improvement in HU at 3.6% Ca suggests that higher calcium might support albumen structural integrity, although benefits may plateau beyond a certain level. Overall, the current data confirm that dietary calcium in the 2.7–3.6% range maintains excellent internal egg freshness, with a subtle benefit toward the higher end of that range when properly balanced.

Yolk color scores ranged from 5.40 (3.3% Ca) to 5.59 (2.7% Ca), showing no statistical difference across treatments ($P > 0.05$; Table 5). The numerically highest color score at 2.7% Ca may relate more to diet composition particularly carotenoid content than to calcium levels. Attia *et al.* (2020) noted that yolk color is more influenced by vitamin D_3 and carotenoid intake than calcium alone. Since quails cannot synthesize carotenoids, yolk pigmentation depends heavily on dietary sources (Zurak *et al.*, 2022). Therefore, although calcium may play a secondary role, its impact on yolk color is marginal unless coupled with pigmentation-enhancing nutrients.

CONCLUSION

Based on the study, a dietary calcium level of 2.7–3.0% with 0.6% total phosphorus (Ca:P ratio of 2.7:1 to 3.0:1) optimizes quail egg production, feed efficiency, nutrient digestibility, and egg quality during the early-phase laying quails. Higher calcium (3.3–3.6%) showed no significant benefit and led to increased excretion and reduced mineral absorption. Moderation in calcium intake is crucial for maximizing productivity and minimizing environmental waste.

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NOVELTY STATEMENT

This study is novel because it is the first to systematically evaluate the effects of dietary calcium-to-phosphorus (Ca:P) ratios in early-phase laying quails, a production stage rarely investigated compared to aged quails or commercial laying hens. The findings reveal that a moderate Ca:P ratio (2.7:1–3.0:1) optimizes nutrient digestibility, mineral absorption, and feed conversion efficiency, whereas higher calcium levels (3.3–3.6%) reduce bioavailability and increase excretion. Unlike previous research that focused mainly on eggshell quality, this study demonstrates the broader influence of mineral balance on production performance. It highlights the environmental implications of excessive calcium through greater nutrient waste. Thus, the research contributes a new integrative framework showing that optimal calcium intake can simultaneously improve productivity, egg quality, and sustainability in quails' nutrition

AUTHOR'S CONTRIBUTION

DS: Conceptualization, methodology, investigation, writing original draft, writing review and editing, funding acquisition, resources, supervision. DW: Methodology, investigation, formal analysis. DK: Manuscript proofreading and editing.

Generative AI and AI-assisted technology statement

No generative AI tools were utilized to create content or perform data analysis in this manuscript. Grammarly, an AI-supported language application, was used only to refine grammar, spelling, and overall clarity. All scientific interpretations and conclusions are entirely the authors' responsibility.

Conflict of interest

The authors have declared no conflict of interest.

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